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1           **Reconstructing the Infilling History within Robert Sharp Crater, Mars:**  
2                           **Insights from Morphology and Stratigraphy**

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13   **Keywords**

14   Mars, Remote sensing, Geologic evolution, Aqueous minerals, Paleo-environments

15

16   **Highlights** (max. 85 characters, including spaces)

17   1. We produce a geologic map of Robert Sharp crater, at the dichotomy boundary.

18   2. Degradation of crater infillings into fretted terrain during Hesperian epoch.

19   3. Sedimentary or volcano-sedimentary airfall filling during Hesperian epoch.

20   4. Occurrence of late fluviolacustrine episodes possibly until the Amazonian period.

## 21 Abstract

22 Recent mineralogical studies suggest past aqueous activities in the 150-km-wide Robert Sharp  
23 impact crater, the western neighbor of Gale crater on Mars. Despite their mineralogical  
24 similarities, Robert Sharp and Gale craters display very different morphologies. Using high-  
25 resolution orbital images, we made morphological and stratigraphical analyses, as well as age  
26 determinations showing that Robert Sharp has experienced a complex geological history. This  
27 includes the formation of fretted terrain and the deposition of airfall material during the early –  
28 middle Hesperian epoch. The presence of valleys, fan deltas, and numerous aqueous minerals  
29 indicates fluviolacustrine episodes during the Hesperian epoch that persisted episodically until  
30 the Amazonian epoch between 1.3 Ga and 500 Ma. Thus, Robert Sharp and Gale craters have  
31 experienced contemporaneous aqueous phases possibly up to two billions years after the  
32 lacustrine environment recorded by the Curiosity rover within Gale crater.

## 33 1 Introduction

34 Robert Sharp impact crater is an open basin found along the Martian crustal dichotomy (Fig. 1,  
35 133.59°E, 4.12°S). Open basins are described as valley-fed depressions with outlets on Mars  
36 (*Fassett and Head, 2008*). Robert Sharp has a quasi-totally degraded northern rim, no apparent  
37 ejecta blanket, and its floor exhibits mesas and knobs. Recent spectral analyses of the data  
38 collected by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM, *Murchie et*  
39 *al., 2007*) and the Thermal Emission Imaging System (THEMIS, *Christensen et al., 2004*) in  
40 Robert Sharp and its surroundings show that the crater and its watershed display a varied  
41 mineralogy (e.g., *Osterloo et al., 2008, 2010; Ruesch et al., 2012; Carter et al., 2015; Ehlmann*  
42 *and Buz, 2015*). Dark sand sheets that cover the surrounding plateaus and dark dunes within the  
43 crater floor contain olivine and high-calcium pyroxene (*Ehlmann and Buz, 2015*). Numerous  
44 chloride-rich deposits appear as light-toned materials close to clay mineral outcrops located in  
45 the southwestern watershed outside the crater (*Osterloo et al., 2008, 2010; Ruesch et al., 2012*).  
46 These chloride-rich deposits are detected using “Observatoire pour la Minéralogie, l’Eau, les  
47 Glaces et l’Activité” (OMEGA, *Bibring et al., 2005*) and THEMIS Decorrelation Stretched  
48 (DCS, *Hamilton et al., 2007*) data, and are commonly located in low-topography areas. An iron  
49 chlorine hydroxide, named akaganeite ( $\beta$ -FeOOH, Cl), has been detected in Robert Sharp  
50 (*Carter et al., 2015*). Akaganeite is a mineral that typically forms in acidic and saline wet

51 environments on Earth. Its occurrence within Robert Sharp may provide significant constraints  
52 on the ancient aqueous environment in the region (*Peretyazhko et al., 2018*). Besides the  
53 detections of akaganeite and chlorides, several deposits containing Fe/Mg phyllosilicates and  
54 other aqueous mineral phases have been observed within the crater and its surroundings (*Carter*  
55 *et al., 2015; Ehlmann and Buz, 2015*). Those latter deposits are usually detected at scarps in the  
56 crater rims and on fan-shaped deposits, which are located in the western half of the crater. This  
57 could indicate chemical interactions with near-neutral to alkaline waters, and hence supports the  
58 existence of past aqueous activity throughout the region. Interestingly, similar minerals have  
59 been detected in Gale crater by the Curiosity rover (Mars Science Laboratory, MSL) (*Ming et al.,*  
60 *2014, Vaniman et al., 2014*). Robert Sharp and Gale craters are found in adjacent watersheds.

61 Robert Sharp crater is either mentioned in the Martian literature for the varied mineralogy found  
62 therein (*Carter et al., 2015; Ehlmann and Buz, 2015*), the presence of fretted terrains (i.e.,  
63 terrains characterized by a complicated mix of cliffs, mesas, buttes, straight-walled and sinuous  
64 canyons) at a more global scale (*Sharp, 1973*), or the fluvial processes that affected the region of  
65 both Robert Sharp and Gale craters (*Ehlmann and Buz, 2015*). Nonetheless, no detailed  
66 geological mapping of the crater has been performed. Such mapping, however, is crucial to  
67 better understand the geological history of Robert Sharp, as well as that of the watershed area.  
68 We therefore focus on constraining the hydrological and geological history of Robert Sharp  
69 crater in relation with the regional geological context. In order to reconstruct the paleo-  
70 environment in the region, we produced a geological map of Robert Sharp by combining a  
71 morphological, stratigraphical and mineralogical study of its infilling materials ([section 4.1](#)). We  
72 also performed crater counts on selected features in order to provide time constraints on the  
73 infilling history in Robert Sharp ([section 4.2](#)). Then, we discuss the possible origin of the  
74 geologic units identified within Robert Sharp ([section 5](#)) and the mineralogy detected within the  
75 crater ([section 6](#)). We propose a chronology of events to reasonably retrace its geological history  
76 ([section 7](#)). Finally, we consider the implications for aqueous activity and geochemical  
77 environments in the region of Robert Sharp and Gale craters ([section 8](#)).

78 [\[Figure 1\]](#)

## 79 **2 Physiography & age**

80 Robert Sharp crater is located between Terra Cimmeria to the south and Elysium Planitia to the  
81 north (Fig. 2a). It is very similar in size to its neighbors, Gale crater to the east (137.8°E, 5.4°S)  
82 and Knobel crater to the south (133.2°E, 6.7°S), with a diameter of ~150 km. The crater consists  
83 of an open basin towards the northern plains since its northern rim has been heavily breached  
84 (Fig. 2a). Its original eastern rim is not exposed at the surface anymore since it appears to be  
85 buried under deposits partially filling the crater and the surrounding plateau. The floor of Robert  
86 Sharp is partially filled with knobs and mesas of varied sizes and shapes forming a  
87 heterogeneous pattern. These landforms are characteristic of the so-called ‘fretted terrain’, as  
88 defined by *Sharp (1973)* (see section 4.1.2). Overall, the eastern part of Robert Sharp’s floor  
89 raises 1.5 km higher than the western part, resulting in a west-east topographic asymmetry (Fig.  
90 2b). The western rim rises up to 500 m of elevation, while the buried eastern rim is now at –1000  
91 m of elevation. A THEMIS brightness temperature map (Fig. 2c) reveals low and high  
92 temperature areas in the crater. A Thermal Emission Spectrometer (TES) dust cover index (Fig.  
93 2d) shows that only the western and southwestern parts of the crater are dust-free, corresponding  
94 to the higher-temperature areas in the THEMIS brightness temperature map from Fig. 2c (*Ruff  
95 and Christensen, 2002*). Conversely, the low temperature areas are probably covered by dust or  
96 unconsolidated sands.

97 [Figure 2]

98 Robert Sharp crater possibly formed in the Noachian epoch, based on the presence of weakly  
99 expressed valley networks incising the crater walls and the stratigraphic relationship with fretted  
100 terrains. The basement of Robert Sharp corresponds to the middle Noachian highland unit  
101 (‘mNh’) in *Tanaka et al. (2014a; 2014b)*. Based on stratigraphical relationships, Robert Sharp is  
102 inferred to be older than Gale (*Ehlmann and Buz, 2015*) which is expected to have been formed  
103 during the late Noachian – early Hesperian transition (*Thomson et al., 2011; Le Deit et al.,  
104 2013*). Thus, Robert Sharp possibly formed between the middle Noachian and the early  
105 Hesperian. Robert Sharp is therefore thought to have formed before or during the decline of  
106 large-scale fluvial activity in the northern highlands in late Noachian (e.g., *Fassett and Head,  
107 2008; Irwin et al., 2005*), and before the formation of fretted terrains expected to be early  
108 Hesperian (*Irwin et al., 2004; Irwin and Watters, 2010*).

### 109 **3 Data and methods**

### 110 **3.1 Geological mapping**

111 We mapped Robert Sharp (Fig. 3) and defined its geological units according to their location and  
112 physical properties such as surface texture, morphology, geometry and thermal inertia.  
113 Morphologic information is provided by high resolution images of the ContExT imager (CTX, 6  
114 m/pixel) (Malin et al., 2007), providing a geomorphological context for higher spatial resolution  
115 observations acquired by the High Resolution Imaging Science Experiment (HiRISE, 25–32  
116 cm/pixel) (McEwen et al., 2007). Brightness temperature variations between surface units are  
117 revealed by the Thermal Emission Imaging System (THEMIS, 100 m/pixel) in night-time  
118 infrared data (Christensen et al., 2004; Fergason et al., 2006). The brightness temperature of  
119 materials at the surface is directly correlated to their thermal inertia that provides information on  
120 the grain size and induration of materials within the first centimeters of the surface. High thermal  
121 inertia surfaces may indicate coarse grain-sized and/or indurated rocks exposed at the surface  
122 while low thermal inertia surfaces indicate smaller grains, poorly indurated rocks, or dust  
123 coating.

124 We used the global raster Digital Elevation Model (DEM) of the Mars Orbiter Laser Altimeter  
125 (MOLA), with a horizontal accuracy of about 200 m and a vertical accuracy of around 1 m  
126 (Smith et al., 2001) for analyzing the stratigraphic relationships between the geological units  
127 (Fig. 4). Where available, we also used the DEM from the High Resolution Stereo Camera  
128 (HRSC, Neukum and Jaumann, 2004; Jaumann et al., 2007) of up to 50 m grid spacing and  
129 vertical deviations from MOLA with few meters (Gwinner et al., 2010).

130 [Figure 3] – [Figure 4]

### 131 **3.2 Age determination**

132 We performed crater counts on CTX images to estimate the model ages of two fan-shaped  
133 deposits, the crater floor, and a chloride-rich deposit. The crater counts were produced using the  
134 CraterTools extension for ArcGIS software (Kneissl et al., 2011). Absolute model ages were  
135 determined using the Craterstats software (Michael and Neukum, 2010), whose models are  
136 derived from the Mars production function of Ivanov (2001) and the chronology function of  
137 Hartmann and Neukum (2001). Only impact craters with diameters greater than 70 m were

138 considered in order to limit the effect of potential secondary craters (*Michael, 2012*) and to  
139 further reduce effects of image resolution.

## 140 **4 Geologic map of Robert Sharp and infilling chronology**

### 141 *4.1 Geologic mapping results*

142 Geological units mapped in Robert Sharp (*Fig. 3*) are described hereafter in stratigraphic order  
143 from the oldest to the youngest. Valleys, fan-shaped deposits, and sinuous ridges are presented  
144 thereafter.

#### 145 *4.1.1 Basement and crater wall deposits*

146 The basement is the oldest unit of the region and consists of “undifferentiated impact, volcanic,  
147 fluvial, and basin materials” mapped as the middle Noachian highland unit (‘mNh’) in the global  
148 geologic map of *Tanaka et al. (2014a; 2014b)*. This Noachian unit is thought to represent parts  
149 of the primitive crust of Mars formed by solidification of a primordial, molten surface and  
150 bombarded by large planetesimal-size objects (*Tanaka, 1986*). Crater wall deposits are seen at  
151 the foot of the southern inner rim of Robert Sharp and at the foot of an isolated basement block  
152 to the north (interpreted to be a remnant of the northern rim) (*Fig. 3*).

