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## Planetary geomorphology

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1 History of the Study of Landforms Volume 5: Geomorphology in the  
2 Second Half of the Twentieth Century

3 Section C: Advances in research on processes and landforms

4 Chapter 25: Planetary geomorphology

5

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9 Abstract

10 With the advent of the space age, planetary geomorphology has become a stand-alone discipline.  
11 This contribution provides a summary of the different processes that have been identified to form  
12 landscapes and landforms on planetary bodies in our Solar System, including rocky planets, icy  
13 planets and moons, dwarf planets, comets and asteroids. I highlight the insights these landforms  
14 have provided into the workings of these bodies and how what has been learnt in space has often  
15 taught us new lessons about the Earth. Finally, I conclude that despite the limitations imposed by  
16 remote sensing, planetary geomorphology has a bright future in planning future missions to explore  
17 our Solar System as well as understanding the data that will be returned.

18 1 Introduction

19 This chapter is rather different from the rest of those in this book. First it is the only one that takes us  
20 away from our own planet. Secondly, it deals with a topic that was not covered, for obvious historical  
21 reasons, in the four previous volumes of the History of the Study of Landforms. Thirdly, it does not  
22 restrict itself to the temporal span of 1965-2000 which is the focus of this book. It reviews progress in  
23 the study of planetary geomorphology up until the present and shows the progress that has been  
24 made since the first successful missions were carried out from the mid-1960s onwards - It was in  
25 1965 that Mariner 4 brought us back the first close-up photographs of another planet: Mars.

26 Planetary geomorphology is a branch of planetary science, which was born in the second half of the  
27 Twentieth Century from astronomy and has foundations in geology, meteorology, chemistry and  
28 biology. The rise of planetary geomorphology as a discipline goes hand in hand with an increasing use  
29 of satellite remote sensing data to study our own planet and the associated development of  
30 techniques to exploit these data.

31 The first remote sensing image of the Earth taken from space was in 1946. Only twenty years later,  
32 the NASA Mariner missions marked the first of a flurry of space missions that have only increased in  
33 number as the century progressed, bringing us images, topography and other data from all the major  
34 bodies in the Solar System and more. The objective of this chapter is not to provide a history of space  
35 exploration, which is done elsewhere (e.g., Burns, 2010), but to highlight the main discoveries and  
36 associated advances in the understanding of the processes and landforms of other worlds spanning  
37 the era of robotic and human exploration of space.

38 In order for landscapes and landforms to be studied the surface of the body has to be resolved at a  
39 sufficient resolution (in the author's opinion at least hundreds of metres per pixel). Hence to date,  
40 planetary geomorphology is restricted to solid bodies in our Solar System and relies on space probes  
41 sent to or near to the body of interest. We therefore have geomorphological information on (listed in  
42 approximate increasing solar distance):

- 43 • Mercury
- 44 • Venus\*
- 45 • The Moon\*
- 46 • Mars\* and its moons Phobos and Deimos
- 47 • Dwarf planet Ceres in asteroid belt
- 48 • Asteroids (Bennu\*, Ryugu \*, Itokawa\*, Vesta, Ida, Eros, Mathilde, Gaspra, Šteins, Toutatis)
- 49 • The satellites of Jupiter (Io, Europa, Ganymede, Callisto)
- 50 • The satellites of Saturn (Pan, Daphnis, Atlas, Prometheus, Pandora, Epimetheus, Janus,  
51 Mimas, Enceladus, Tethys, Telesto, Calypso, Dione, Helene, Rhea, Titan\*,Hyperion, Iapetus,  
52 Phoebe)
- 53 • The satellites of Neptune (Proteus, Triton)
- 54 • The satellites of Uranus (Miranda, Ariel, Umbriel, Titania, Oberon)
- 55 • Dwarf planet Pluto and its moon Charon
- 56 • Trans-Neptunian Kuiper belt object "Arrokoth"
- 57 • Comets (Tempel 1\*, Churyumov–Gerasimenko 67P\*, Borrelly, Wild 2, Hartley 2)

58 (A \* symbol indicates a landed mission)

59 This exploration has revealed a suite of familiar and unfamiliar processes and landforms compared to  
60 those found on Earth. This review will consider first processes and landforms already known from  
61 studying the Earth before the space exploration era and then move towards those processes and  
62 landforms less studied before Planetary Geomorphology became a distinct subdiscipline. Each  
63 section will highlight lesser-known landforms and knowledge gained from studying other worlds. For  
64 an exhaustive list of the landforms present on other worlds I refer the reader to the Encyclopaedia of  
65 Planetary Landforms (Hargitai and Kereszturi, 2015). For brevity only one or two references are cited  
66 per topic, with the intent that an interested reader can use them to access to the wider relevant  
67 literature on each topic.

## 68 2 Planetary aeolian landforms and processes

69 All bodies with an atmosphere have wind and aeolian landforms have been reported from: Mars,  
70 Venus Titan and Pluto (Lorenz and Zimbelman, 2014; Telfer et al., 2018), as well as of course Earth.  
71 For a full review of planetary aeolian landforms and associated processes I refer interested readers to  
72 Bourke et al. (2019). The observation of aeolian bedforms including ripples, megaripples and dunes  
73 on other planetary bodies (Figure 1a,b) has been very important for understanding the basic physics  
74 underlying aeolian processes, because these planetary bodies provide different atmospheric  
75 densities and particle densities spanning a wider range of parameter space than accessible on Earth  
76 at the landscape-scale (Kok et al., 2012; Lapôtre et al., 2020). Martian aeolian bedforms have a wider  
77 diversity of form and size than their terrestrial equivalents (e.g., Bourke, 2010; Sullivan et al., 2020),  
78 which has led to researchers to question whether the basic physics underlying their formation are  
79 indeed the same. A prime example is the landform called a Transverse Aeolian Ridge (Figure 1c)  
80 which at < 1 m tall are thought to represent megaripples whose morphology is determined by  
81 grainsize sorting rather than reptation and creep and whose origin remains unknown at larger

82 amplitudes (Zimbelman and Foroutan, 2020). Another example comes from radar images of  
83 longitudinal parallel and occasionally bifurcating ridges have been interpreted to be longitudinal  
84 dunes (Figure 1d) on Venus and Titan. Such dunes on Earth indicate strongly unimodal winds yet the  
85 “physics of saltation on Titan and Venus is fundamentally different from that on Earth and Mars [...]”  
86 dominated by direct fluid lifting” (Kok et al., 2012).

87 Hence, planetary observations have also revealed aeolian processes that are only experienced on  
88 extra-terrestrial environments resulting in potentially unique landforms. These include bedforms  
89 created by ablation (in the form of sublimation of ices – see also Section 11) rather than particle  
90 movements (Bordiec et al., 2020), which have so far only been studied in detail on the Antarctic ice  
91 cap (van den Broeke and Bintanja, 1995) or in ice caves (Obleitner and Spötl, 2011). Another  
92 surprising result was the discovery of dunes on the comet 67P Churyumov–Gerasimenko, which has  
93 no atmosphere (Jia et al., 2017; Thomas et al., 2015). These “dunes” are thought to form at times  
94 when the comet is close to the sun causing vigorous outgassing and strong winds being setup  
95 between sunlit and shadowed areas on the surface (Jia et al., 2017). Scouring “upwind” and build-up  
96 of sediment on the “downwind” of boulders supports this hypothesis (Mottola et al., 2015).

97 Abrasion by particles lofted by the wind results in erosional aeolian landforms, such as yardangs and  
98 the landscape-scale (Figure 1e) and ventifacts at the “field” scale (e.g., Wells and Zimbelman, 1997) –  
99 the orientation of these landforms is used as an important indicator of prevailing wind directions.  
100 Yardangs have been studied in most detail on Mars, but also have been suggested on Venus (Greeley  
101 et al., 1995), Titan (Paillou et al., 2016) and as an alternative interpretation of the “dunes” on Pluto  
102 (Moore et al., 2018). The study of yardangs on Mars drove a renaissance for their study on Earth  
103 (Goudie, 2007) where their climate significance is still debated. Ventifacts have been observed at the  
104 surface of Mars and are remarkably similar to those found on Earth (Knight, 2008; Laity and Bridges,  
105 2009) and most modern studies of terrestrial ventifacts refer to planetary-driven research on this  
106 topic.

107 Wind can also drive the formation of inverted landforms, which have been of particular importance  
108 in revealing ancient fluvial processes on Mars (Davis et al., 2016; Day and Kocurek, 2016)(Section 3).  
109 Wind is the agent that erodes and deflates the sediments surrounding the channel(s) which are more  
110 resistant to abrasion (Figure 1e). This additional resistance can come about from cementation,  
111 coarser grainsizes or lava capping (e.g., Williams et al., 2009).

112 Particular to Mars are landforms related to the copious dust at its surface, which also influences the  
113 atmospheric circulation on that body (e.g., Madeleine et al., 2011). Dust via airfall is incorporated in  
114 sedimentary deposits and ice-deposition landforms (e.g. the polar caps - Kieffer, 1990; or the ice-dust  
115 latitude dependant mantle - Mustard et al., 2001). Unique to Mars are “Slope Streaks” which are  
116 landforms associated with dust motion down steep slopes (e.g., Schorghofer et al., 2007; Sullivan et  
117 al., 2001), see Section 7 for further details. Dust Devils are atmospheric vortices which are common  
118 on Mars (Figure 1f) and have been observed by every landed mission (e.g., Ferri et al., 2003; Greeley  
119 et al., 2006b; Ryan and Lucich, 1983; Thomas and Gierasch, 1985). They can also be found in deserts  
120 on Earth (Balme and Greeley, 2006), yet on Mars they often remove the dust on the surface leaving a  
121 tortuous track in their wake which is clearly visible from orbit. Much recent research on terrestrial  
122 dust devils has been driven by the desire to better understand the phenomenon on Mars (e.g., Balme  
123 et al., 2012; Reiss et al., 2010).

### 124 3 Planetary fluvial landforms and processes

125 The possibility of extraterrestrial fluvial geomorphology was first revealed by the discovery of valley  
126 networks and channel systems on the surface of Mars (Masursky, 1973) (Figure 2a). On Saturn's  
127 satellite Titan fluvial landforms in the form of valley networks (Porco et al., 2005; Tomasko et al.,  
128 2005) are thought to be formed by flowing liquid methane eroding the 'bedrock' of ice (Perron et al.,  
129 2006) (Figure 2b). Together with the observation of lakes (see section 4), the existence of valley  
130 networks on Titan has led to the hypothesis of a hydrocarbon-cycle driven by the decade-long  
131 seasonal cycle and atmospheric synthesis of hydrocarbons. On Venus, the river-like canali could be  
132 lava channels or carved by, another as-yet unidentified, fluid (Jones and Pickering, 2003; Kargel et al.,  
133 1994; Komatsu and Baker, 1994). Equally dendritic valleys on Pluto have been proposed to be carved  
134 by flowing liquid nitrogen (Stern et al., 2017) - the favoured alternate interpretation as glacial in  
135 origin, is described in Section 8.

136 The observation of valley networks motivated the hypothesis that Mars had a full-hydrological cycle  
137 early in its history, when its atmospheric density was higher allowing surface liquid water to be stable  
138 (Baker et al., 1991; Pollack et al., 1987). This valley networks are visible in a degraded (Ansan et al.,  
139 2008; Baker and Partridge, 1986) or inverted (Davis et al., 2016) state on the oldest visible surfaces of  
140 Mars (Figure 2a). Some of these valleys have low tributary order/number and by analogy with valleys  
141 with similar morphology on Earth have been interpreted to originate via groundwater sapping (Luo  
142 and Howard, 2008), hence revealing the potential presence of aquifers, although this interpretation  
143 has been questioned (Lapotre and Lamb, 2018). Some have also been interpreted to originate from  
144 sub-icesheet drainage (Grau Galofre et al., 2020), attesting to potentially widespread glaciation early  
145 in Mars' history (Fastook and Head, 2015). The observation of meandering channel belts on Mars  
146 brought into question the hypothesis that vegetation was a prerequisite for developing meanders  
147 early in Earth's history (Ielpi and Lapôtre, 2020).