#### 153 *4.1.2 Fretted terrain*

154 The fretted terrain consists of isolated buttes with sharp-crested or flat tops, informally named  
155 knobs and mesas, respectively. The term ‘fretted terrain’ is defined on the basis of their  
156 morphology and not their lithology (*Sharp, 1973*). Their lithology can be diverse, but difficult to  
157 assess from orbit. These buttes are several hundred meters to tens of kilometers-wide and are  
158 several hundreds of meters to 2 km in height. The surface of the knobs and mesas is smooth and  
159 flat (*Figs. 5a–c*). The fretted terrain is located within the crater and is extending to the north of  
160 the crater towards the lowlands (*Fig. 2*). The fretted terrain is less abundant in the western half of  
161 the crater than in the eastern half, as western mesas and knobs are relatively smaller and less  
162 numerous, displaying a west-east asymmetry (*Figs. 3 and 4*).

163 [*Figure 5*]

#### 164 *4.1.3 Draping units*

165 The draping deposits are observed in the eastern half of the crater and on the surrounding plateau  
166 (Fig. 3). No clear contact is seen between the fretted terrains and the draping deposits. They  
167 appear to dip parallel to the crater floor, and lie topographically and stratigraphically above the  
168 fretted terrains and the eastern nearby plateaus (Fig. 4). Draping deposits are divided into two  
169 sub-units based on their respective surface texture: Dp1 (rough) and Dp2 (smooth). The Dp1 unit  
170 shows a rough surface texture (Figs. 5d–e), and covers an area of 5200 km<sup>2</sup>. It is commonly  
171 found in the center and eastern side of Robert Sharp (Fig. 3) where it embays and molds knobs  
172 and mesas (Fig. 5f). The Dp2 unit appears to be stratigraphically above the Dp1 unit (Figs. 5d–f)  
173 and it has a smoother surface texture than the Dp1 unit (Fig. 5e). With an area of about 5000  
174 km<sup>2</sup>, the Dp2 unit extends to the plateau to the east of Robert Sharp where it appears to mantle  
175 Gale’s ejecta.

#### 176 *4.1.4 Polygonal ridges*

177 Polygonal ridges are locally crosscutting the draping deposits and a few mesas of the fretted  
178 terrain (Fig. 3). They form networks of light-toned ridges exposed as isolated patches, randomly  
179 distributed across the draping units and the fretted terrains. They range between –1100 m and –  
180 2130 m in elevation (Fig. 5g). Ridges are heterogeneous in size and shape, each ridge varying  
181 from one hundred of meters to several hundreds of meters in length, and several tens of meters in  
182 width (Fig. 5h). Ridges do not intersect with preferential angles within the ridge networks.

#### 183 *4.1.5 Crater floor deposits*

184 The crater floor deposits are found at the bottom of Robert Sharp (Fig. 3). The crater floor  
185 deposits mostly occupy the southern and northern sections of the western half of Robert Sharp  
186 (Fig. 6a). They cover an area of about 6660 km<sup>2</sup> and are exposed in the lower part of the crater,  
187 down to –2700 m altitude (Fig. 4). This unit embays knobs of the fretted terrain and is thus  
188 stratigraphically above and younger than the fretted terrain. Traces of akaganeite have been  
189 detected in local depressions jointly with clays and possible carbonates (Carter et al., 2015). The  
190 diverse mineralogy within the crater is better described in section 6.

191 [Figure 6]

#### 192 *4.1.6 Valleys, fan-shaped deposits and sinuous ridges*

193 Valleys have been deeply incised into the southwestern and western walls of Robert Sharp (Figs.  
194 6b–c). Most of them are several tens of kilometers long, rectilinear to slightly sinuous in  
195 planview, and with poor tributary development. Only the southernmost valley (Fig. 6c) has  
196 multiple tributaries and is several hundred kilometers long, with a valley head within the  
197 highlands north of Herschel crater (*Irwin and Howard, 2002*). Additionally, this valley appears  
198 to be interconnected by several shallow basins along its network, identified as ‘intravalley  
199 basins’ in *Irwin and Howard (2002)*. Valleys breaching Robert Sharp walls are approximately 1–  
200 2 km wide, and the depth is around 250 m in the western valleys and around 1 km in the  
201 southernmost valley. They have little to no tributary development along their entrenched lower  
202 reaches inside the crater rim.

203 Well-preserved fan-shaped deposits are located at the terminus of some valleys, at the northwest  
204 (132°43'E, 3°37'S) and southwest (132°53'E, 5°7'S) of the crater (Figs. 7a–b). The northwestern  
205 fan-shaped deposit (84 km<sup>2</sup>) and the southwestern one (142 km<sup>2</sup>) superpose the crater floor  
206 deposits. The two deposits present flat-topped surfaces with some evidence of channelization.  
207 Their distal margin is clearly outlined by frontal scarps at about –2400 m in elevation (Figs. 7c–  
208 d). Given the lack of remnant buttes close to the fan-shaped deposits, the present frontal scarps  
209 may be close to the primary depositional front with limited backward erosion. The longitudinal  
210 profiles of the fan-shaped deposits show gently sloping tops with an average plain gradient of  
211 about 1–2 degrees (3% slope) over a length of approximately 10 km, followed by steeply dipping  
212 fronts that abruptly merge into the adjacent plains. The frontal scarps have been estimated to dip  
213 6–11 degrees (10–20% slope) on the basis of HRSC DEM data. Both deposits reach thicknesses  
214 between 100 and 300 m. This thickness is certainly not uniform over the entire fan-shaped  
215 deposits surface and decreases towards the apex, as the fan-shaped deposits are superposed on  
216 sloping crater walls. Their surfaces are partially covered by dark materials probably derived from  
217 the dune fields present on the southern section of the crater floor deposits. Phyllosilicates have  
218 been detected located within scarps in the fan-shaped deposits (*Ehlmann and Buz, 2015*). Their  
219 spectral signature is identical or near identical to those found in the southern plateau alongside  
220 the chloride deposits (*Osterloo et al., 2008, 2010; Ruesch et al., 2012*). More details about the  
221 phyllosilicates and chlorides deposits are provided in a later section (section 6).

222 [Figure 7]

223 Several sinuous ridges are observed on the crater floor deposits (Fig. 6d). They are poorly  
224 ramified and are oriented parallel to the direction of the steepest slope. The length of these ridges  
225 does not exceed 10 km long. Their width is usually of several tens of meters and varies along the  
226 ridges. The spatial resolution of MOLA and HRSC DEM topographic data do not permit to  
227 measure the height of these ridges. Measurements of the length of ridge shadows provide an  
228 approximate height of several meters.

#### 229 **4.2 Age of selected geologic units in Robert Sharp crater**

230 Crater counts were performed on the fan-shaped deposits, the crater floor deposits as well as the  
231 chloride-rich deposits located on the plateau south of Robert Sharp. No crater counts have been  
232 done on the fretted terrain, which appears to be covered with a dusty mantle (Fig. 2c) preventing  
233 any reliable crater counts. The estimated ages of the southwestern and northwestern fan-shaped  
234 deposits are about  $1.43 \pm 0.58$  Ga and  $512 \pm 83$  Ma, respectively (Figs. 8a–b). Crater counting in  
235 the southwestern fan-shaped deposit points to a resurfacing event at ~120 Ma. This suggests a  
236 recent episode of sediment deposition and erosion with at least one episode of fluvial reworking,  
237 or aeolian degradation. These results are consistent with those obtained by *Ehlmann and Buz*  
238 (2015), and correspond to early – middle Amazonian ages.

239 The two fan-shaped deposits are stratigraphically above the crater floor deposits that have an  
240 estimated age of ~3 Ga, which corresponds to the late Hesperian – early Amazonian boundary  
241 (Fig. 8c). *Ehlmann and Buz (2015)* estimated an older age of ~3.6 Ga for the floor of Robert  
242 Sharp considering the floor of the whole crater (including the fretted terrain and draping  
243 deposits) without distinguishing the different infilling units in the crater.

244 We also performed the crater counts on a local depression exhibiting chloride-rich deposits  
245 initially detected in *Osterloo et al. (2008, 2010)* and *Ruesch et al. (2012)*. Those deposits are  
246 located on the neighboring plateaus at the southwest of the valley entrance to Robert Sharp and  
247 west of Knobel (131.94°E, 6.4°S, bottom-left corner in Fig. 3). Fig. 8d reveals that this  
248 depression has an Amazonian age, about  $1.12 \pm 0.33$  Ga, similar within uncertainties to that of  
249 the southwestern fan-shaped deposit. *Ehlmann and Buz (2015)* also estimated a similar age of  $1.1$   
250  $\pm 0.3$  Ga. These results suggest a synchronous formation of these chloride-rich deposits and the  
251 southwestern fan-shaped deposit.

252 [Figure 8]

253 The two fan-shaped deposits and the chloride-basin are very small areas (84–142 km<sup>2</sup> and 36  
254 km<sup>2</sup>, respectively) that may not yield reliable, representative ages because they may not include  
255 any less numerous, typically more widely-spaced larger craters that would be captured in  
256 statistics covering a larger area (e.g., *von der Bogert et al., 2015; Warner et al., 2015; Palucis et*  
257 *al., 2020*). As a result, the statistics obtained may reflect an artificially young age for these  
258 surface units. Although the crater counts are subject to associated statistical limitations, we  
259 observe that the relative age of these small areas is consistent with stratigraphic relationships,  
260 when existing. By putting together their superposition relationships and crater counts, the fan-  
261 shaped deposits and chloride-basin are younger than underlying units, further constraining their  
262 formation to Hesperian or after (see also *Ehlmann and Buz, 2015*).

## 263 **5 Interpretation of the geological units**

### 264 **5.1 Fretted terrain**

265 The fretted terrain present in Robert Sharp is similar in shape and size to that commonly found  
266 elsewhere along the crustal dichotomy, between the southern highlands and the northern  
267 lowlands. It consists of plateaus, mesas, knobs and mounds in a highly irregular configuration  
268 separated by wide, flat-floored channels, valleys and troughs (*Sharp, 1973; Carr, 1995*). These  
269 landforms are commonly interpreted to result from the erosion of a thick pile of material with  
270 weak properties that could have accumulated from sedimentary or volcano-sedimentary  
271 processes (*Tanaka, 1986; Maxwell and McGill, 1988; Fassett and Head, 2007*). To date, the  
272 origin and development of the fretted terrain on Mars remains poorly understood. No  
273 mineralogical analysis has been performed yet on mesas and knobs within Robert Sharp,  
274 probably due to the lack of CRISM data at high resolution and the abundance of dust in the  
275 region (**Fig. 2d**). Due to the location of Robert Sharp, the mesas and knobs found there could be  
276 part of a vast fretted terrain in Aeolis Mensae (10°N–10°S, 120°–150°E). Interestingly,  
277 morphologic and thermal observations by *Irwin et al. (2004)* suggest that the fretted terrain in  
278 Aeolis Mensae is composed of friable sedimentary materials. These materials differ  
279 compositionally from the older highland materials but may resemble the sediments from the  
280 younger Medusae Fossae terrains. Medusae Fossae layered materials are thought to be made of

281 friable and variably consolidated deposits, such as dust, volcanic ash (*Scott and Tanaka, 1982;*  
282 *Bradley et al., 2002; Mandt et al., 2008; Kerber et al., 2011*), or even ice-rich polar deposits  
283 (*Schultz and Lutz, 1988; Head and Kreslavsky, 2004*). All these proposed origins imply  
284 atmospheric transport and airfall deposition of sedimentary materials that could be responsible  
285 for deposits forming the fretted terrain.

286 Many different hypotheses were proposed to explain the apparent break up and removal of such  
287 material: (1) fluvial and aeolian erosion (*Breed et al., 1982; Carr, 1995; McGill, 2000; Irwin et*  
288 *al., 2004*), (2) subsurface removal by groundwater flow (*Carr, 1995; Carr, 1996*), and (3)  
289 faulting and tectonism (*Sharp, 1973; Irwin and Watters, 2010*). *Breed et al. (1982)* posit that  
290 fretted terrains may result of an important aeolian deflation and mass wasting overprint on a  
291 landscape initially carved by running water. More recent analyses (e.g., *Denton and Head, 2018*)  
292 tend to favor fluvial and groundwater activity as possible fretting processes. Nonetheless, further  
293 examinations at larger scale are required to assess the relative proportions of surficial and  
294 subsurface hydrous activity (overland flow, groundwater flow, and ice melting) as mechanisms  
295 for removal of material from the fretted terrains. Nowadays, little to no evidence of former  
296 fluvial activity coeval to the fretted terrain degradation remains in Robert Sharp floor. Therefore,  
297 most flow paths or other evidence must have been completely masked by later significant, non-  
298 fluvial degradation.