148 Outflow channels on Mars – thought to represent colossal outbursts of water (Baker and Kochel,  
149 1979) from pressurised aquifers (Marra et al., 2015) - reach hundreds of kilometres in width and  
150 thousands in length (Figure 2c). They are characterised by streamlined obstacles and often multiple  
151 terrace levels indicating several pulses of activity (Warner et al., 2009). The outflow channels often  
152 originate at "Chaos Terrain" which also exists on Mercury (Rodriguez et al., 2020), Europa and Pluto  
153 (Skjetne et al., 2021) (Figure 2d), and hence is not a landform directly connected to fluvial processes.  
154 Chaos terrain is thought to form by the fracturing of a layer of crust sliding over a lower lubricated  
155 layer (water in the case of Mars and Europa and glacial flow of N<sub>2</sub> ice for Pluto). Alternatively, such  
156 outflow channels could be carved by very fluid lava (Leverington, 2011), as is thought to be the case  
157 for analogous channels found on Mercury (Byrne et al., 2013).

158 Mars' surface hosts many enigmatic discontinuous channel segments, some of which have been  
159 related to water release by impacts (Mangold, 2012). Others terminate in landforms that resemble  
160 alluvial fans on Earth, such as Peace Vallis and its fan that was explored by the Curiosity Rover and  
161 found to contain conglomerates (Williams et al., 2013). These observations, together with those of  
162 the outflow channels point to surface water occurring only episodically, which contrasts with the  
163 older valley networks which point to a full-hydrological cycle having existed on Mars. As surface  
164 liquid water is not thought to have been stable for the last 1 Ga due to low atmospheric pressure and  
165 humidity, all together this points to Mars's surface becoming more arid over time.

166 The smallest planetary landforms thought to be related to fluvial activity are kilometre-scale martian  
167 gullies (Figure 2e) (Conway et al., 2019; Malin and Edgett, 2000) and the metres-wide and up to  
168 hundreds of metres long Recurring Slope Lineae or "RSL" on Mars (Figure 2f) (McEwen et al., 2011).

169 Martian gullies resemble first-order drainage systems dominated by debris flow processes on Earth,  
170 yet present-day flows in martian gullies during local winter argue against a completely fluvial origin  
171 (Diniega et al., 2010; Dundas et al., 2019) – see Section 11. RSL are low albedo streaks that grow in  
172 the hottest times of year extending from rocky steep slopes (Ojha et al., 2014) and have been  
173 suggested to be water or brine seeps (Stillman et al., 2020), however the temporal and spatial limits  
174 of orbital observations mean their origin remains enigmatic and could represent a uniquely martian  
175 surface process and landform (F. Schmidt et al., 2017).

#### 176 4 Coastal, lacustrine and karstic processes and landforms

177 Mars is the only planet besides Earth in the Solar System which is suspected to have had ocean-scale  
178 open bodies of standing liquid (in this case water). Mars' valley networks and outflow channels  
179 generally terminate in the northern lowlands and it is around these plains that two or more levels of  
180 putative shorelines have been identified (Carr and Head, 2019; Parker et al., 1993). These shorelines  
181 are characterised by a continuously traceable contact (expressed by albedo and/or topographic  
182 contrasts - Figure 3a) over thousands of kilometres and interpreted to represent wavecut  
183 platform(s). The lack of features typically associated with paleoshorelines on Earth, such as terraces,  
184 or barrier ridges (Ghatan and Zimbelman, 2006; Malin and Edgett, 1999), means this interpretation  
185 remains contentious. Variations in their altitude have been attributed to tectonic deformation post-  
186 formation (Citron et al., 2018), and are also used as evidence against the landforms representing  
187 shorelines (Sholes et al., 2021). The evidence for an ancient ocean is bolstered by the presence of  
188 deltas whose altitudes are consistent with the ocean levels represented by the shorelines (Di Achille  
189 and Hynek, 2010). Some of the shoreline landforms are alternately interpreted as the wash-up  
190 deposits of tsunamis (Figure 3b) (Costard et al., 2017; Rodriguez et al., 2016), which also implies the  
191 presence of an ocean.

192 Deltas are also one of the key lines of evidence in favour of the prevalence of paleolakes on ancient  
193 Mars (Mangold et al., 2012) (Figure 3c). Other lines of evidence include sedimentary and in situ  
194 observations by the Mars Science Laboratory rover Curiosity (Stein et al., 2018), spectral  
195 observations from orbit (Dehouck et al., 2010), and morphological arguments – e.g., channels ingress  
196 into depressions, but have no outlet or a higher elevation outlet (Cabrol and Grin, 1999; Fassett and  
197 Head III, 2008; Goudge et al., 2016, 2015). The only other body in the Solar System thought to host  
198 (or have hosted) seas or lakes is Saturn's Moon Titan (Figure 3d), whose 1.5 bar nitrogen-dominated  
199 atmosphere and -180°C surface temperature means that liquid methane is believed to be the main  
200 constituent of these lakes or seas, which are mainly located in polar regions. While some of these  
201 bodies are connected to drainage systems, others are thought to be the result of karstic-type  
202 dissolution processes (Mastrogiuseppe et al., 2019). Deposits interpreted to be evaporitic associated  
203 with basins located at Titan's tropics are inferred to be paleolakes or paleoseas (Moore and Howard,  
204 2010), which could have resulted from seasonal (decadal timescales) or longer-term climatic changes  
205 on Titan (MacKenzie et al., 2014).

206 Numerous sulphate salt deposits exist on Mars and hundred-metre-scale depressions within them  
207 have been linked to karstic processes (Baioni and Sgavetti, 2013; Sefton-Nash et al., 2012) potentially  
208 related to groundwater circulation (Grindrod and Balme, 2010). Dissolution has been invoked to  
209 partly explain the collapse features associated with chaos terrain (described in Section 3).  
210 Pseudokarst is where material is lost by mechanisms other than dissolution e.g. thermokarst, which  
211 in a planetary context has been employed to describe karst-like features caused by temperature  
212 induced volatile loss in contrast to the terrestrial definition which involves melting of ice-rich  
213 permafrost. These karstic landforms are described further in Section 11 and martian thermokarst  
214 initially also attributed to melting ice-rich permafrost are referred to in Section 8).

## 215 5 Planetary tectonic landforms and processes

216 Tectonic landforms are ubiquitous on planetary surfaces. Even the smallest bodies that have been  
217 explored, such as comets, show signs of fracturing which result from interior forces (El-Maarry et al.,  
218 2015). However, only the Earth has plate tectonics, whose action profoundly influences its  
219 landscapes, making it one of the most dynamic surfaces in the Solar System. Europa, which is an icy  
220 Moon of Jupiter, may have an analogous system of plates, but in this case the plates are made of  
221 water ice floating on a liquid water “mantle” (Kattenhorn and Prockter, 2014) (Figure 4a). The  
222 detailed morphology of Europa’s plates was key in motivating the dynamic modelling that underpins  
223 our understanding of this planet’s interior. A similar “jostling plates” model has been advanced for  
224 Venus based on analogy with deformational structures observed in actively deforming continents on  
225 Earth (Byrne et al., 2021). Typical compressional tectonic landforms include wrinkle ridges, high relief  
226 ridges and lobate scarps (Figure 4b, c), common on Mercury (Byrne et al., 2014), Mars (Herrero-Gil et  
227 al., 2019; Nahm and Schultz, 2011), and the Moon (Schleicher et al., 2019; Watters et al., 2010). They  
228 are thought to be compound landforms representing folds above faults, but not common on Earth  
229 (Crane, 2020) hampering their interpretation. Global mapping these compressional tectonic features  
230 on Mercury has provided an independent estimate of its global contraction (Byrne et al., 2014).

231 Typical extensional forms include graben (Figure 4d) and are found commonly throughout the solar  
232 system. Graben systems are sometimes associated with pit-chains, which are thought to be caused  
233 by fracture dilation (Ferrill et al., 2011) (Figure 4e) and whose origin is also interpreted to be  
234 magmatic (see section 6):

235 Extensional tectonic features are very common on the icy moons of Jupiter, Saturn, and Neptune and  
236 their patterns have been vital in understanding the forces that influence these bodies including tidal  
237 stresses from their planets, crustal thickness, and mantle motions (Collins et al., 2009). Tectonic  
238 landforms on these icy satellites can be unique, for example the double ridges on Europa (Figure 4a),  
239 or the twisting double ridge-sets on Triton, or the prominent single equatorial ridge on Iapetus  
240 (Figure 4f).

## 241 6 Planetary volcanic landforms and processes

242 The definition of volcanism has been extended beyond magmatic volcanism in a planetary science  
243 context, to include also sedimentary volcanism and cryovolcanism and each are thought to produce  
244 somewhat distinct landforms. Magmatic volcanism requires interior heating and an availability of  
245 silicates to produce magma, so generally related volcanic landforms are found on terrestrial planets  
246 of the inner solar system, as well as Earth’s Moon and Jupiter’s innermost moon Io. Volcanism at the  
247 largest scale (hundreds to thousands of kilometres) is recognised in the form of volcanic constructs,  
248 such as Tuulikki Mons on Venus (Basilevsky et al., 2012) (Figure 5a) or Olympus Mons on Mars  
249 (Morris, 1982) and/or volcanic plains, such as the Mare of the Moon (Figure 5b) (Stuart-Alexander  
250 and Howard, 1970) or the Northern Plains of Mercury (Denevi et al., 2013). Peculiar to Venus are  
251 coronae, arachnoids and novae, which are large patterns of fractures (concentric, concentric-radial  
252 and radial, respectively) believed to be volcanic in origin (Head et al., 1992). Io is the only planetary  
253 body in the Solar System where volcanic eruptions have actually been observed occurring (McEwen,  
254 1998).

255 Recognisable at the kilometre to tens of kilometre-scale on Mars, the Moon, Venus and Io are  
256 individual lava flows (Figure 5c – io “dark flow”) and lava channels. On the Moon sinuous rilles  
257 (Figure 5d) – sinuous channels hundreds of metres to kilometres in width and up to 500 km long -  
258 were initially attributed to water (Peale et al., 1968), but are now generally acknowledged to be lava  
259 channels carved predominantly by thermal erosion (Hurwitz et al., 2013). “Skylights” (Figure 5e) –

260 deep nearly vertically walled circular to elliptical depressions – on Mars and the Moon are  
261 interpreted to represent the collapse of the roof of lava tubes and present considerable interest as  
262 natural habitats which could be exploited for human exploration (Sauro et al., 2020). Larger pit  
263 chains are thought to represent collapse on the withdrawal of lava from dikes (Wyrick, 2004) but  
264 could also be tectonic in origin (see Section 5).

265 Evidence for explosive volcanism is usually smaller-scale (tens of kilometres) and more subtle in its  
266 surface expression, taking the form of pits with associated red-colouration on Mercury (Kerber et al.,  
267 2011) (Figure 5f), low-albedo markings on the Moon (Gustafson et al., 2012) and km-scale volcanic  
268 cones on Mars (Brož and Hauber, 2012).

269 Sedimentary volcanism (often called mud volcanism) is driven by the circulation of water through a  
270 planetary crust generally driven by tectonic forces or density contrasts and has been reported on  
271 Mars (Figure 6a). Here, movement of groundwater is thought to have remobilised ancient  
272 sedimentary deposits creating pitted cones and lobate-fronted flow features (Oehler and Allen,  
273 2010). On Earth, mud volcanoes are the most commonly expressed landform resulting from  
274 sedimentary volcanism and differ from their volcanic counterparts in terms of morphology, however  
275 this distinction is harder to make on other bodies because of differences in environmental conditions  
276 are difficult to directly infer the potential morphologic impacts (Brož et al., 2020).