299 It has been suggested that the materials forming the fretted terrain were deposited during the  
300 early Hesperian epoch, at around 3.7–3.6 Ga (*Irwin et al., 2004; Irwin and Watters, 2010*), hence  
301 shortly after the impact that formed Robert Sharp basin. *Fassett and Head (2007)* estimated the  
302 formation and erosion time of the fretted terrain to range between 100 and 300 Ma, involving an  
303 erosion relatively shortly after their formation during Hesperian. Moreover, the lack of an  
304 observable central peak in Robert Sharp (unlike its neighbors: Gale and Knobel craters) could be  
305 related to its older age, implying more erosion of its peak and rims, followed with more  
306 deposition of the materials that were degraded into fretted terrains.

## 307 *5.2 Draping deposits*

308 The draping deposits (Dp1 and Dp2 units) are mostly found in the eastern half of Robert Sharp  
309 and on the eastern surrounding plateaus towards Gale. No volcanic candidate landforms such as

310 lavas flows with lobes or vents are observed, suggesting that the draping deposits did not form as  
311 volcanic flows. Considering their location both in a depression and on plateaus, a lacustrine  
312 origin seems dubious. The high elevation of the eastern plateau-would imply an extremely deep  
313 lake (~2 km deep). We found no confining topography on the eastern plateau that would enable  
314 ponding to form a lake between Robert Sharp and Gale craters. Likewise, no fluvial channel,  
315 sinuous ridge, or apparent cross-bedding have been observed within the draping deposits,  
316 implying that a fluvial origin is also unlikely. The draping deposits mantle and are conformable  
317 to the basement. We therefore favor that these deposits may correspond to airfall and/or aeolian  
318 material consisting of fine-grained erodible sediment, such as dust, volcanic ash, and aeolian  
319 sand (like the fretted terrain).

320 Deposits having similar erosional aspect with relatively weak material are observed in the  
321 Medusae Fossae Formation (MFF) and may have the same origin as our draping deposits. *Ojha*  
322 *and Lewis (2018)* recently suggested that such deposits could be consistent with extremely  
323 porous (low-density) material like volcanic ash deposits. The presence of such airfall material  
324 has been predicted in Gale crater from orbital analyses, and are expected to be a major  
325 component of the 5 km-high Gale central mound, Aeolis Mons (e.g., *Le Deit et al., 2013*). Thus,  
326 Robert Sharp draping deposits may share common origin with some deposits of Aeolis Mons.  
327 Most sedimentary rocks in Gale are thought to have been deposited, buried, lithified, exhumed,  
328 and eroded before 3.3–3.1 Ga (*Grotzinger et al., 2015*). Considering that the crater floor deposits  
329 that presumably postdate the draping deposits are inferred to be ~3 Ga in age (*Fig. 8c*), the  
330 draping deposits in Robert Sharp may be older than 3 Ga and therefore deposited coevally with  
331 some deposits of Aeolis Mons in Gale crater.

### 332 *5.3 Valleys, sinuous ridges, fan-shaped deposits, and crater floor deposits*

333 Valleys incised along Robert Sharp's western walls are short and rectilinear, and have only few  
334 tributaries and display theater-like valley heads. These characteristics are often considered to be  
335 associated with valleys formed by groundwater seepage rather than surface runoff (e.g., *Sharp*  
336 *and Malin, 1975; Harrison and Grimm, 2005; Pelletier and Baker, 2011; Baker et al., 2015*).  
337 Such valleys often terminate in small and pristine scarp-fronted deposits, which exhibit little or  
338 no fan-head trenching or incision of the outer bounding scarp (e.g., *Irwin et al., 2005; Hauber et*  
339 *al., 2013*). *Lapotre and Lamb (2018)* argue that seepage erosion can only occur in loose or

340 weakly consolidated rock and not in competent rock like the Noachian basaltic bedrock.  
341 According to experimental observations (*Howard and McLane, 1988; Marra et al., 2014*), valley  
342 formation by seepage is limited to narrow ranges in aquifer permeabilities and sediment sizes  
343 that are characteristic of loose sediment. Nonetheless, a combination of groundwater and surface  
344 flows can explain the valley erosion in the basaltic basement (e.g., *Lamb et al., 2006; Pelletier*  
345 *and Baker, 2011; Amidon and Clark, 2015*). As for the southernmost valley, it is longer and  
346 more sinuous. This appears to be a typical example of a well-developed valley network incised  
347 by runoff on Mars (*Carr, 1996; Irwin and Howard, 2002*). Its lower reaches could have been  
348 reactivated coevally with the western valleys. The crosscutting of the western valleys into fretted  
349 terrain suggests a brief reactivation of highland fluvial activity after the fretted terrain formed  
350 (*Irwin et al., 2004*). This reactivation likely consisted of multiple flow episodes of similar  
351 magnitudes, as inferred from the lack of trenching or incision of the front scarps of the two  
352 deltas. The relationship with the fretted terrains indicates that the incision occurred during or  
353 after the early Hesperian epoch.

354 The sinuous ridges found within Robert Sharp crater (*Fig. 6d*) are interpreted as inverted  
355 channels, formed after inversion of the relief by differential erosion. Due to the lack of clear  
356 evidence for glacial activity in the crater it seems unlikely that these sinuous ridges are  
357 subglacial eskers. They are morphologically similar to those seen in Gale and they present a  
358 consistent downslope orientation which corroborates the idea that those features represent an  
359 older aqueous drainage pattern (e.g., *Anderson and Bell, 2010; Le Deit et al., 2013; Palucis et*  
360 *al., 2014*).

361 The two fan-shaped deposits have a morphology and topography characteristic of single scarped,  
362 smooth, prograding deltas; with flat-topped surfaces and distal margins clearly marked by steep  
363 frontal scarps (e.g., *Irwin et al., 2005; deVilliers et al., 2013*). Deltas display a steep peripheral  
364 scarp at their outer margin, a genetic distinction that contrasts with the slightly concave  
365 longitudinal profile of alluvial fans (*Moore and Howard, 2005*). Such deltas usually result from a  
366 river encountering a stagnant body of water (e.g., a lake), and would imply a lacustrine episode  
367 within Robert Sharp crater. The scarp crests on the two deltas occur at the same elevation (−2400  
368 m), consistent with ponding in the western half of the Robert Sharp basin (*Fig. 7*). On the basis  
369 of our longitudinal profiles (*Fig. 7*), the front scarps are estimated to dip 6–11 degrees, consistent

370 with Gilbert-type deltas (*Gilbert, 1980; Nemec, 1990*). We suggest that Robert Sharp deltas may  
371 resemble terrestrial shallow fan deltas (*Galloway, 1976; Wescott and Ethrude, 1990*). On Earth  
372 such deltas encroach onto low-gradient shelves with very shallow water depths near river  
373 mouths. The gently dipping part may have been the subaerial portion of the delta, while the more  
374 inclined part corresponds to the submerged delta front. Similar deltas are found on Mars, e.g.,  
375 Pancake delta within Gale crater (*Palucis et al., 2016*), with an arcuate shape, a fairly well  
376 preserved delta front, and surface area of  $\sim 100 \text{ km}^2$ . Considering that the floor of Robert Sharp  
377 crater lies at an elevation as low as around  $-2700 \text{ m}$ , we can estimate a lake depth of about 100–  
378 300 m (in agreement with the  $\sim 200 \text{ m}$  deep paleolake predicted by *Rivera-Hernández and*  
379 *Palucis, 2019*). Our crater counting predicts that both deltas have Amazonian ages, while the  
380 adjacent crater floor deposits have an older age close to the late Hesperian to early Amazonian  
381 transition (*Fig. 8*). The crater floor deposits are located topographically below the two deltas in  
382 Robert Sharp, and possibly stratigraphically lower (*Fig. 9a*). It is possible that they were  
383 deposited before the deltas, and more precisely, before the last lacustrine episode associated to  
384 the delta formation. They may correspond to draping deposits that have been buried by lacustrine  
385 deposits that formed at the outlet of the deltas and were later exhumed. If the draping deposits  
386 were not completely exhumed, some of the crater floor may still be lacustrine deposits (*Fig. 9b*).

387 Interestingly, Robert Sharp's sinuous ridges are seen on the crater floor deposits, indicating a  
388 possible channelization coeval to (or prior) the lacustrine episode within the crater. Then, the  
389 channels could have been buried by lacustrine deposits. Finally, their exhumation and subsequent  
390 segmentation by aeolian abrasion started after the lake disappearance, and still continues  
391 nowadays.

#### 392 **5.4 Polygonal ridges**

393 Polygonal ridges within Robert Sharp have morphologies indicating an origin by mineralization  
394 of fractures. Such ridges are interpreted as fractures filled and cemented by minerals that were  
395 precipitated from near-surface groundwater (e.g., *Thomson et al., 2011; Kerber et al., 2017*).  
396 *Kerber et al. (2017)* classified Robert Sharp ridges as 'Nili-type' ridges. They consist of mostly  
397 light-toned ridges of varying thickness intersecting at a wide variety of angles, like most  
398 polygonal ridges described in the Nili Fossae and Nilosyrtris regions (*Ebinger and Mustard,*  
399 *2015; Kerber et al., 2017; Pascuzzo et al., 2019*). Similar features are seen within Gale and,

400 more precisely, were found at the basis of Aeolis Mons (*Anderson and Bell, 2010; Thomson et*  
401 *al., 2011; Siebach and Grotzinger, 2014; Kronyak et al., 2019*), and in the eastern part of Gale  
402 (*Le Deit et al., 2013*). Polygonal ridges in Robert Sharp show similarities with polygonal ridges  
403 in Gale in terms of morphology, but not in size. Gale's polygonal ridges are smaller than those in  
404 Robert Sharp and are tens of meters long (e.g., *Le Deit et al., 2013*). In Gale, they have been  
405 attributed to the preferential cementation of material due to the circulation of fluids through  
406 fracture systems (*Thomson et al., 2011; Kerber et al., 2017*). The morphological similarities  
407 between Gale's polygonal ridges and those identified in Robert Sharp (Nili-type ridges) suggest  
408 that Gale's polygonal ridges are simply smaller versions of Nili-types. These polygonal ridges  
409 are indicative of fluid circulation within the fretted terrain and the draping materials that may be  
410 coeval to the late lacustrine phase in Robert Sharp crater.

## 411 **6 Robert Sharp's mineralogy**

412 Several mineral types have been detected in Robert Sharp crater and surroundings (*Fig. 10*).  
413 *Ehlmann and Buz (2015)* detected Fe/Mg smectites in the southwest fan delta, the most common  
414 hydrated minerals found on Mars (*Carter et al., 2013*). Their infrared signature displays spectral  
415 absorption bands at 1.4, 1.9 and 2.3  $\mu\text{m}$ , which is consistent with a composition intermediate  
416 between end-member smectites nontronite (Fe-rich) and saponite (Mg-rich) (*Viviano-Beck et al.,*  
417 *2014; 2015*). They appear in light-toned layered deposits along the delta front and at its foot  
418 (*Ehlmann and Buz, 2015, Figs. 10d–e*). Fe/Mg clay minerals may be authigenic and have formed  
419 either during the transport of sediment or within the lake itself. Alternatively, they may be  
420 detrital and have formed upstream by near-surface weathering and were subsequently transported  
421 and deposited in the fan. This latter hypothesis is supported by the occurrence of clays exposed  
422 along the channel incising the southern wall of the crater and on the perched plateau associated  
423 with chlorides (*Osterloo et al., 2008, 2010; Ruesch et al., 2012*). In addition to Fe/Mg smectites,  
424 *Ehlmann and Buz (2015)* found Al smectites (montmorillonite, kaolinite), or possibly hydrated  
425 silica locally in the southwest delta, with typical spectral absorption bands at 1.4, 1.9 and 2.2  $\mu\text{m}$ .  
426 Hydrated silica is commonly observed on fan deltas on Mars, and may have formed in-situ  
427 through chemical alteration during surface water flow and ponding (e.g., *Carter et al., 2012;*  
428 *Hauber et al., 2013; Pan et al., 2019; Pineau et al., 2020*). Al smectites may have formed in

429 deltaic environments by weathering. This formation process has also been proposed for a delta  
430 located at the dichotomy boundary in Lybia Montes (*Erkeling et al., 2012; 2015*).

431 Other hydrated minerals within Robert Sharp such as akaganeite and Fe carbonates (siderite)  
432 were reported by *Carter et al. (2015)*. Akaganeite ( $\beta$ -FeOOH, Cl) is an iron chlorine hydroxide  
433 that is associated on Earth to acidic and oxidizing conditions in a drying lake or lagoon (*Bibi et*  
434 *al., 2011*). Akaganeite occurs systematically in small depressions in Robert Sharp (*Figs. 10f–g*),  
435 which correspond to possible late stage ponding locations. Similar deposits are found in localized  
436 topographic lows in Jezero crater and northeast Syrtis (*Dundar et al., under review*).

437 Thanks to the analysis of the CRISM multispectral data, we found mixtures of Fe/Mg smectites,  
438 Al smectites (or hydrated silica), and sulfates in close proximity to the polygonal ridges lying on  
439 the draping deposits (*Fig. 10h*). This is likely related to mineral cementation associated with  
440 diagenesis in sediments, like in Gale (*Siebach and Grotzinger, 2014*). Additionally, the geometry  
441 and characteristics of the polygonal ridges as well as the presence of sulfates support the idea  
442 that the ridges are formed by chemical alteration or precipitation of minerals in or along pre-  
443 existing fractures. Sulfate salts can precipitate during alteration by circulating groundwater  
444 (*Andrews-Hanna and Lewis, 2011*), as suggested in Gale crater (*Grotzinger et al., 2014; 2015;*  
445 *Siebach and Grotzinger, 2014*). Other examples of filled fractured networks present in sulfate-  
446 bearing deposits were reported in Candor Chasma (*Okubo and McEwen, 2007*) and northeast  
447 Syrtis Major (*Ehlmann and Mustard, 2012*). However, our newly detected mixtures of smectites  
448 and sulfates within Robert Sharp are found in an area of the crater covered by dust (*Fig. 2d*) and  
449 that is only observed through CRISM data at low spatial resolution ( $\sim 200$  m per pixel) and low  
450 spectral resolution ( $\sim 50$  nm per channel) (*Murchie et al., 2007; Pelkey et al., 2007*). Thus, these  
451 detections are less robust than the previous ones obtained with CRISM data at scales of  $\sim 18$  m  
452 per pixel and spectral resolutions of 6.55 nm per channel.

453 [*Figure 10*]

## 454 **7 Robert Sharp's geological history**

455 After its formation between the middle Noachian and early Hesperian epoch (*Fig. 11a*), Robert  
456 Sharp has experienced an infilling stage with sedimentary and/or volcano-sedimentary material  
457 during the early Hesperian (*Fig. 11b*). Subsequently, this material underwent a significant

458 degradation, leading to the fretted terrain formation during the early Hesperian epoch. The crater  
459 floor is therefore predominantly dotted with mesas and knobs (Fig. 11c). Later, the draping  
460 deposits have partially or entirely filled the crater as well as the surrounding plateaus to the east  
461 of Robert Sharp through airfall/aeolian deposition of fine-grained sediment like dust and/or  
462 volcanic ash (Fig. 11d). These deposits are not found in the western floor of the crater and it is  
463 difficult to determine whether they once filled the western side of the crater or not. Fluvial  
464 activity leads to the incision of the western and southwestern walls of Robert Sharp and carried  
465 sedimentary material within the crater. Then, the fan-shaped deposits and the crater floor  
466 deposits record lacustrine episodes filling the lower parts of the crater between the Hesperian and  
467 early Amazonian epoch (Fig. 11e). The fretted terrain and draping deposits might have been  
468 exposed over a broader area in the crater during the Hesperian epoch, and then removed by late  
469 fluvial and aeolian degradation in the western part of the crater. The deltas and chloride-rich  
470 deposits show model ages of ~1 Ga to hundreds of Ma (Fig. 8), but due to the small counting  
471 areas and the possibility of removal of the oldest craters, our ages may be underestimated (e.g.,  
472 *von der Bogert et al., 2015; Warner et al., 2015; Palucis et al., 2020*). However, stratigraphic  
473 relationships were taken into account when existing, and they show that the deltas and chloride-  
474 basin are younger than the underlying materials, hence implying a formation during the  
475 Hesperian or after. Afterwards, this activity becomes progressively more spatially localized and  
476 episodic in the Hesperian – Amazonian period, with deposition of the chloride-rich material in  
477 local depressions and remobilization of Fe/Mg phyllosilicates in deltas. Finally, after the  
478 disappearing of the lake, the crater floor exhibits a plethora of mineral phases suggesting diverse  
479 environmental conditions (Fig. 11f), from neutral, reducing to mildly acidic, highly saline and  
480 oxidizing conditions.

481 [Figure 11]

## 482 **8 Implications of aqueous activity for the Robert Sharp and Gale craters region**

483 Like Robert Sharp, Gale exhibits several morphologic features suggestive of fluvial, deltaic and  
484 lacustrine processes in its interior, notably the presence of well-defined valleys incising the crater  
485 from the west and south, and fan-shaped deposits resembling deltas at their termini (e.g.,  
486 *Anderson and Bell, 2010; Le Deit et al., 2013; Palucis et al., 2014; 2016*). Deltas in the western  
487 half of Gale suggest a series of lake stands postdating the formation of the layered mound –

488 Aeolis Mons – in the Hesperian epoch (*Le Deit et al., 2013; Grant et al., 2014; Palucis et al.,*  
489 *2016*). They show evidence of late resurfacing during the Hesperian and possibly Amazonian  
490 epochs (*Grant et al., 2014; 2019; Palucis et al., 2014*), and therefore yield ages broadly  
491 comparable to those obtained for the two deltas in Robert Sharp (*Fig. 8*, also in *Ehlmann and*  
492 *Buz, 2015*). This could indicate a contemporaneous aqueous phase in both Robert Sharp and Gale  
493 craters. Moreover, recent K-Ar dating of a mudstone and a sandstone in Gale performed by the  
494 Curiosity rover yield an Amazonian (<3.0 Ga) bulk age (*Martin et al., 2017*). Large-scale fluvial  
495 activity on Mars is thought to have ceased by the early Hesperian (*Irwin et al., 2005; Fassett and*  
496 *Head, 2008*), though fluvio-deltaic activity possibly continued during the early – middle  
497 Amazonian period near the two craters (*Hauber et al., 2013*). By contrast, the Murray formation  
498 at the base of Aeolis Mons in Gale corresponds to lacustrine sandstones and mudstones that were  
499 emplaced before the formation and degradation of Aeolis Mons in its current morphology (*Stein*  
500 *et al., 2018; Stack et al., 2019*). Hence, Gale underwent another, older lacustrine phase prior to  
501 3.3–3.1 Ga in the Hesperian epoch (*Grant et al., 2014; Grotzinger et al., 2015*). The crater floor  
502 deposits currently exposed in Robert Sharp crater may record a similar lacustrine phase.  
503 However, orbital data alone do not allow to decipher the sedimentary facies and lithology of the  
504 rocks forming the crater floor deposits.

505 Orbital detection of akaganeite mixed with Fe carbonates within Robert Sharp suggests acidic,  
506 chlorinated and oxidizing conditions during a lacustrine phase (*Carter et al., 2015*). Interestingly,  
507 akaganeite was detected as a minor phase in mudstone samples drilled by Curiosity rover within  
508 Gale (in Yellowknife Bay, *Ming et al., 2014; Vaniman et al., 2014*). However, the presence of  
509 Ca sulfates and magnetite and the lack of Fe sulfates within those samples indicate a quasi-  
510 neutral and poorly saline environment during this aquatic phase of Gale (*Grotzinger et al., 2014;*  
511 *2015*). The existence of these two contrasting environmental conditions has been later supported  
512 by recent experimental works (*Peretyazhko et al., 2018*). Robert Sharp and Gale craters may  
513 have undergone different geochemical environments through time.

## 514 **9 Conclusion**

515 Our findings reveal that Robert Sharp was shaped by a variety of geological processes of  
516 different nature, such as fretted terrain formation, airfall deposition, fluvial, deltaic and lacustrine  
517 phase(s), and chemical precipitation. After the impact that formed the crater near the middle

518 Noachian and early Hesperian epoch (*Tanaka, 1986*), Robert Sharp experienced the deposition  
519 and erosion of the fretted terrain, followed by the airfall deposition draping previous formations  
520 during the Hesperian epoch (*Irwin et al., 2004; Irwin and Watters, 2010*). The presence of fluvial  
521 valleys and fan deltas as well as hydrous minerals within the crater and on its watershed,  
522 suggests a history of past fluviolacustrine activity throughout the region. The detection of  
523 akaganeite, a mineral with very specific formation conditions (*Carter et al., 2015; Peretyazhko*  
524 *et al., 2018*), indicates that Robert Sharp has experienced a mildly acidic, highly saline and  
525 oxidizing environment during the last alteration phase of a drying lake. The fluviolacustrine  
526 phase is likely related to the aqueous activity that formed the chloride-rich deposits on the  
527 neighboring plateaus (*Osterloo et al., 2008, 2010, Ruesch et al., 2012*), as well as the deltas. The  
528 last episodes of aqueous activity may be as recent as the early – middle Amazonian period,  
529 between 1.43 Ga and 512 Ma. As demonstrated with Robert Sharp, the region is shown to have  
530 experienced several episodes of aqueous activity well after the late Noachian – early Hesperian  
531 boundary, probably extending to the middle Amazonian epoch.

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799 **Figures & Captions** [2-column for all figures, and color should be used online only]

800 **Fig. 1:** Robert Sharp crater as seen through a mosaic of CTX images. Frames indicate the  
801 locations of the following figures; for the fretted terrains (yellow), draping deposits (brown),  
802 crater floor deposits (dark green), fluvial landforms (blue) and fan-shaped deposits (light green).

803 **Fig. 2:** Location and physiography of Robert Sharp. (a) MOLA DEM showing regional context  
804 of Robert Sharp and its two neighbors (Gale and Knobel craters) along the crustal dichotomy  
805 (isohypses every 200 m) (*Smith et al., 2001*). (b) MOLA DEM centered on Robert Sharp  
806 (isohypses every 200 m). (c) Qualitative thermal inertia ( $\text{J}\cdot\text{m}^{-2}\cdot\text{K}^{-1}\cdot\text{s}^{-1/2}$ , *Ferguson et al., 2006*)  
807 derived from THEMIS IR night-time (100 m.px<sup>-1</sup>). (d) TES dust cover index (DCI) based on the  
808 emissivity value in the 1350–1400 cm<sup>-1</sup> range (maximum dust at 0.9 and minimum dust at 1.0).  
809 The DCI is sensitive to the presence of silicate dust on the surface: orange and red colors indicate  
810 areas that likely are dust covered while blue areas likely are dust-free (*Ruff and Christensen,*  
811 *2002*). The maps (a), (b) and (d) overlap a map from THEMIS IR day-time (100 m.px<sup>-1</sup>).

812 **Fig. 3:** Morphologic map of Robert Sharp units defined as described in text, based on their  
813 location and physical properties such as surface texture, morphology, geometry and thermal  
814 inertia. Mesas and buttes from the fretted terrain (*Ft* unit, yellow), draping deposits that cover the  
815 eastern part of the basin and surrounding plateau (*Dp1–2* units, light and dark brown), crater  
816 floor deposits that lie flat on the western and southwestern parts of the basin (*Cf* unit, green), two  
817 fan-shaped deposits (*Fsd* unit, light blue) at the outlets of valley networks (cyan), and finally the  
818 sinuous ridges exposed on the crater floor (dark blue). The criteria used to distinguish the rough  
819 from smooth draping deposits (*Dp1* and *Dp2* units, respectively) are based on the texture aspect  
820 and brightness of the units in the CTX images (10-meter scale roughness). Locations of  
821 geological cross-sections in *Fig. 4* are indicated.

822 **Fig. 4:** Geological cross-sections derived from MOLA DEM data: (a) west to east, (b) northwest  
823 to southeast and (c) southwest to northeast sections. The units are color-coded such as in the  
824 geological map of Robert Sharp (*Fig. 3*).

825 **Fig. 5:** (a) – (c) Mesas and knobs corresponding to the fretted terrains described in *Irwin et al.*  
826 (*2004*) and *Irwin and Watters (2010)*. (d) CTX image showing the draping units. (e) Close-up  
827 view of the contact between the *Dp1* unit with a rough surface texture and the *Dp2* unit with a

828 smoother appearance (HiRISE image, PSP\_009360\_1760\_RED). (f) CTX image showing the  
829 draping deposits embaying and molding knobs and mesas. (g) Distribution of polygonal ridges  
830 (purple areas) found in Robert Sharp through a portion of CTX images. (h) Close-up view of a  
831 network of polygonal ridges (HiRISE image, ESP\_042247\_1760\_RED).