277 Cryovolcanism is thought to be more abundant in the icy moons of the outer planets (Ahrens, 2020;  
278 Kargel, 1995), where liquid water and ice, are thought to substitute almost directly the more familiar  
279 lava and silicic rocks in the functioning of the volcanic plumbing system. On Ceres, brine driven  
280 cryovolcanism is thought to explain the bright faculae, such as Cerealia Facula in Occator Crater  
281 (Nathues et al., 2020) (Figure 6b). Inspired by planetary research cryovolcanic processes have been  
282 cited as a potential cause for explosive pits that occurred in continuous permafrost on the Yamal  
283 Peninsula in Russia (Buldovicz et al., 2018).

284 Diapirism (either compositional or thermal), where a less dense material rises through a denser one  
285 above it is often associated with sedimentary- or cryo-volcanism. The resulting landforms can be a  
286 result of tectonic deformation rather than extrusion at the surface. Several enigmatic terrains have  
287 been attributed to diapirism or associated convection: the honeycomb and banded terrain in Hellas  
288 basin on Mars (Figure 6c - cassis) (Bernhardt et al., 2016), Cantaloupe terrain on Triton (Schenk and  
289 Jackson, 1993) or the cellular structure of Sputnik Planitia on Pluto (Howard et al., 2017b) (Figure 6d).

## 290 7 Mass movements on planetary bodies

291 Landslides have been identified on nearly every solid planetary surface observed in the solar system.  
292 Notably the long runout landslides observed on bodies as diverse as Mars (Crosta et al., 2018;  
293 McEwen, 1989), Mercury (Brunetti et al., 2015), the Moon (Boyce et al., 2020), Iapetus (Singer et al.,  
294 2012), Callisto (Moore et al., 1999), Pluto's moon Charon (Beddingfield et al., 2020), Ceres (Duarte et  
295 al., 2019) and Comet 67P (Lucchetti et al., 2019) (Figure 7a-c, landslide on Ceres, Callisto Moore et al,  
296 Mars, Mercury) have inspired a comparative planetology approach seeking to understand the  
297 physical processes underlying the motion of the long-runout landslides. The role that volatiles do or  
298 do not play in the mobility of landslides is a key recurring theme. On one hand being used as an  
299 argument to support inclusion of volatiles on Iapetus (Singer et al., 2012) and on the other being  
300 used to refute their action on comet 67P (Lucchetti et al., 2019). For Ceres (Johnson and Sori, 2020;  
301 B. E. Schmidt et al., 2017) as for Mars, both cases have been presented and no consensus has yet  
302 been achieved (Harrison and Grimm, 2003; Johnson and Campbell, 2017).



303 Peculiar to Mars are a landform called “Slope Streaks” (Figure 7d) (Sullivan et al., 2001), which are  
304 thought to represent avalanches of dust-sized material, taking the form of contrasting albedo,  
305 downslope-widening streaks, up to several kilometres in length and hundreds of metres wide. Slope  
306 Streaks usually appear as relatively dark (and sometimes relatively light) downslope oriented streaks  
307 with barely detectable or negligible relief (Brusnikin et al., 2016; Chuang et al., 2007), which fade to  
308 the background albedo over time. They often widen from a point source and can be sinuous,  
309 overcome obstacles and have digitate margins. They can overtop small obstacles (Brusnikin et al.,  
310 2016) yet are generally diverted by topographic irregularities (Miyamoto, 2004), so can form complex  
311 bifurcating features. The involvement of liquid water has been invoked to explain their mobility on  
312 low slopes (Bhardwaj et al., 2017), but dry granular mechanisms seem to also provide an adequate  
313 explanation (Dundas, 2020).

314 Images at better than 1 m/pix on the Moon have revealed a diversity of mass movements on steep  
315 slopes, including lobate and digitate dry granular flows on Moon (Figure 7e,f) (Senthil Kumar et al.,  
316 2013; Xiao et al., 2013). The Moon and Mercury host unique surface textures hinting at slower  
317 downslope movement of the surface regolith, including “elephant hide texture” on the Moon and  
318 “chevron texture” on Mercury, whose precise origin is unknown (Zharkova et al., 2020). On Mars,  
319 tens to hundreds of metre-scale lobate forms on slopes have been associated with the existence of a  
320 solifluction-type movement on Mars (Gastineau et al., 2020; Johnsson et al., 2012) and are found in  
321 association with other landforms interpreted to be periglacial in origin (see Section 8).

## 322 8 Planetary glacial and permafrost landforms and processes

323 Mars has an extensive suite of landforms at its mid-latitudes which are commonly accepted to be  
324 debris covered glaciers (Figure 8a) dating from the last 1 Ga of Mars’ history. These glaciers can cover  
325 tens to hundreds of kilometres and reach hundreds of metres thick. Their water ice core has been  
326 revealed through orbital radar sounding (Petersen et al., 2018; Plaut et al., 2009), and their surface  
327 textures indicate slow viscous deformation. Modelling studies (Karlsson et al., 2015; Parsons et al.,  
328 2011) and the general lack of landforms associated with melt imply that the ice is likely perennially  
329 frozen to the glacier bed (cold-based glaciers). The rare discovery of ridges interpreted to be eskers  
330 connected to extant glaciers suggests that this constraint is only occasionally overcome (Butcher et  
331 al., 2020; Gallagher and Balme, 2015). Isolated eskers and moraine-like ridges have been interpreted  
332 to be signs of ancient glaciation and/or icesheets (Butcher et al., 2016; Head and Marchant, 2003).

333 On Pluto the existence of glaciers of N<sub>2</sub> ice has been reported (Howard et al., 2017a). These take the  
334 form of smooth material filling topographic lows in highland terrains with longitudinal albedo  
335 lineations indicating flow direction, which appear to flow out onto Sputnik Planum at lower elevation  
336 where the lineations blend into the plains materials (Figure 8b). These glaciers are hundreds of  
337 kilometres in length. The only other planetary body where debris covered glaciers have been  
338 proposed is the dwarf planet Ceres (B. E. Schmidt et al., 2017), but their ambiguous morphology  
339 means that landsliding could also be a viable interpretation.

340 Permafrost conditions exist on many bodies, particularly those in the outer solar system, yet  
341 landforms typically associated with permafrost on Earth generally imply the degradation of ground  
342 ice, or at least cycling of temperatures near water’s triple point to produce terrain modifications e.g.,  
343 periglacial landforms. One exception is the formation of polygon crack patterns in ice-rich soil by  
344 thermal contraction, which only requires temperature cycling – metre to decametre-scale examples  
345 of these landforms have been widely reported at latitudes greater than 50°N and S on Mars  
346 (Mangold, 2005; Mellon et al., 2009) where ground ice is thought to be prevalent (Feldman et al.,  
347 2011). Periglacial landforms have been reported on Mars, implying the action of freeze-thaw cycling

348 in the planet's recent history and hence their interpretation as such remains a subject of debate.  
349 These landforms include:

- 350 • Gullies, which are alcove-channel-fan systems hundreds of metres to kilometres in  
351 length, which are found on steep slopes in the mid to high latitudes on Mars (Figure 2e)  
352 (Harrison et al., 2015; Malin and Edgett, 2000). Their resemblance at landscape and  
353 landform-scale to gullies carved by overland-flow and debris flow on Earth means that  
354 they have been widely interpreted to form by these processes (Balme et al., 2006;  
355 Conway and Balme, 2016; de Haas et al., 2015), and the source of water is likely from  
356 snow and/or ground ice thaw. Yet their present activity has led to a re-evaluation of this  
357 interpretation (see Section 11 - Sublimation landforms and processes).
- 358 • Surface albedo and/or clast patterns that resemble, and have a similar-scale to, sorted  
359 patterned ground on Earth, including sorted circles on flat ground and stripes on sloping  
360 terrain (Gallagher et al., 2011; Soare et al., 2016) (Figure 8c).
- 361 • Lobate forms interpreted to be solifluction lobes (see section 7) (Figure 8d).
- 362 • Polygonal patterned ground where the centres are lower than the margins and those  
363 margins form double-ridges implying the existence of ice wedges (Soare et al., 2021,  
364 2014) (Figure 8e).
- 365 • Scalloped depressions (Soare et al., 2008) and polygon junction pits (Costard et al., 2016)  
366 were initially interpreted to be true thermokarst (i.e. caused by thaw). However,  
367 together with expanded craters (Viola et al., 2015) are now thought to be caused by  
368 sublimation (Dundas et al., 2015), see Section 11.
- 369 • Tens to hundreds of metre isolated hills or mounds with summit cracks/depressions  
370 interpreted to be caused by ice-heave, otherwise known as "pingos" (Burr et al., 2009;  
371 Soare et al., 2005) (Figure 8f).

## 372 9 Weathering

373 Weathering on planetary bodies produces regolith from rock via a range of breakdown processes,  
374 some of them unknown on Earth. The landscape expression of these weathering processes includes  
375 softening of primary landforms, such as impact craters, following a generally diffusive trend (Fassett  
376 et al., 2017; Soderblom, 1970). Landforms directly linked to weathering processes, include regolith  
377 surface textures and rock shapes, which tend to be expressed at the metre-scale or less. Hence, *in*  
378 *situ* observations are best suited to inferring weathering processes are limited to the Moon, Mars,  
379 asteroids Bennu and Ryugu and comet 67P.

380 On bodies without an atmosphere the surface is subject to a range of processes not experienced at  
381 Earth's surface, including solar wind sputtering and micrometeorite impacts. In addition, thermal  
382 stress and fatigue are greatly accentuated by the high amplitude thermal variations experienced on  
383 many planetary surfaces compared to Earth (El Mir et al., 2019; Molaro and Byrne, 2012). Cracked  
384 rocks or "Puzzle rocks" observed on Bennu (Walsh et al., 2019), Ryugu (Sasaki et al., 2021), the Moon  
385 (Ruesch et al., 2020) and Mars (Eppes et al., 2015; Hörz et al., 1999) have been linked to thermal  
386 fatigue and/or micrometeorite impacts (Figure 9a). On Mars rocks can also be sculpted by the wind –  
387 producing ventifacts (Bridges et al., 1999; Greeley et al., 2006a; Thomson et al., 2008) (see also  
388 Section 2). Pitted boulder surfaces on Mars have been linked to transient melting of snow (Head et  
389 al., 2011) and volatile-related processes have been implicated in accelerating rock chute formation  
390 (Levin et al., 2021) and boulder breakdown (de Haas et al., 2013).

391 A consequence of rock breakdown is rockfalls, which have been observed to occur in repeat imaging  
392 of Mars (Grindrod et al., 2021; Vijayan et al., 2021) (Figure 9b). Roll/bounce marks left in the regolith

393 in the wake of boulders (Figure 9c) have shown rockfall to be a recently active process on the Moon  
394 (Arvidson et al., 1975; Bickel et al., 2020). Patterns in the distribution of rockfall tracks have been  
395 used to provide evidence for rock breakdown by thermal stress on Mars on the timescale of < 1Ma  
396 (Tesson et al., 2020), seismic activity on Mars (Roberts et al., 2012) and on the Moon (Senthil Kumar  
397 et al., 2016), as well as inform the regolith strength on the Moon (Bickel and Kring, 2020).

398 Some puzzling aspects of surface regolith appearance have been attributed to surface sintering  
399 caused by solar irradiation (Zharkova et al., 2020) (Figure 9d).

## 400 10 Impact Cratering

401 The process of impact cratering dominates most planetary surfaces apart from the Earth, Venus,  
402 Titan and Io which either have dense atmospheres reducing the incoming impactor population  
403 and/or surface processes that act to erase any crater landforms that are created. Impact craters  
404 create topographic relief that can serve as a catalyst for other surface processes and they expose  
405 materials from planetary interiors to active surface processes. For example, impacts can cause  
406 substantial seismic shaking (Schultz and Gault, 1975) and therefore can initiate mass movements (see  
407 Section 7).