832 **Fig. 6:** (a) Crater floor deposits. The isohypses – every 100 meters – reveal topographic basin in  
833 the mid-western floor of the crater. (b) – (c) Valleys found in the northwestern and southwestern  
834 walls of the crater, respectively. (d) Sinuous ridges embedded in the crater-floor deposits within  
835 Robert Sharp.

836 **Fig. 7:** (a) Northwestern ( $132.73^{\circ}\text{W}$ ,  $3.6^{\circ}\text{S}$ ) and (b) southwestern ( $132.9^{\circ}\text{W}$ ,  $5.1^{\circ}\text{S}$ ) fan-shaped  
837 deposits observed through CTX images. Topographic profile of (c) the northwestern and (d) the  
838 southwestern fan-shaped deposits (in light green) derived from the HRSC DEM with a vertical  
839 exaggeration of 5.6. The mean elevation at frontal scarp is about  $-2400$  m for both deposits. Note  
840 that the morphology of both fan-shaped deposits appears broadly similar to the Pancake delta in  
841 Gale crater (*Palucis et al., 2016*).

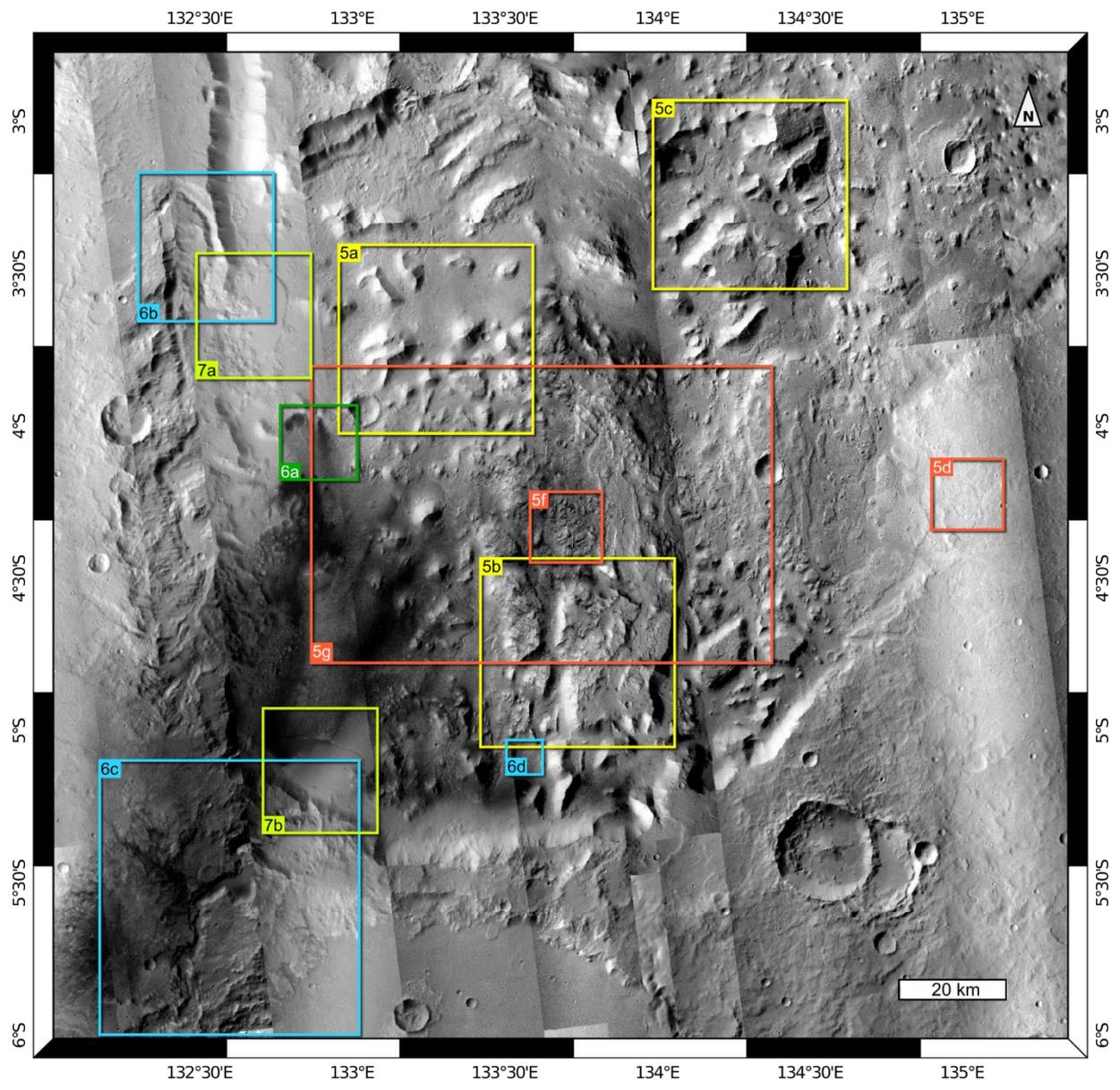
842 **Fig. 8:** Age determination of surface units within and near Robert Sharp by crater-counting. (left)  
843 craters counted (in white) and the counting areas (in blue or green) on a mosaic of CTX images,  
844 except for (c) in a map THEMIS day-time. (right) crater size-frequency distribution that provide  
845 an inferred model age of the (a) southwestern and (b) northwestern fan-shaped deposits, (c) the  
846 crater floor deposits, and (d) the valley floor hosting the chloride-rich deposits ( $131^{\circ}56'\text{E}$ ,  
847  $6^{\circ}25'\text{S}$ ).

848 **Fig. 9:** (a) Simplified stratigraphic column for the main units within Robert Sharp. (b) Possible  
849 evolution of the crater floor based on the degradation of the lacustrine deposits (exhumation of  
850 the draping deposits).

851 **Fig. 10:** (a) Mars Orbiter Camera (MOC,  $230 \text{ m}\cdot\text{px}^{-1}$ ) map of Robert Sharp with spectral  
852 detections (color-coded) performed therein using the multispectral CRISM data. (b) MOC map  
853 of the southern perched plateau with detections in an enclosed basin: Fe/Mg smectites near  
854 chlorides (*Ruesch et al., 2012*). Chloride-rich deposits are indicated by the pink star, see also Fig.  
855 3 (*Osterloo et al., 2008; 2010; Ruesch et al., 2012*). (c) to (h) show closer views of the spectral  
856 detections within the crater through CTX and HiRISE mages. (c) Fe/Mg smectites and Al

857 smectites (or hydrated silica) in delta fan (*Ehlmann and Buz, 2015*). They are observed as light-  
858 toned layered deposits along the delta front and at its foot, white arrows in (d) and (e). (f) and (g)  
859 show two sites of akaganeite with carbonates and Fe/Mg smectites located in small local  
860 depressions (*Carter et al., 2015*). (h) shows a mixture of hydrated minerals on the draping  
861 deposits and near polygonal ridges, with examples of spectra of hydrated minerals (mixtures)  
862 detected on the draping deposits.

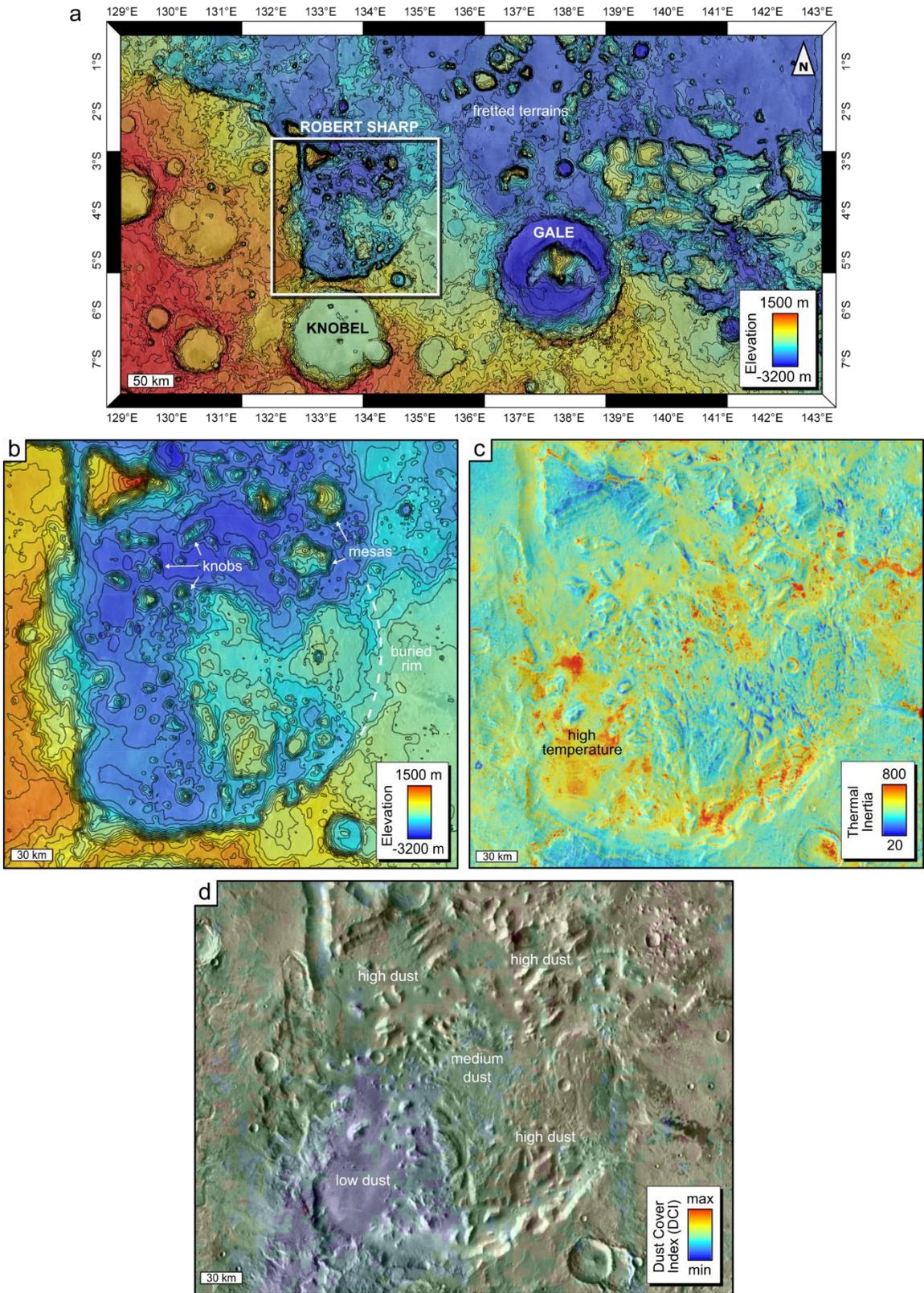
863 **Fig. 11:** Cartoon model illustrating the timing of geological events from the formation of Robert  
864 Sharp to the present. (\*) Age inferred by *Irwin et al. (2004)* and *Irwin and Watters (2010)*.



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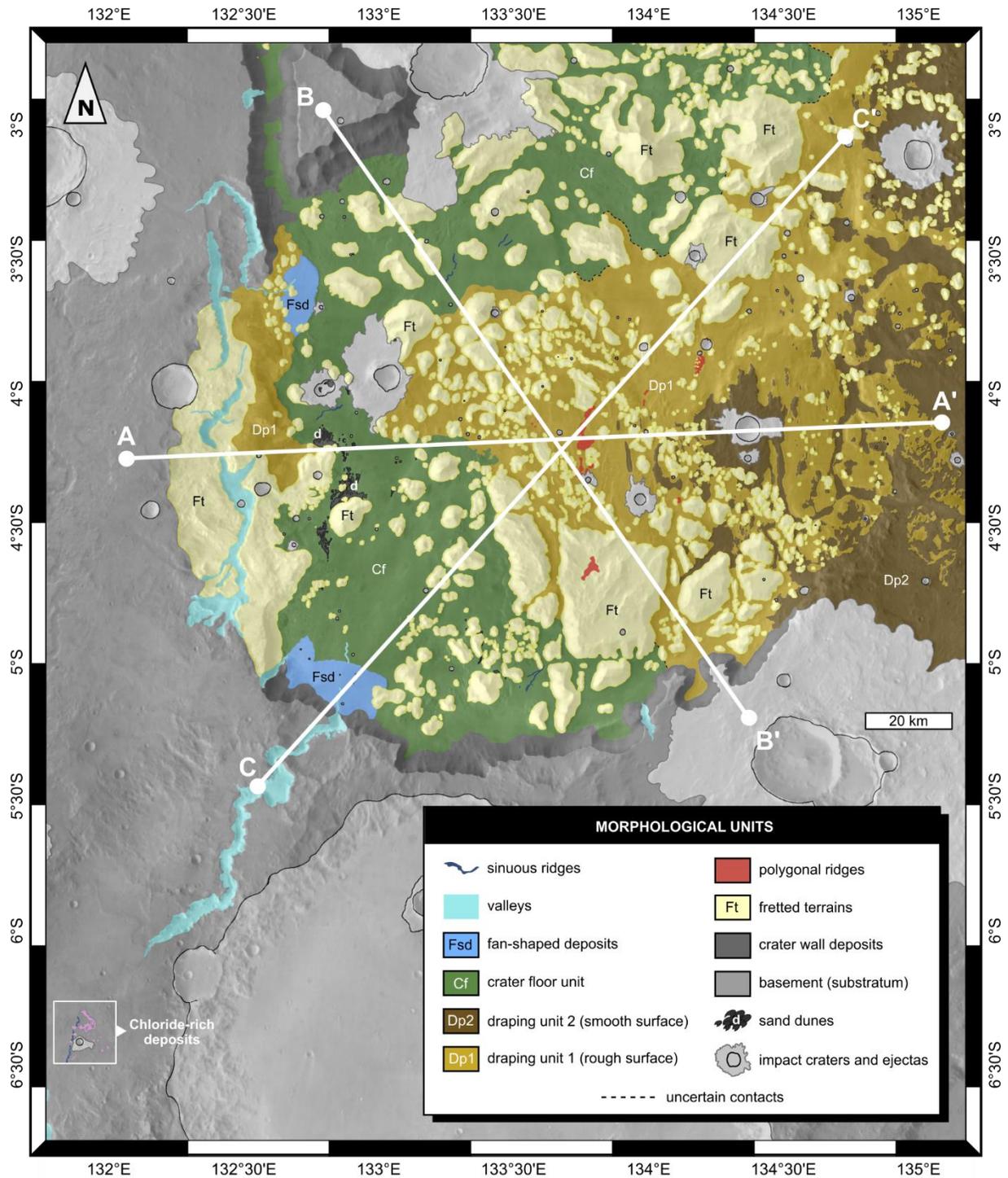
Figure 1



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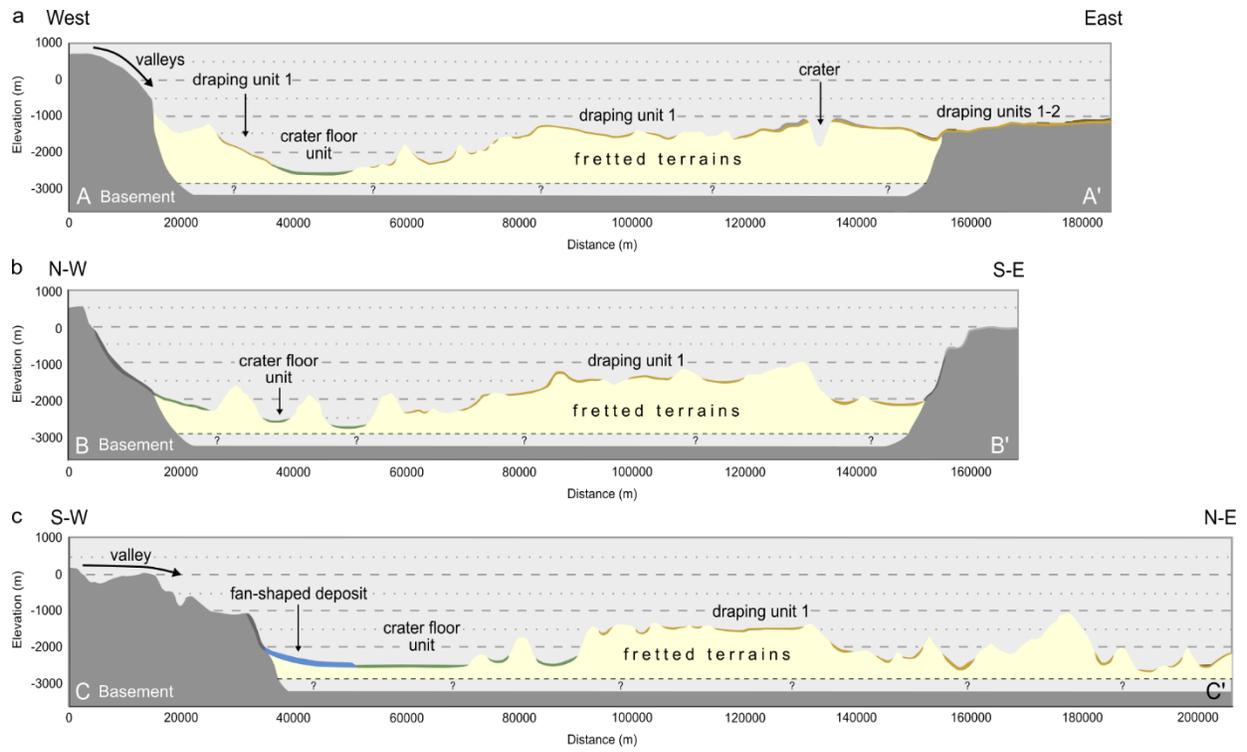
Figure 2



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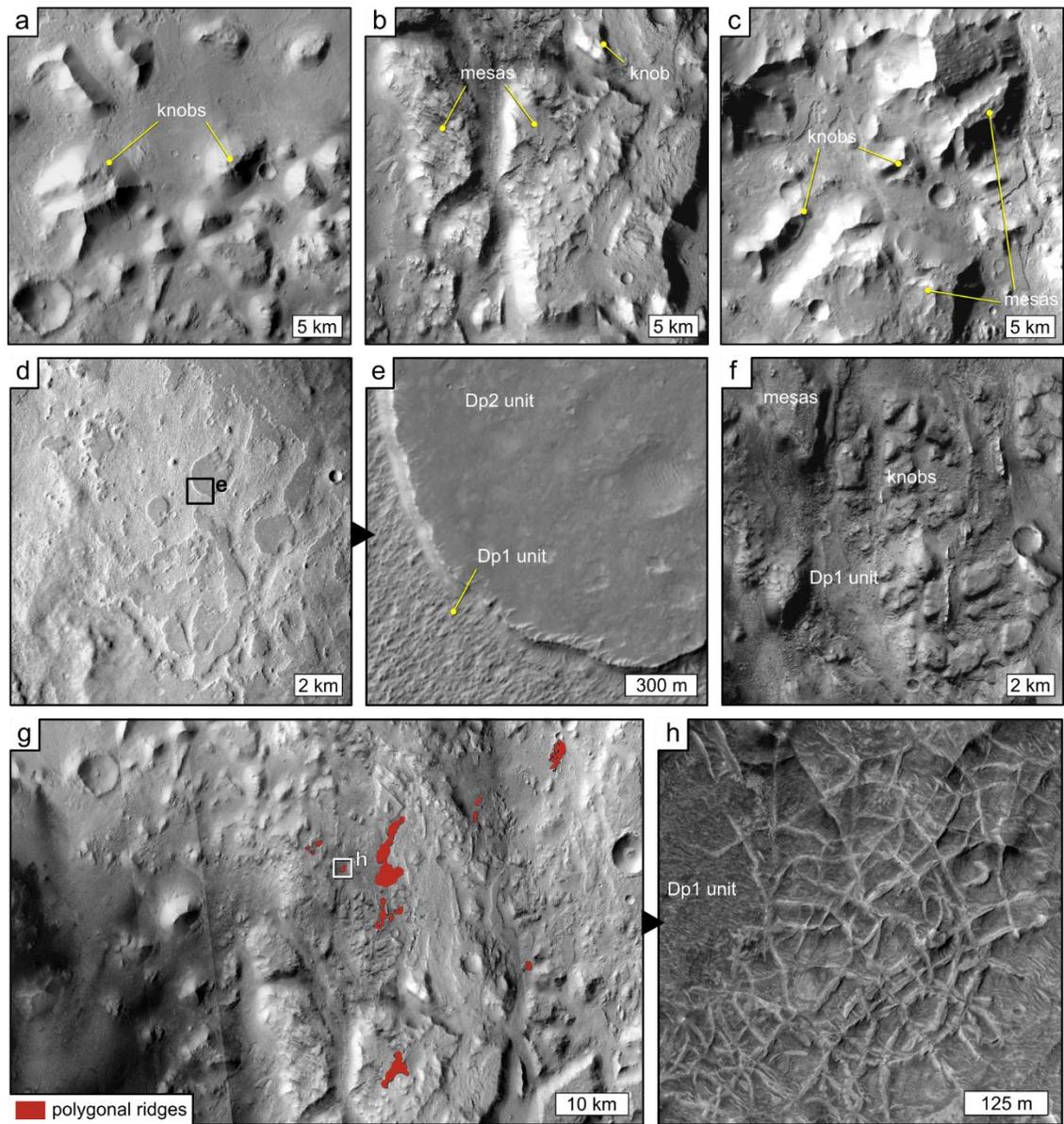
Figure 3



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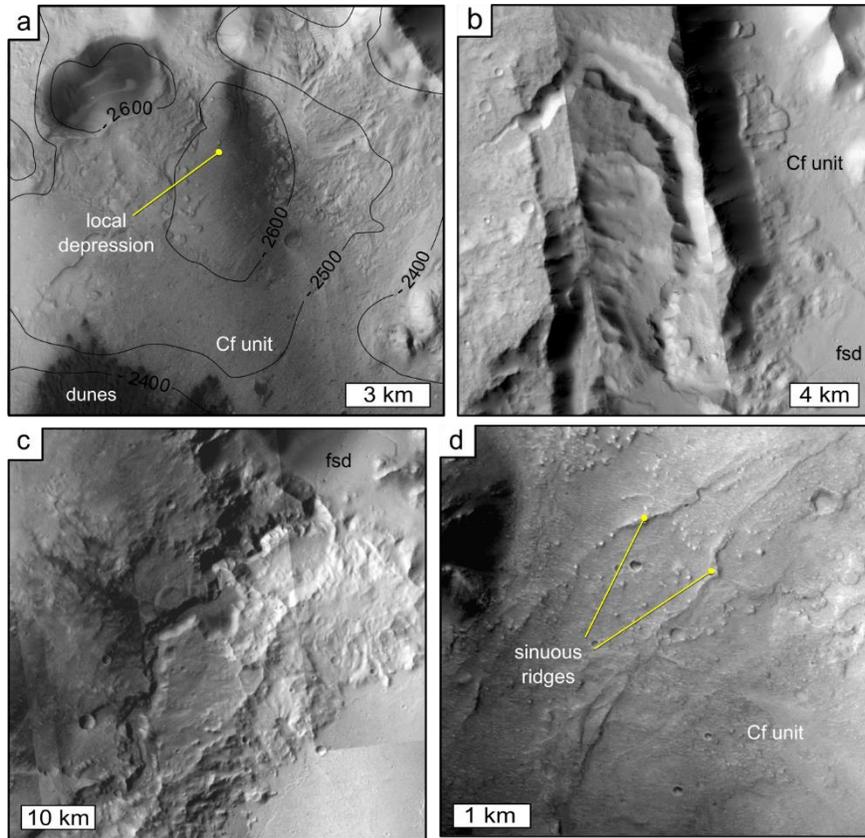
Figure 4