408 The shape of an impact crater is primarily a function of the gravity, impactor size and the target  
409 surface composition (Melosh, 1989). Other factors, such as impact speed and angle, impactor  
410 composition, or target structure, also play a role in modulating the crater shape, but for the purposes  
411 of this review will not be considered in further detail. With increasing impactor sizes craters evolve  
412 from “simple” bowl-shapes towards more “complex”, including flat-floored with a central peak up to  
413 multi-ringed basins (Figure 10a-c). The crater diameter at which the simple-to-complex transition  
414 occurs varies from planetary body to planetary body and is traditionally represented by plotting the  
415 population of craters on a logarithmic depth-diameter diagram. For example, on Mars the simple-to-  
416 complex transition occurs at crater diameters of ~8 km, on Europa it occurs at ~1 km and Vesta at 28  
417 km (Hiesinger et al., 2016).

418 Impact craters eject material from their cavity forming unique morphologies, such as ejecta blankets,  
419 secondary crater clusters/chains, and visible radial “rays” which can be global in extent (Figure 10d).  
420 Impact melt, found within the cavity and in the ejecta, shares many morphological characteristics  
421 with lava and in ancient terrains on the Moon and Mercury, the distinction between them can be  
422 challenging (Denevi et al., 2013). The outcrops located in crater walls and central peaks can provide  
423 relatively fresh exposures of subsurface materials providing insights into the subsurface composition  
424 of a body without having to drill *in situ* (Quantin et al., 2012).

425 Impact craters substantially disturb the crust (Kenkmann et al., 2014) and as a result can form a  
426 structural conduit for endogenic processes that are then expressed at the surface, such as  
427 hydrothermal circulation (Osinski et al., 2013), explosive volcanism (Thomas et al., 2014), or  
428 cryovolcanism (Nathues et al., 2020).

429 Impact craters are used as an essential dating tool in planetary science, as their size-frequency  
430 distribution is a function of the exposure age of a surface (Hartmann and Neukum, 2001). The  
431 degradation state of the craters, hence the ability to recognise the surface processes that have  
432 influenced them, is an important factor when interpreting the results of the crater size-frequency  
433 distribution (Michael and Neukum, 2010).

## 434 11 Sublimation landforms and processes

435 Environments dominated by sublimation are rare on Earth, hence entire landforms or landscapes  
436 dominated by this phase change are restricted to other planetary bodies. In particular the icy  
437 satellites of the outer Solar System have surfaces dominated by various ices and whose sublimation  
438 is thought to explain some of the most unusual landscapes (Mangold, 2011). For example, the entire  
439 surface of Jupiter's moon Callisto is thought to have been extensively modified by the sublimation of  
440 CO<sub>2</sub> and H<sub>2</sub>O ices at its surface leaving a terrain dominated by dissected ridges and knobs (Figure 11a)  
441 (White et al., 2016). Helene, in the Saturn system, has a sculpted surface attributed to remobilisation  
442 of a thick layer of particles whose origin is sublimation from the plumes of Enceladus (Figure 11b)  
443 (Hirata et al., 2014).

444 Comets are another planetary body where sublimation is the dominant landscape forming process  
445 every time the comet approaches the sun. The first cometary orbital data from the Rosetta mission  
446 to comet 67P revealed astonishingly diverse landscapes, including dunes (see Section 2), retreating  
447 steep sided pits and cliffs (Figure 11c) (Vincent et al., 2015) and cracks and fissures (El-Maarry et al.,  
448 2015). The steep sided pits and cliffs are thought to be correlated to the plumes of outgassing  
449 (Vincent et al., 2016). Gassy outbursts were also noted to mobilise dust on asteroid Bennu, yet the  
450 geomorphic effect if any in this setting remains unclear (Lauretta et al., 2019).

451 On other bodies, depressions are the most common landform associated with sublimation and can  
452 be considered akin to karst on Earth. The perennial CO<sub>2</sub> ice found at the South Polar cap of Mars,  
453 undergoes retreat each year in the form of enlarging and coalescing circular to elliptical steep sided  
454 pits typically several hundred metres in diameter and metres deep, dubbed "swiss cheese" (Buhler et  
455 al., 2017) (Figure 11d). The loss of excess water ice from the ground via sublimation in the mid-  
456 latitudes of Mars results in "scalped depressions" (Dundas et al., 2015; Soare et al., 2007) –  
457 shallow-sloping depressions of hundreds of metres in extent, with an arcuate and steeper backwall.  
458 In the some of the same regions, sublimation expands polygonally patterned contraction cracks  
459 producing chains of pits and possibly cavities (Séjourné et al., 2011). Volatile loss has also been  
460 invoked to explain shallow, steep-sided depressions on Mercury which are surrounded by a relatively  
461 bright halo – "hollows" (Blewett et al., 2011) (Figure 11e). The discovery of these landforms was part  
462 of the realisation that Mercury's crust is not actually depleted in volatiles as once thought (Nittler  
463 and Weider, 2019).

464 The seasonal retreat of the CO<sub>2</sub> ice deposits across the surface of Mars results in a uniquely martian  
465 process caused by basal sublimation of the CO<sub>2</sub> ice (Kieffer et al., 2006). CO<sub>2</sub> ice is translucent to solar  
466 radiation, hence the increasing incoming solar radiation in late winter to early spring can heat the  
467 regolith under the CO<sub>2</sub> ice, causing it to sublimate and CO<sub>2</sub> gas to be trapped underneath it. The gas  
468 pressure builds until the ice above breaks, releasing the gas in a jet which deposits dark dust from  
469 under the ice onto the still bright icy surface. This phenomenon most commonly manifests itself as  
470 dark fans or spots (Hansen et al., 2013) and on the steep slopes of dunes can even appear as digitate  
471 (Gardin et al., 2010). The sediment mobilised under the ice is thought to explain the observation of  
472 "spiders" – dendritic networks of channels leading to one or more "nodes" (Thomas et al., 2011)  
473 (Figure 11f). Individual spiders can be hundreds of metres in size and they can extend across many  
474 kilometres. Although spiders have not been observed to grow, similar branching networks have been  
475 observed to appear and grow on dunes ("furrows") (Portyankina et al., 2010). Sediment mobilisation  
476 by sublimating CO<sub>2</sub> is thought to explain ongoing sediment motions observed in martian gullies which  
477 only occur in winter (Dundas et al., 2019). In particular, a uniquely martian morphology called "linear  
478 gullies" is thought to be formed by levitating blocks of CO<sub>2</sub> ice falling from icy dune crests (Diniega et

479 al., 2013). Volatile loss is believed to drive the formation of gully-like-landforms on the asteroid Vesta  
480 (Scully et al., 2015) and on Mercury (Malliband et al., 2019).

## 481 12 Discussion & Conclusions

482 Planetary geomorphology is distinctive from Earth-based geomorphology in that it is very reliant on  
483 remote sensing and often a more global-scale perspective is taken on unravelling the formation of  
484 landscapes and landforms. Satellite data of the Earth have spurred a number of studies taking a  
485 similar planetary-scale perspective on Earth (Chen et al., 2019; Poulos et al., 2012), but more often  
486 studies are local and/or regional in scale and scope. Planetary geomorphology is enticing to many,  
487 because of the aspect of exploration and the possibility of making unusual discoveries on alien  
488 worlds. Planetary geomorphology can drive key advances to better understand our own planet  
489 (Baker, 1993; Sharp, 1980).

490 One of the major limitations of planetary geomorphology is the problem of equifinality and the  
491 uncertainty of what landforms can be produced by processes unknown on Earth (Baker, 2014). To  
492 infer processes from landforms and landscapes is not an exact science and always open to  
493 interpretation. Access to the field can resolve many ambiguities on Earth, yet in a planetary context  
494 this is rarely an option and can lead to impasses where researchers just do not have enough data to  
495 disambiguate the leading hypotheses. Yet, as shown in this contribution, planetary geomorphology  
496 remains an essential tool in understanding the internal and external forces shaping bodies in the  
497 Solar System.

498 Planetary Geomorphology is likely to continue to grow, because the ability to interpret process from  
499 remote sensing data is key to planning future missions, for example deciding where to land or  
500 acquire certain types of data. Image and topographic data are the cornerstones of every new mission  
501 and future exploration will only add to our database of new and surprising planetary landforms and  
502 landscapes. Further, these landscapes have much to teach us about our own planet.

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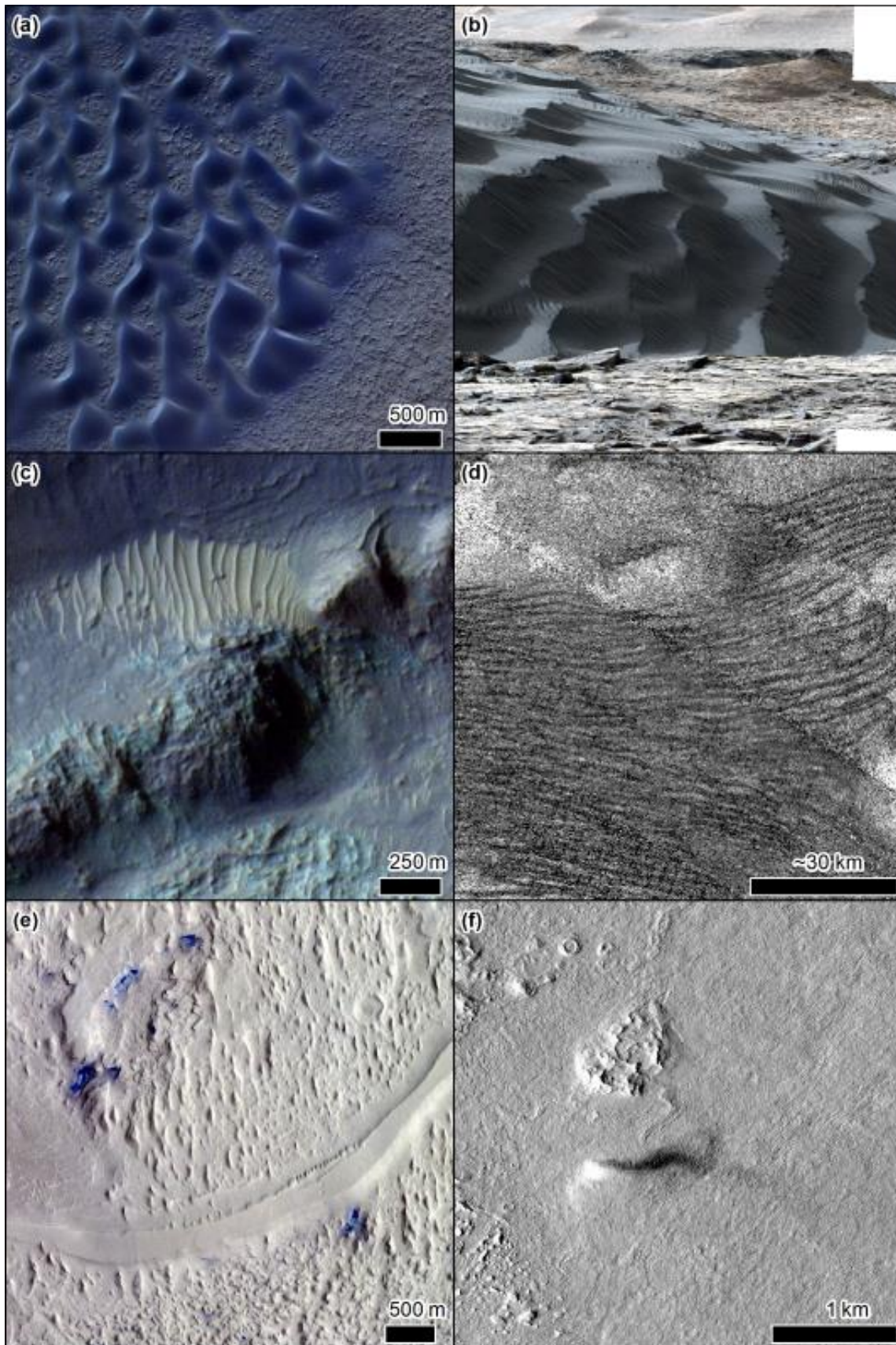
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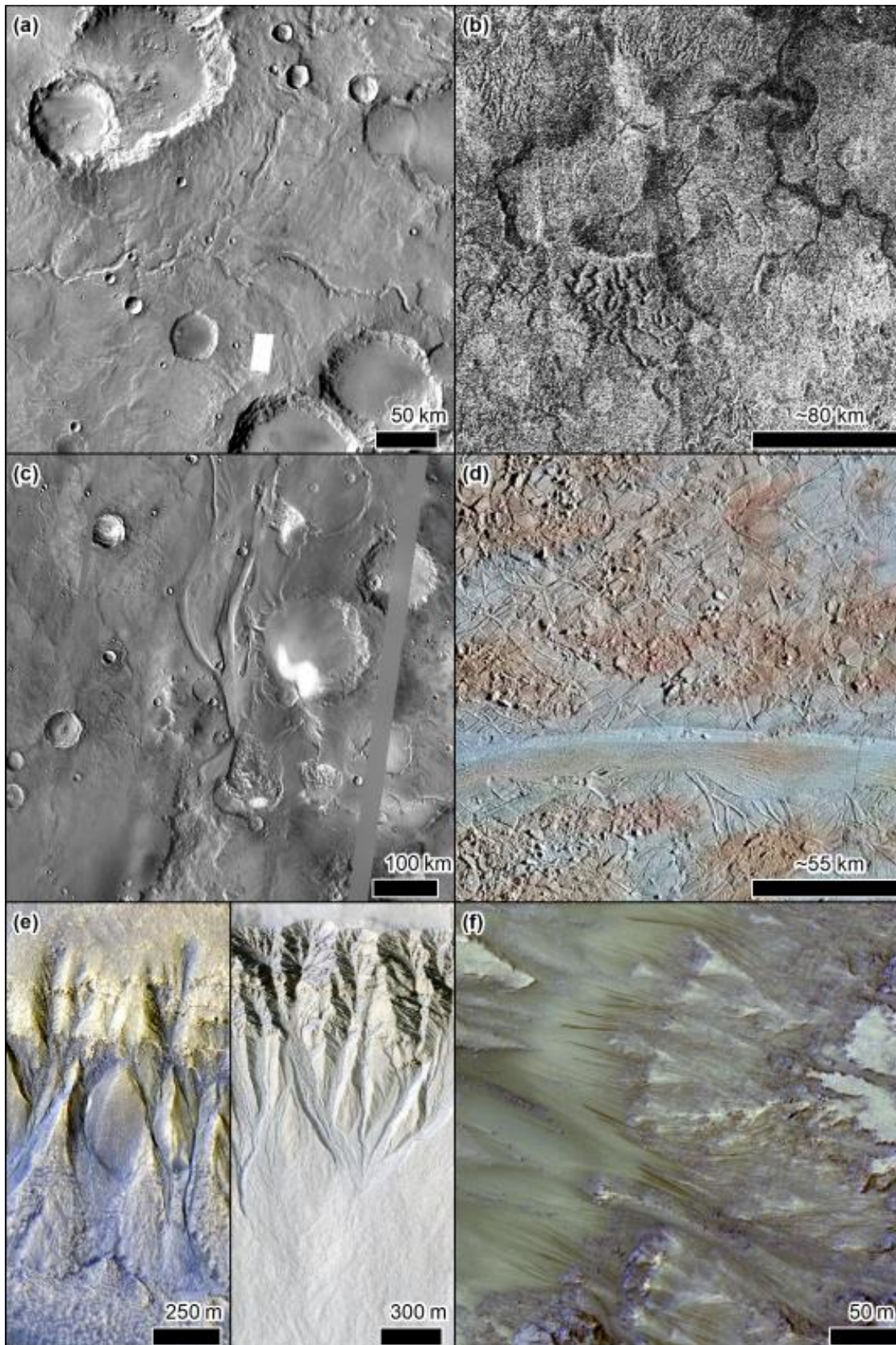
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1315 Figure 1: Aeolian planetary landforms. a) Dark Dunefield on the floor of a 35-km-diameter crater in  
 1316 Aonia Terra on Mars (sunlight from the left), CaSSIS image MY36\_015406\_006\_0, credit  
 1317 ESA/Roscosmos/Unibe. b) Large ripples (spacing 2-2.5 m) superposed by smaller impact ripples on

1318 the secondary lee slope of Namib Dune in Gale Crater on Mars (sunlight from the left). Mosaic of MSL  
1319 Mastcam images from sol 1192 (Ewing et al., 2017), credit NASA/JPL-Caltech/Malin Space Science  
1320 Systems. c) Transverse aeolian ridges (TARs) on the floor of a 17-km-diameter crater in Margaritifer  
1321 Terra on Mars (sunlight from the left), CaSSIS image MY36\_015406\_006\_0, credit  
1322 ESA/Roscosmos/Unibe. (d) Cassini Synthetic Aperture radar image of the Shangri-La Sand Sea on  
1323 Titan (PIA20710). Image credit NASA/JPL-Caltech/ASI. (e) Yardangs and an inverted channel in Aeolis  
1324 Mensae region of Mars (sunlight from the right), CaSSIS image MY34\_005683\_188\_2, credit  
1325 ESA/Roscosmos/Unibe. (f) Dust Devil in Amazonis Planitia on Mars (sunlight from the left), CTX image  
1326 D02\_028082\_2155. Credit NASA/JPL/MSSS. North is up in all images apart from (b).



1327

1328 Figure 2: Fluvial planetary landforms. a) Evros Vallis, a valley network in Sinus Sabaeus region of Mars

1329 (sunlight from the left). The image is the Day IR THEMIS controlled mosaic available from the USGS.

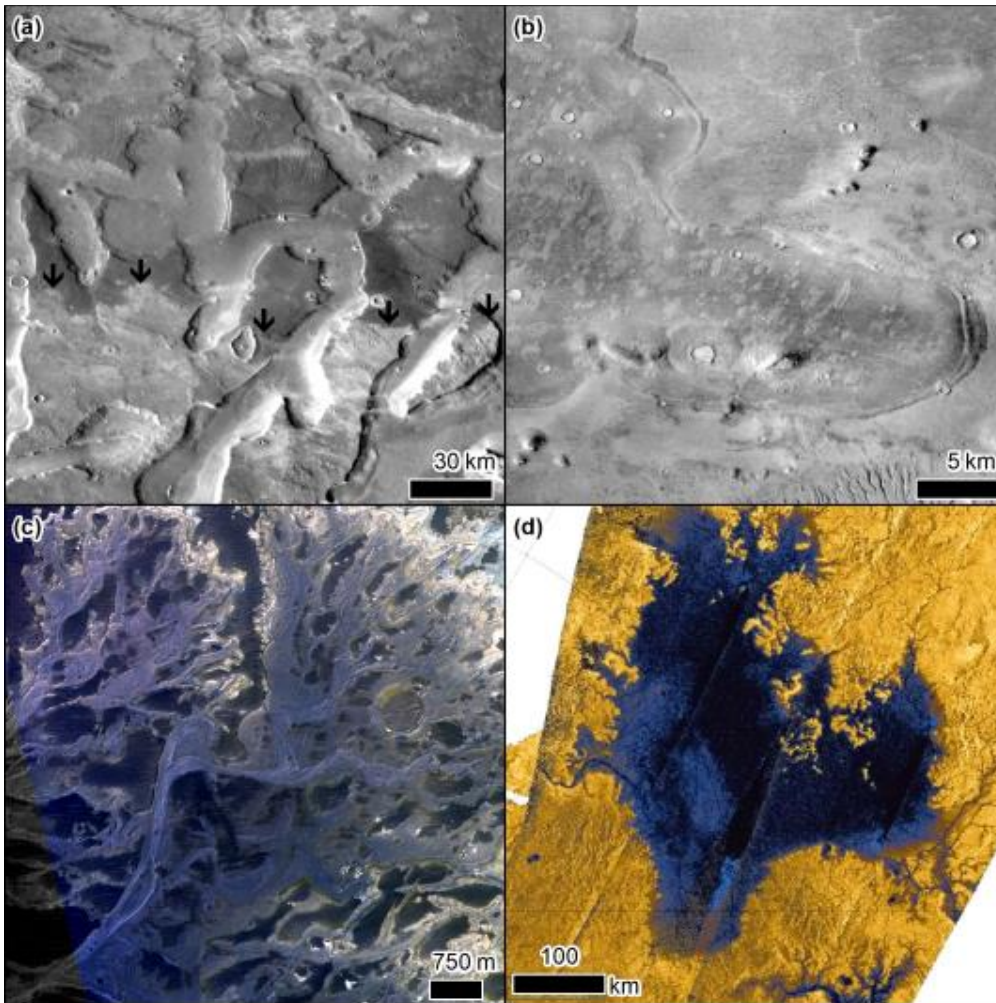
1330 b) A synthetic aperture radar image of valleys near Titan's south pole taken by the Cassini spacecraft

1331 image reference PIA10219, credit NASA/JPL-Caltech/ASI. c) Baetis Chaos leading north into Maja



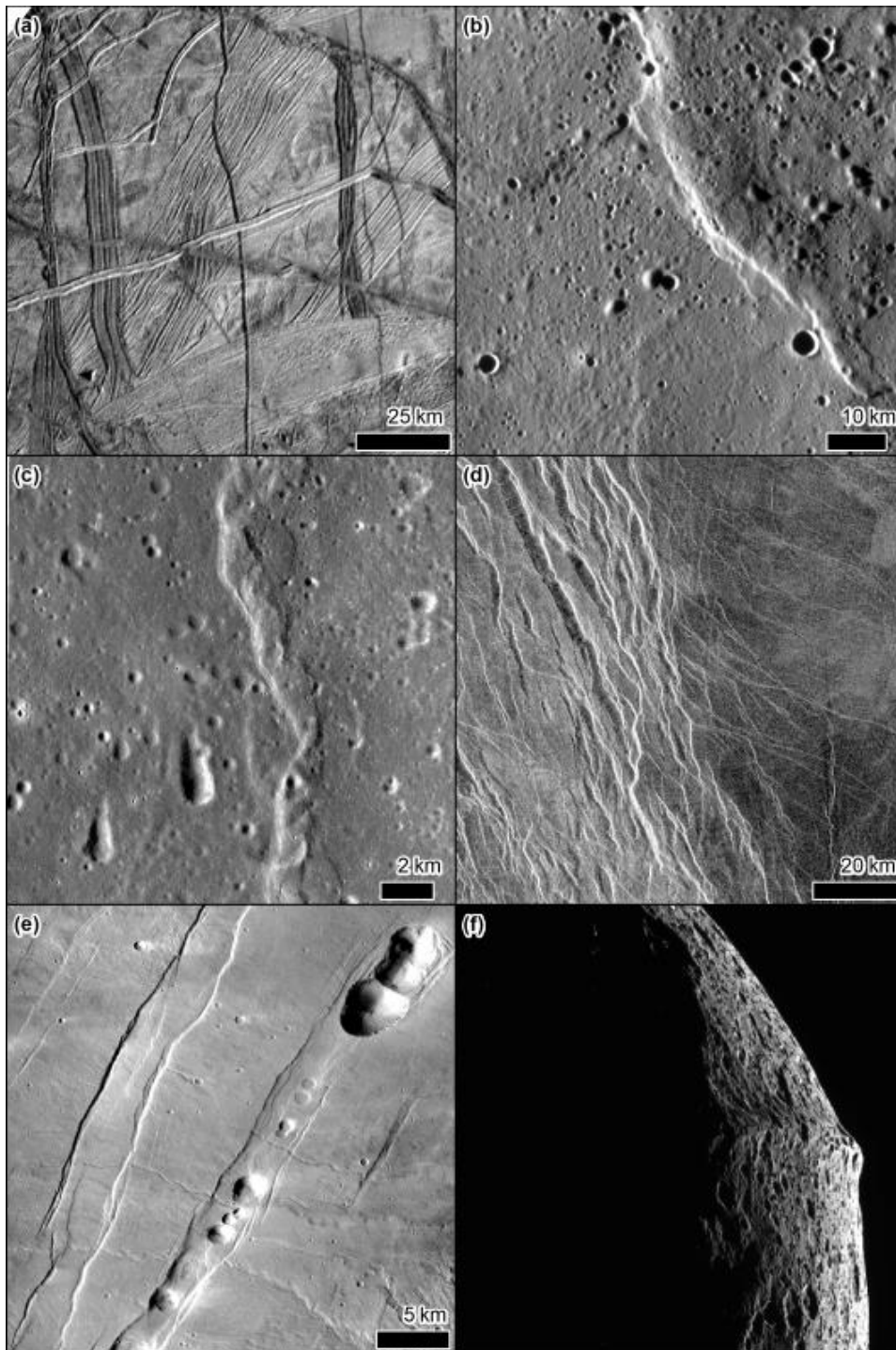
1332 Valles outflow channel on Mars (sunlight from the left). The image is the Day IR THEMIS controlled  
 1333 mosaic available from the USGS. d) Chaos terrain on Europa near Agenor Linea (sunlight from the  
 1334 right) taken by Galileo, image reference PIA23873, credit NASA/JPL-Caltech/SETI Institute. e) Two  
 1335 false-colour images of gullies on Mars (sunlight from the left in both): left Crater in Terra Cimmeria  
 1336 HiRISE image PSP\_004019\_1420 and right Gasa Crater, HiRISE image PSP\_003939\_1420, credit  
 1337 NASA/JPL/UofA. f) Recurring Slope Lineae in Palikir Crater (sunlight from the left), HiRISE image  
 1338 ESP\_031102\_1380, credit NASA/JPL/UofA. North is up in all images.