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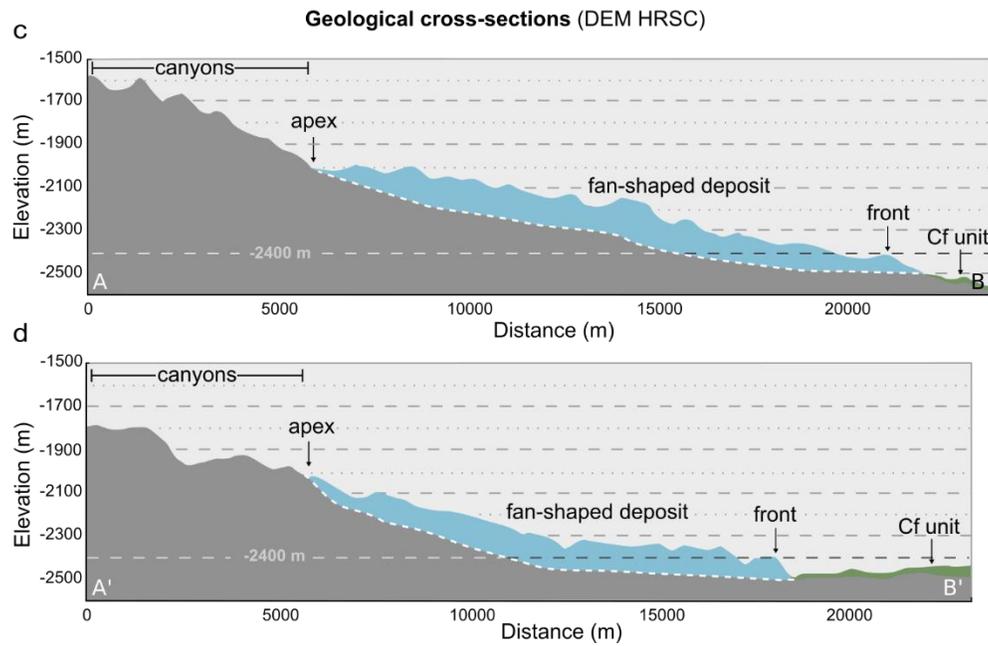
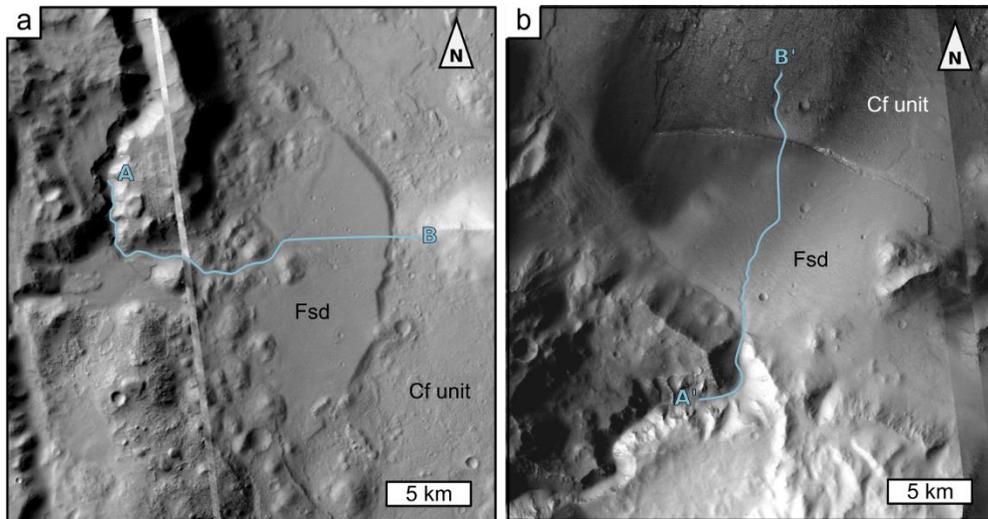
Figure 5



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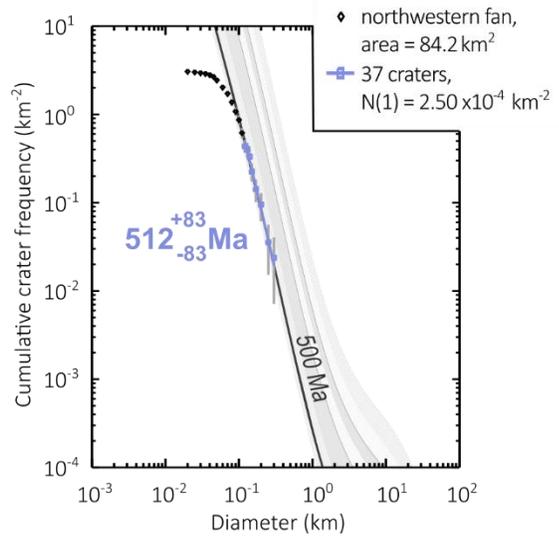
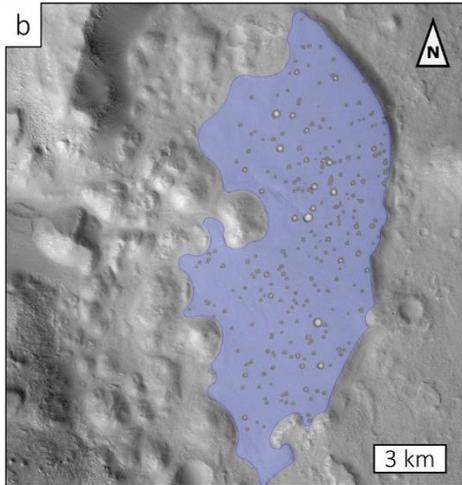
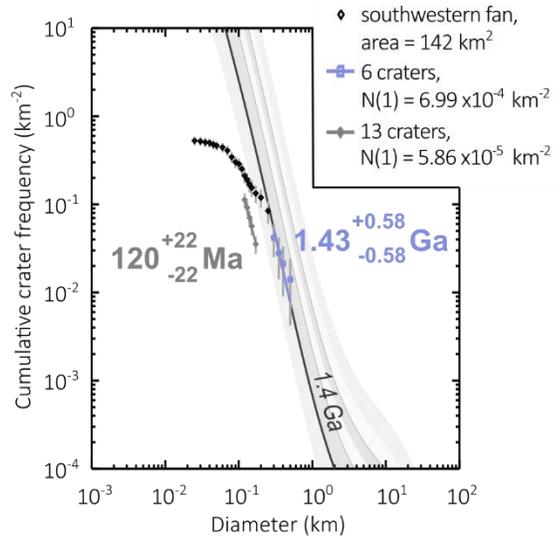
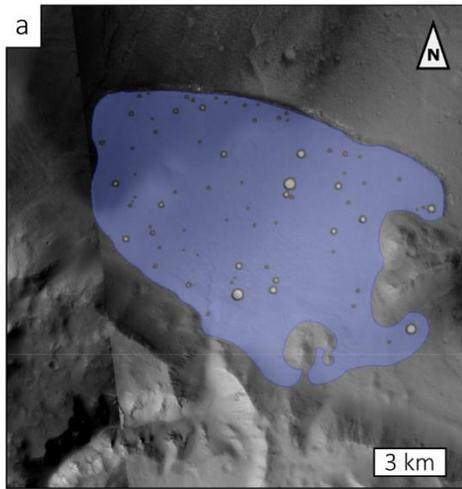
Figure 6



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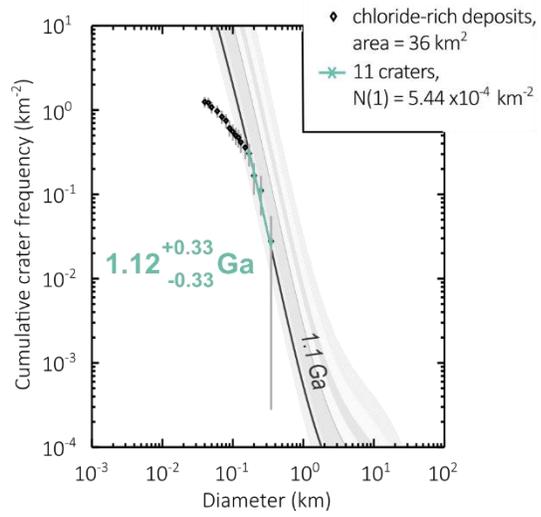
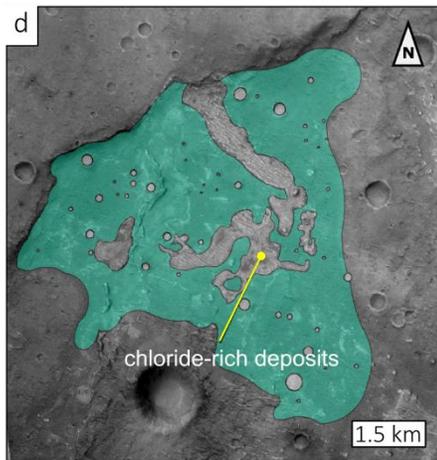
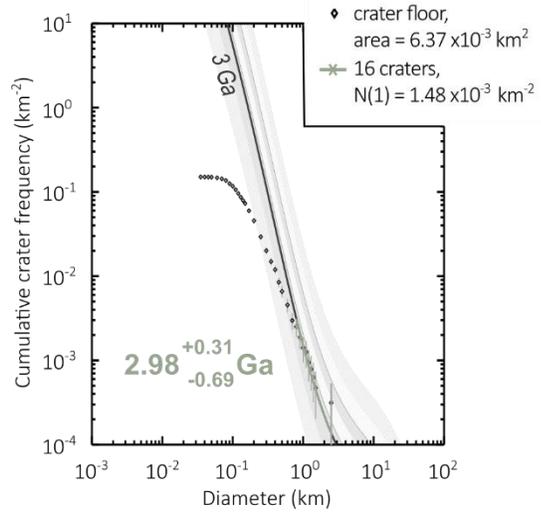
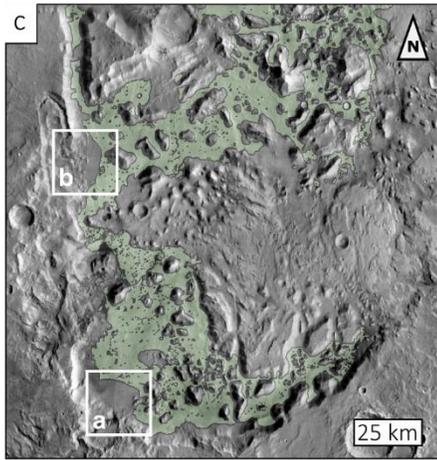
Figure 7



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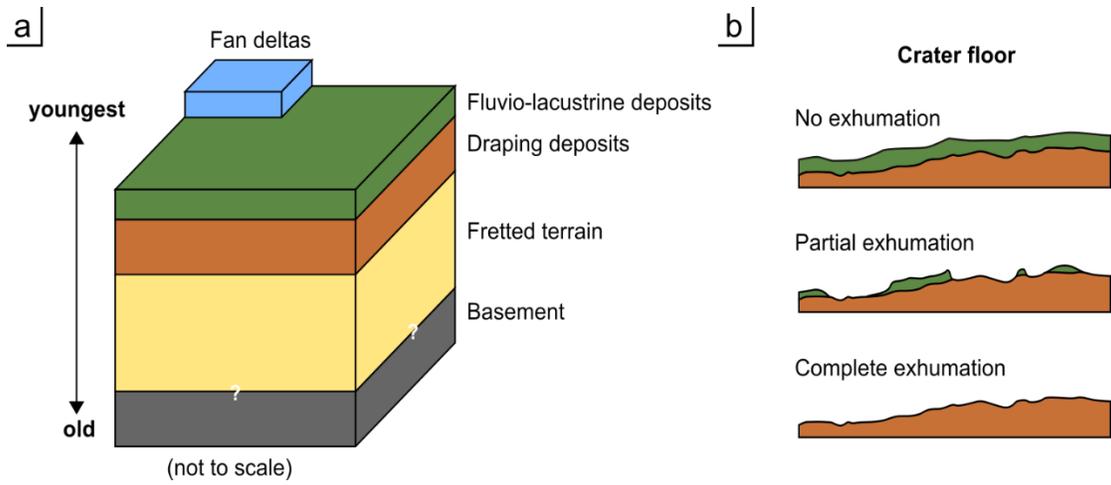
880

Figure 8 (1)