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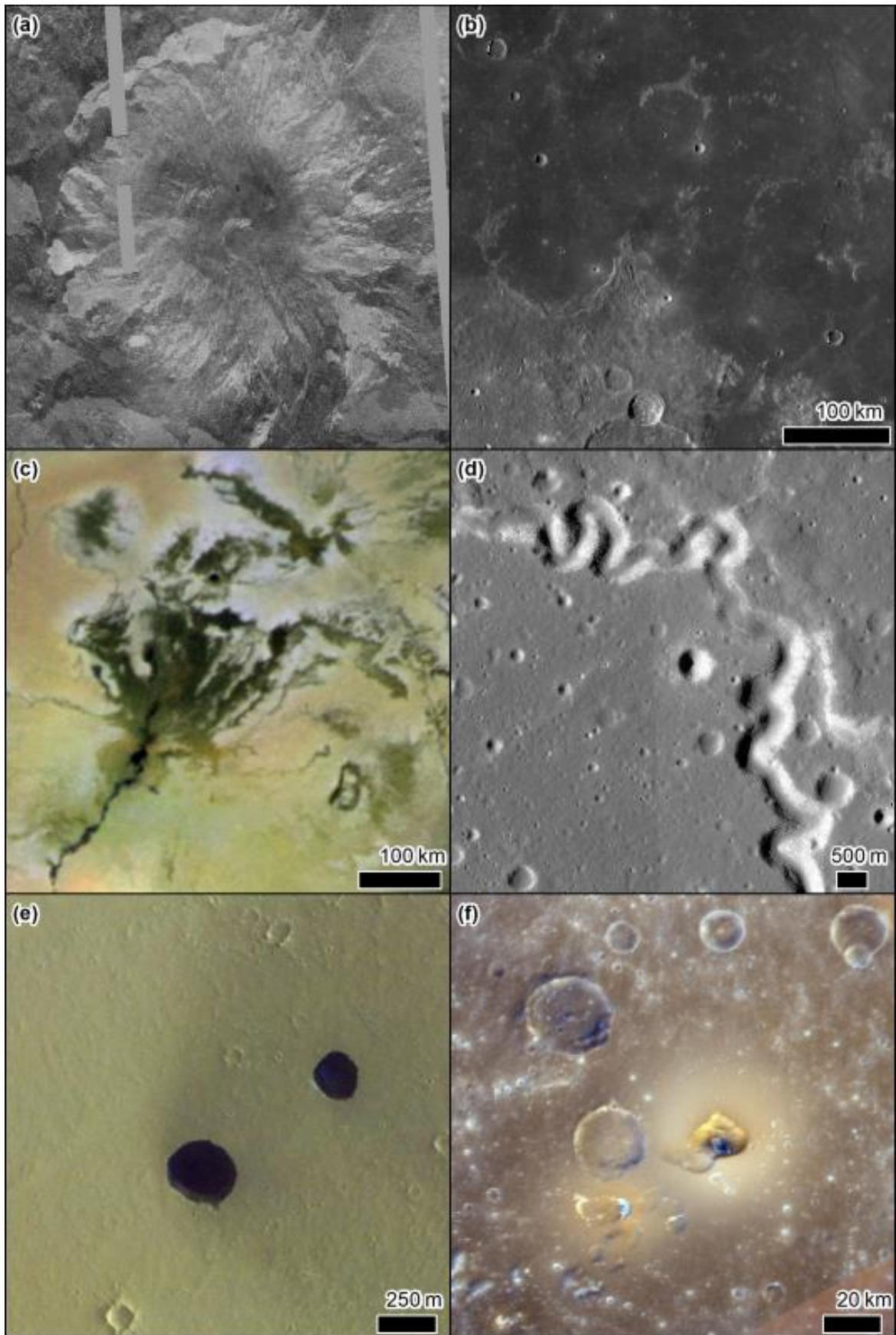
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1341 Figure 3: Coastal and lacustrine planetary landforms. a) Albedo contrast (black arrows) interpreted as  
 1342 a shoreline of a former norther ocean on Mars as seen in the Day IR THEMIS controlled mosaic  
 1343 available from the USGS (sunlight from the left). B) Lobate features interpreted to be tsunami runup  
 1344 deposits originating from an impact into a former norther ocean (sunlight from the left). CTX image  
 1345 P17\_007835\_2249, credit NASA/JPL/MSSS. c) CaSSIS false colour image of the inverted distributary  
 1346 channel systems within Eberswalde Crater on Mars, interpreted to be eroded remnants of a delta  
 1347 that formed within a lake in the crater (sunlight from bottom-right). CaSSIS images  
 1348 MY34\_004384\_206\_1 and MY34\_004384\_206\_2, credit ESA/Roscosmos/Unibe. d) Cassini false-  
 1349 colour radar image of Ligeia Mare, the second largest known sea of liquid hydrocarbons on Titan,  
 1350 credit: NASA/ESA/T. Cornet. North is up in all images.



1351

1352 Figure 4: Tectonic planetary landforms. a) The surface of Europa divided into “plates” criss-crossed by  
 1353 fractures containing internal parallel ridges. Galileo SSI image 4700R, credit NASA/JPL-Caltech/SETI  
 1354 Institute. b) A lobate scarp on Mercury (sunlight from the left), MESSENGER MDIS NAC image  
 1355 EN1014447282M, credit NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie  
 1356 Institution of Washington. c) Wrinkle ridge on the Moon (sunlight from the left), LROC NAC images  
 1357 M181023296 and M104376385, credit NASA/GSFC/ASU. d) Graben on Venus, extract of the Venus  
 1358 Magellan SAR FMAP Left Look Global Mosaic from the USGS. e) Graben and pit chains on Mars  
 1359 (sunlight from the left), CTX image B18\_016700\_2167, credit NASA/JPL/MSSS. f) Limb image of  
 1360 Iapetus, showing the 20 km high equatorial ridge, taken by Cassini N1568094172\_2. North is up in all  
 1361 images except f.



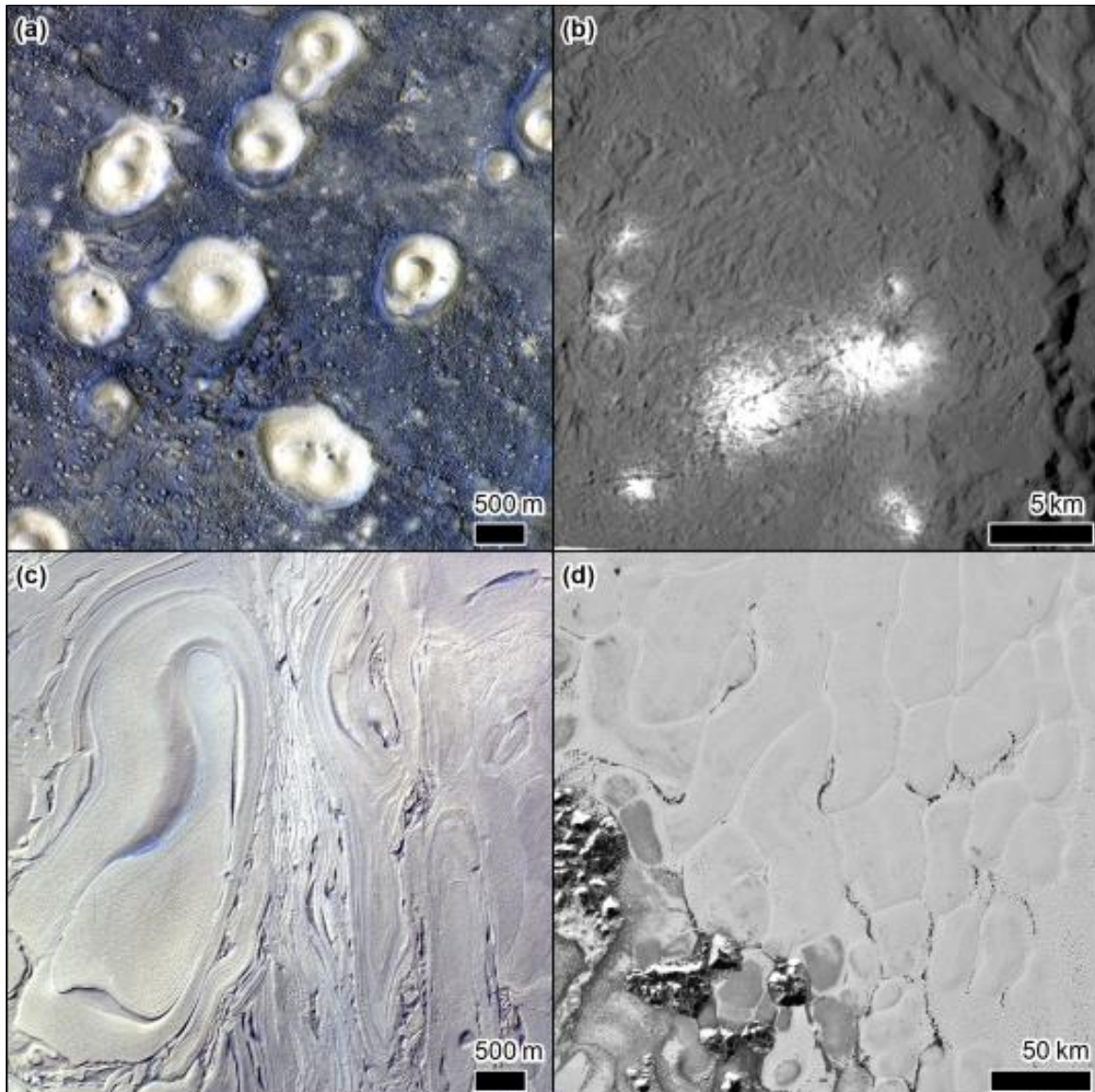
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Figure 5: Volcanic planetary landforms. a) Tuulikki Mons a shield volcano on Venus, extract of the Venus Magellan SAR FMAP Left Look Global Mosaic from the USGS. b) The lunar maria with portions

1365 of embayed impact crater rims visible and the contact with the highlands towards the bottom left  
 1366 (sunlight from the left). LORC WAC global mosaic made available by the USGS. c) Volund dark  
 1367 volcanic field on Io (Veeder et al., 2009) using the USGS Io basemap combining Voyager and Galileo  
 1368 images. d) Sinuous rilles on the Moon (sunlight from the left), LROC NAC image M1157998924, credit  
 1369 NASA/GSFC/ASU. e) Skylights on Mars (sunlight from the top-right), with the east-facing walls barely  
 1370 visible. CaSSIS false colour image MY36\_015278\_162\_0, credit: ESA/Roscosmos/Unibe. f) Agwo  
 1371 Facula on Mercury, where the central vent is surrounded by smooth deposits with an orange  
 1372 coloration in the MDIS enhanced colour mosaic overlain by MDIS WAC image EW1012888774 (where  
 1373 sunlight is from the bottom), credit NASA/Johns Hopkins University Applied Physics  
 1374 Laboratory/Carnegie Institution of Washington. North is up in all images.

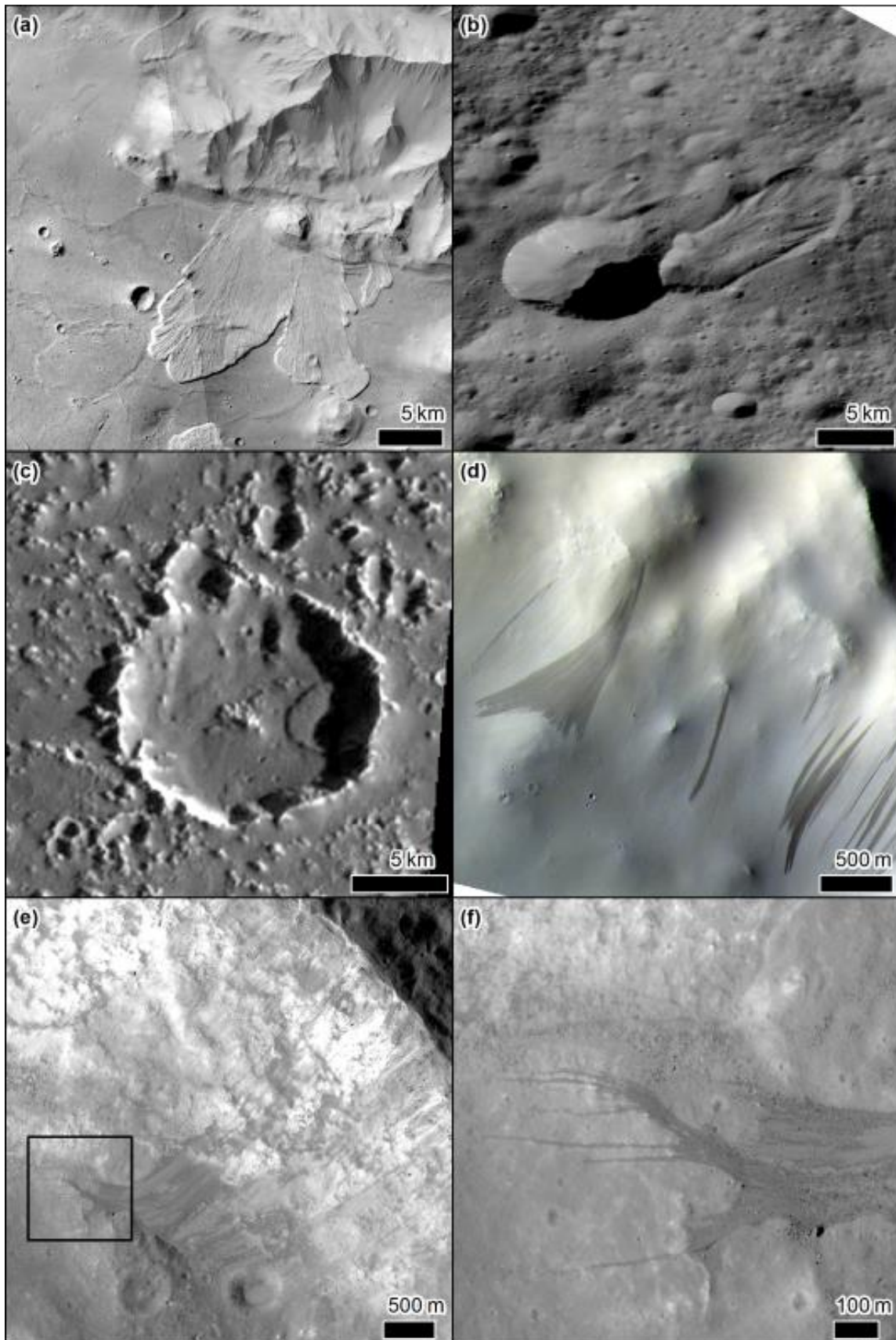


1375  
 1376 Figure 6: Sedimentary volcanism and cryo-volcanic landforms. a) Pitted cones interpreted to result  
 1377 from mud volcanism in Acidalia Planitia on Mars (sunlight from the top-right). CaSSIS image  
 1378 MY35\_009227\_048\_0 credit: ESA/Roscosmos/Unibe. b) Bright faculae in Occator Crater on Ceres  
 1379 interpreted to be salt deposits resulting from cryovolcanism (sunlight from the right). DAWN framing  
 1380 camera image FC21B0070808\_16169044543F6C, credit NASA/JPL-Caltech/UCLA/MPS/DLR/IDA. c)  
 1381 The enigmatic banded terrain on the floor of Hellas Basin on Mars (sunlight from the left). CaSSIS  
 1382 image MY36\_015427\_317\_0 credit: ESA/Roscosmos/Unibe. d) The mysterious cellular structure of

1383 Sputnik Planitia on Pluto (sunlight from the top), image New Horizons global mosaic from the USGS.

1384 North is up in all images.

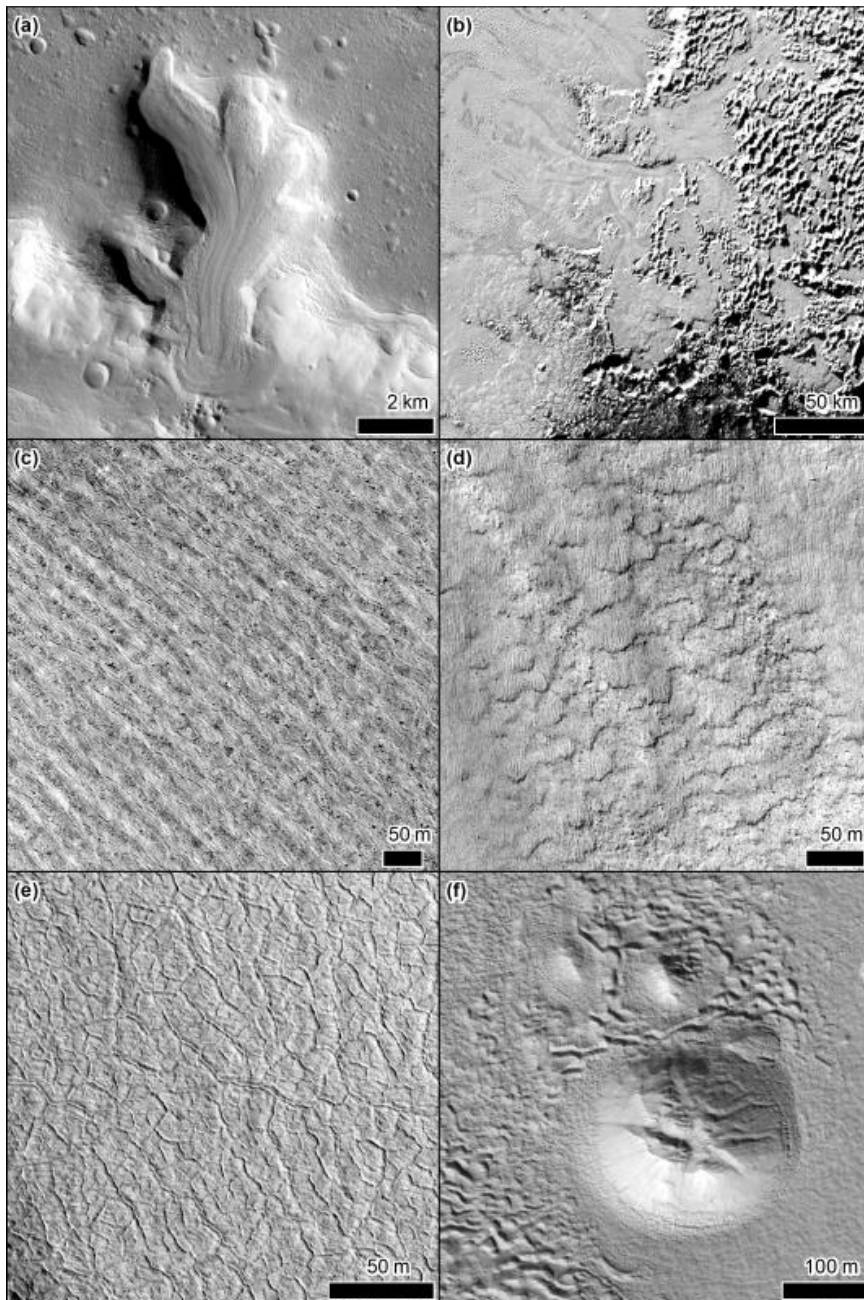
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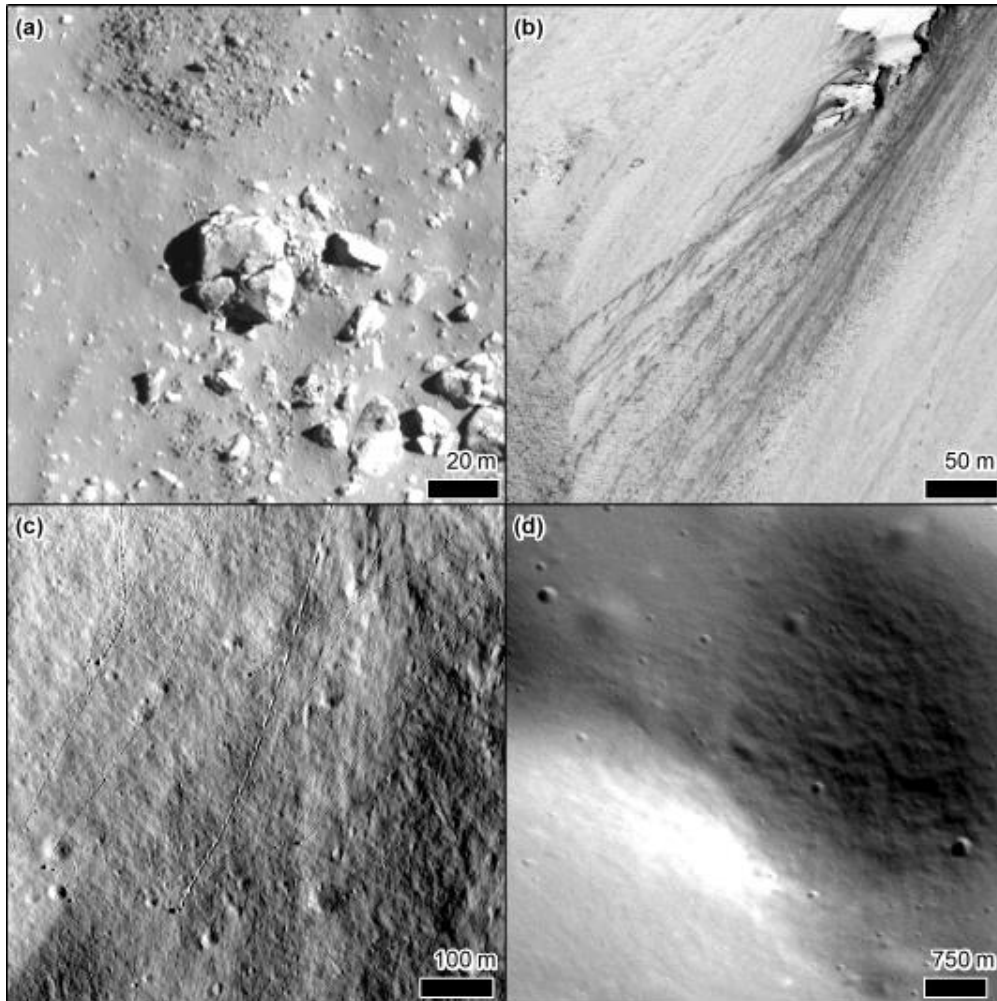
Figure 7: Planetary Mass Movements. a) Landslides in Valles Marineris on Mars (sunlight from the left), CTX images D20\_034988\_1669, G19\_025850\_1688, credit NASA/JPL/MSSS. b) Landslide on Ceres (sunlight from the bottom), DAWN FC FC21A0061028\_16091125549F1D. c) Landslide on Callisto (sunlight from the right), Galileo SSI image 2840R, credit NASA/JPL-Caltech/SETI Institute. d)

1391 Slope Streaks on Mars (sunlight from the left), CaSSIS image MY36\_015392\_011\_0 credit:  
 1392 ESA/Roscosmos/Unibe. e) Granular flows in Kepler Crater on the Moon (sunlight from the left), LROC  
 1393 NAC images credit: NASA/GSFC/ASU. f) Zoom in on the termini of the granular flows in panel e. North  
 1394 is up in all images.