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882

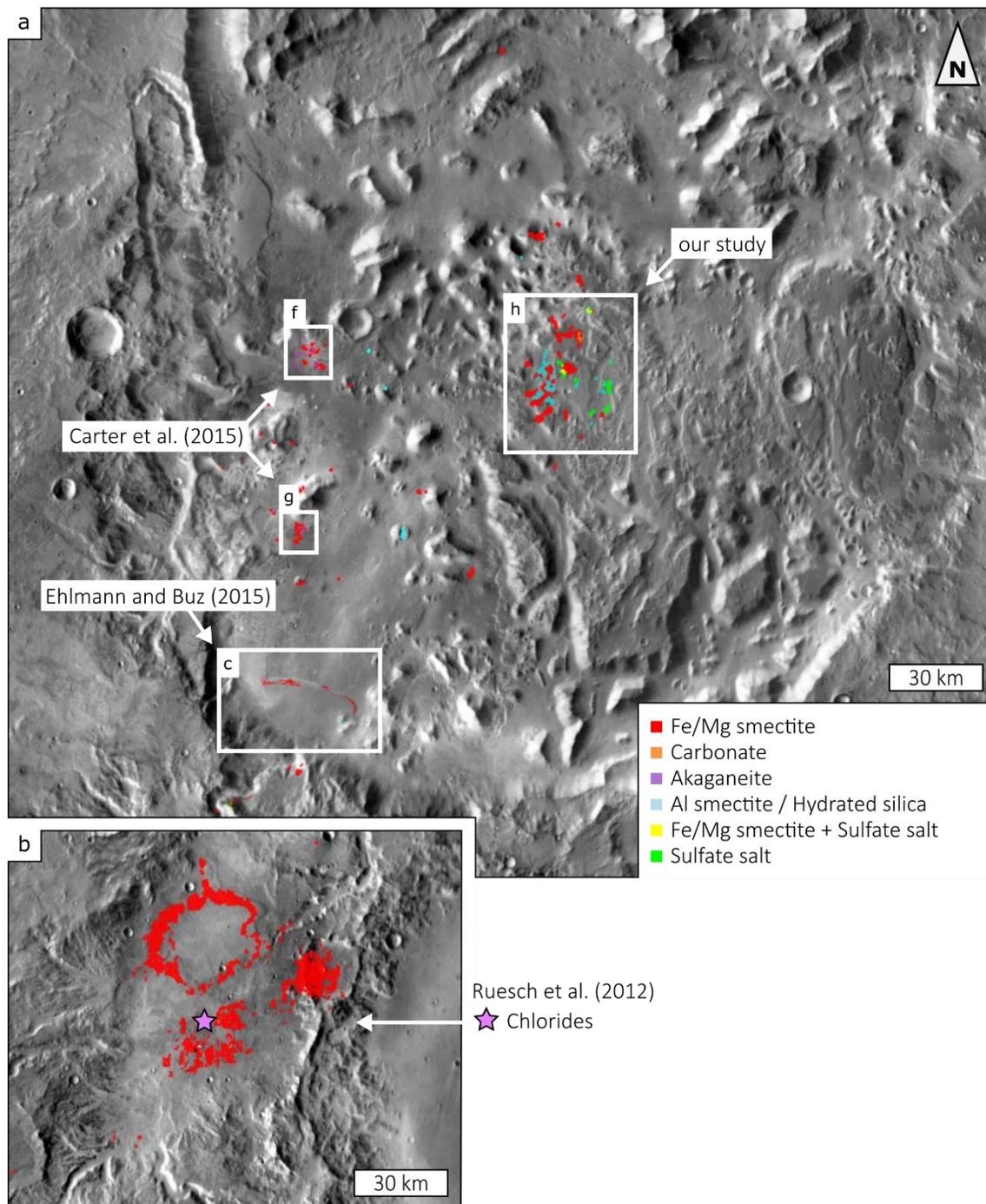
Figure 8 (2)



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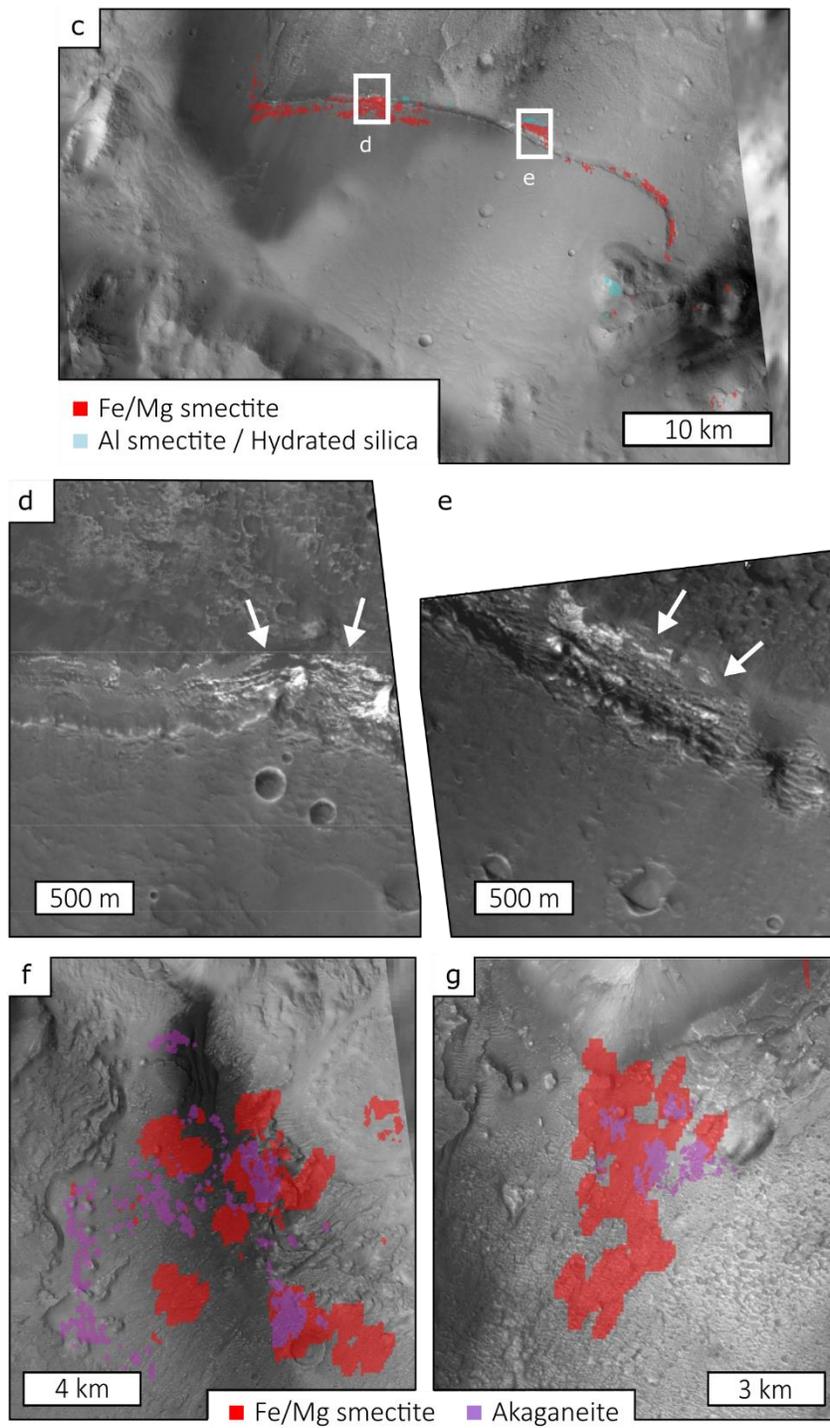
Figure 9



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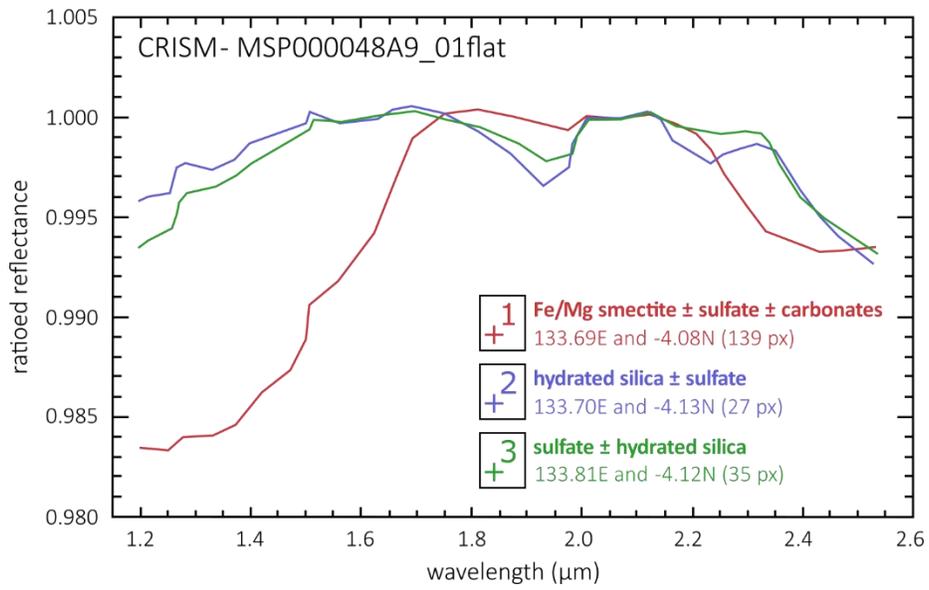
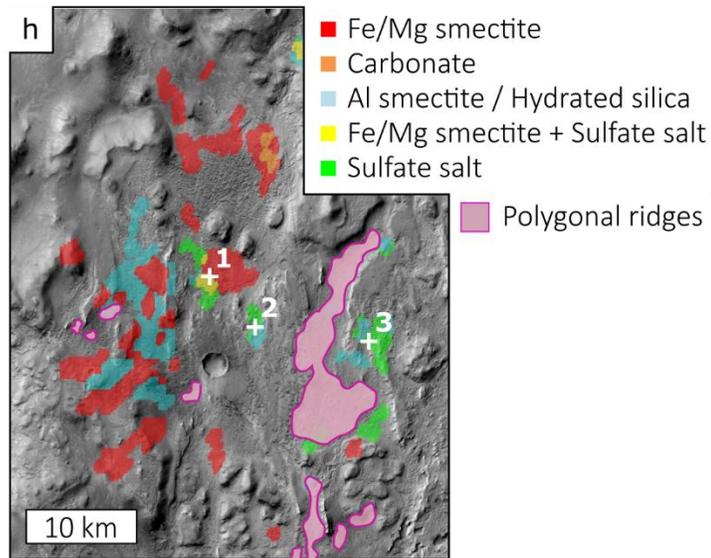
Figure 10 (1)



887

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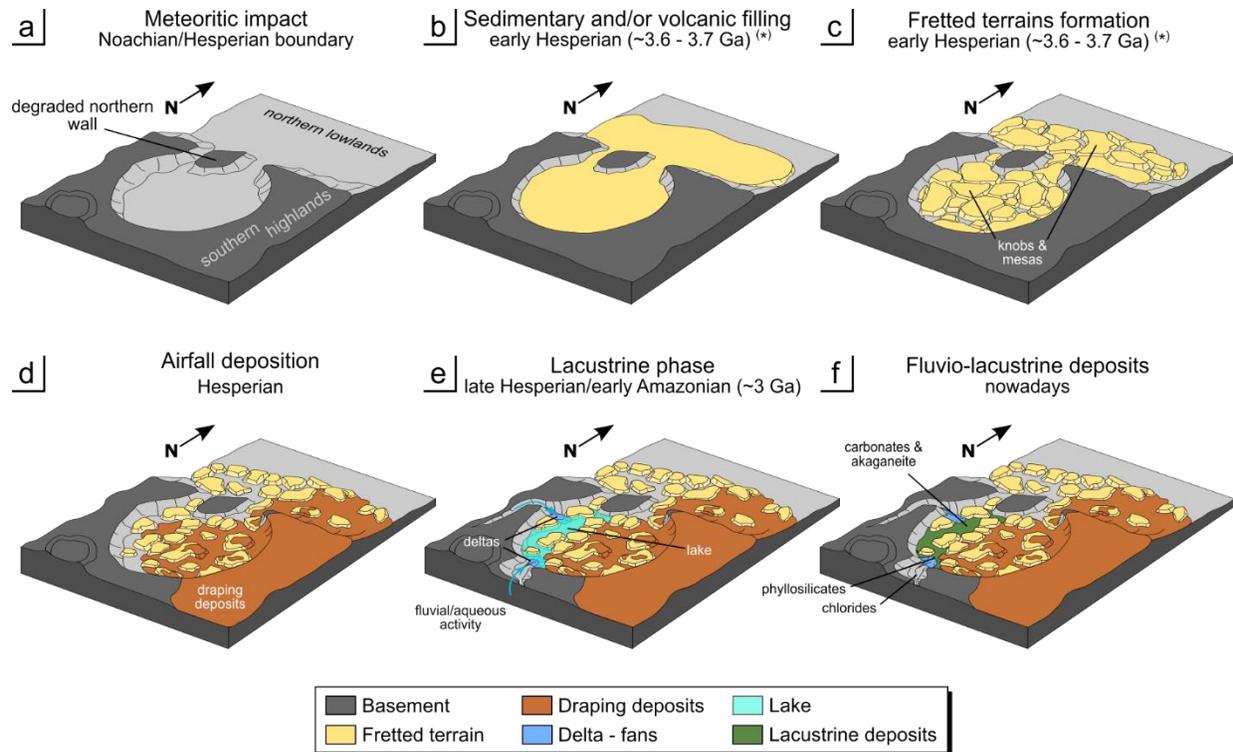
Figure 10 (2)



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Figure 10 (3)



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Figure 11