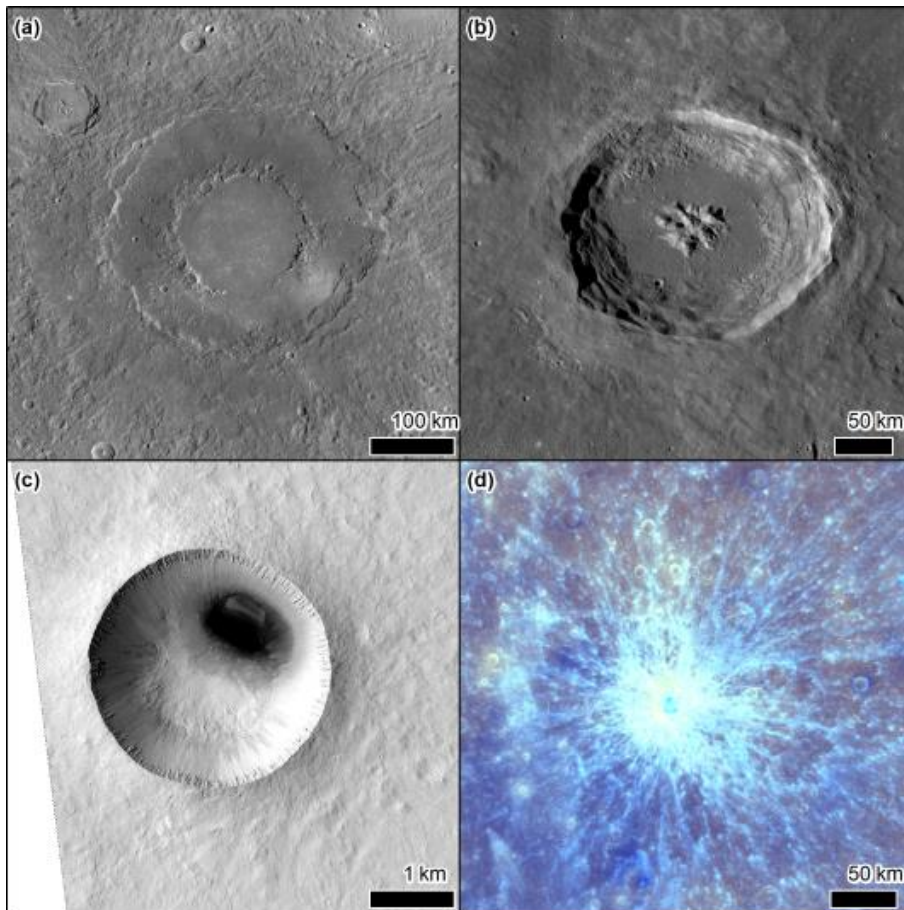
1395  
 1396 Figure 8: Planetary glacial and periglacial landforms. a) Debris covered glacier on Mars (sunlight from  
 1397 the left), CTX Image B05\_011776\_2208, credit NASA/JPL/MSSS. b) Glacial flows on Pluto imaged by  
 1398 New Horizons (sunlight from top-left), taken from the Global Mosaic available from the USGS. c)  
 1399 Linear arrangements of boulder propagating downslope interpreted to be sorted patterned ground  
 1400 on an impact crater wall in the high northern latitudes on Mars (sunlight from top-left), HiRISE image  
 1401 PSP\_009580\_2485, credit NASA/JPL/UofA. d) Lobate forms on the wall of an impact crater on Mars  
 1402 interpreted to be solifluction lobes (sunlight from the left), HiRISE image ESP\_023679\_1365, credit  
 1403 NASA/JPL/UofA. e) Polygonal fractured ground where the polygon boundaries are raised as single or  
 1404 double ridges, termed low centres polygons (sunlight from bottom-left), HiRISE image

1405 PSP\_005821\_1095 credit NASA/JPL/UofA. f) A mound with a fractured summit near Moreaux Crater  
1406 on Mars interpreted to be a pingo (sunlight from bottom-left), HiRISE image ESP\_058140\_2225 credit  
1407 NASA/JPL/UofA. North is up in all images.



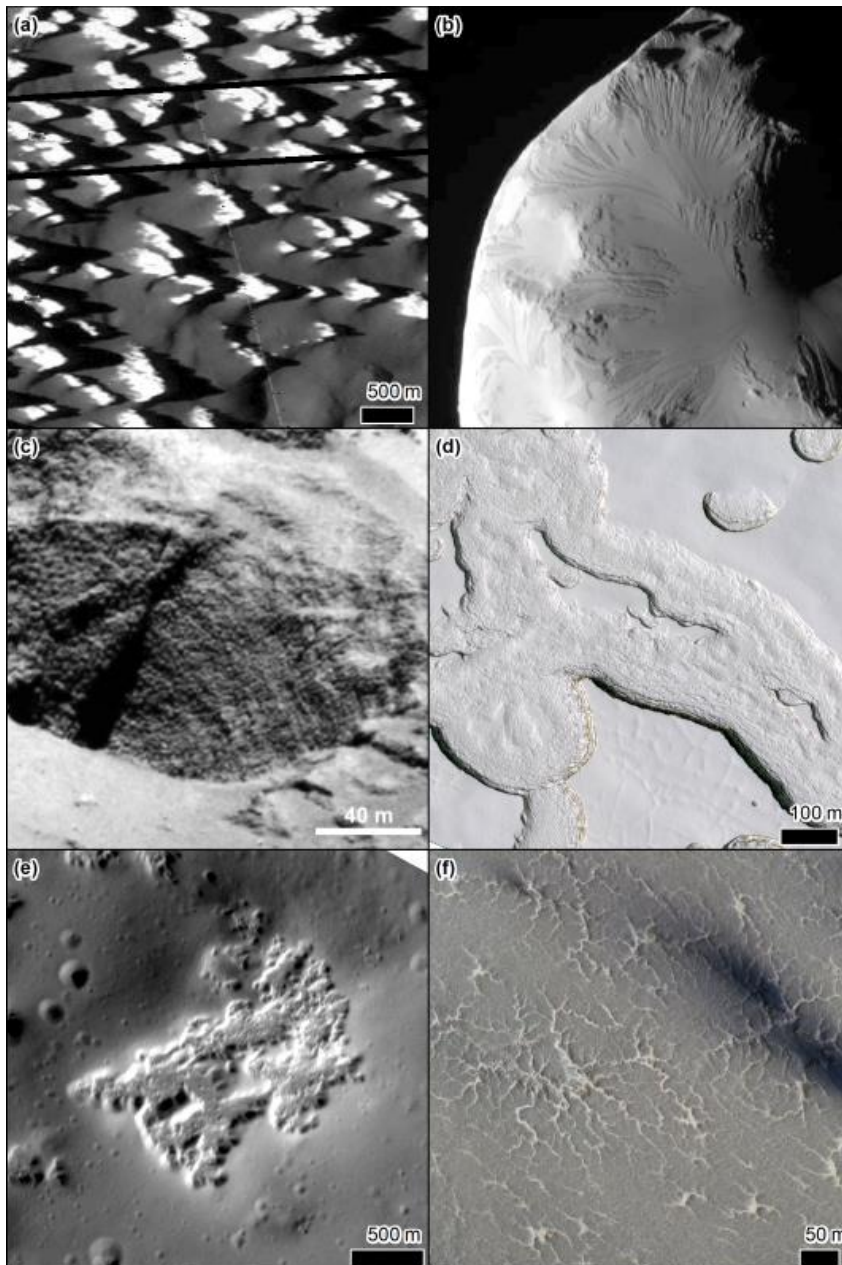
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1409 Figure 9: Weathering on planetary surfaces. a) Fractured rocks around Byrgius A Crater on the Moon  
1410 (sunlight from the right), LROC NAC image M175698856LE, credit NASA/GSFC/ASU. b) Tracks and low  
1411 albedo “ejecta” left by recent rockfalls on a crater wall on Mars (sunlight from the left), HiRISE image  
1412 PSP\_004110\_1640, credit NASA/JPL/UofA. c) Multiple rocks which have left depressions behind them  
1413 while rolling and bouncing over the lunar surface (sunlight from the right), LROC NAC image  
1414 M1198659818LE, credit NASA/GSFC/ASU. d) Undulating, irregular surface texture on Mercury  
1415 (sunlight from the bottom-left), termed “Elephant hide” (Zharkova et al., 2020) MDIS NAC image  
1416 EN1042186062M, credit NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie  
1417 Institution of Washington. North is up in all images.





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1419 Figure 10: Impact craters on Planetary bodies. a) Rachmanioff, an impact basin on Mercury, with  
 1420 noticeable multiple rings (sunlight from the right), MDIS global BDR mosaic, credit NASA/Johns  
 1421 Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington. b) Arstillus, a  
 1422 complex crater with central peak and wall terraces on the Moon (sunlight from the left), LRO global  
 1423 WAC mosaic, credit NASA/GSFC/Arizona State University. c) ~ 2km diameter simple crater on the  
 1424 floor of Pasteur Crater on Mars (sunlight from the left), HiRISE image ESP\_045152\_2000, credit  
 1425 NASA/JPL/UofA. d) Petipa, an impact crater with rayed ejecta on Mercury (sunlight from overhead),  
 1426 MDIS global enhanced color mosaic, credit NASA/Johns Hopkins University Applied Physics  
 1427 Laboratory/Carnegie Institution of Washington. North is up in all images.



1428

1429 Figure 11: Sublimation dominated landscapes and landforms. a) Pinnacle terrain on Callisto Galileo  
 1430 (sunlight from the left) SSI image 5214R, credit NASA/JPL-Caltech/SETI Institute. b) Image of the  
 1431 surface of Helene a moon of Saturn (sunlight from the left) taken by the Cassini spacecraft image  
 1432 reference N1687119876\_1, credit NASA/JPL-Caltech/ASI, scene is about 30 km across. c) Oblique  
 1433 image of the wall of a steep pit revealing internal structure (sunlight from the left), on comet  
 1434 67P/Churyumov–Gerasimenko taken by the OSIRIS narrow-angle camera, credit ESA/Rosetta/MPS  
 1435 for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA. d) Siss cheese terrain in the CO<sub>2</sub> ice  
 1436 on the south polar cap of Mars (sunlight from the bottom-left), HiRISE image ESP\_057828\_0930,  
 1437 credit NASA/JPL/UofA. e) Hollows on Mercury (sunlight from the bottom-right), MDIS NAC image  
 1438 EN1042186062M, credit NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie  
 1439 Institution of Washington. f) Spiders on Mars (sunlight from the top-right), where the dark marks are  
 1440 dust fans deposited by seasonal jets, HiRISE image ESP\_055604\_0930, credit NASA/JPL/UofA.