



25 moderate Martian gravity can enable future colonization, and the Martian obliquity and the day  
26 length are also comparable to Earth, giving the red planet its distinct seasons. Thus, it is not a  
27 surprise that the leading space agencies and space companies are investing significant resources  
28 in enabling further Mars exploration within the next couple of decades. However, while  
29 technological advancements in engineering and computing have certainly bolstered this  
30 confidence, the contribution from the vast influx of orbiter and rover observations, in the past  
31 two and half decades in facilitating our understanding of the Martian atmosphere, terrain, and  
32 subsurface, cannot be ignored (Bhardwaj et al., 2019a).

33 This prompts the need to revisit the first holistic and comprehensive account of Viking  
34 Mission-based interpretations of Martian geomorphology, titled “The geomorphology of Mars”  
35 and authored by Prof. Victor R. Baker in 1981. Undoubtedly there have been considerable  
36 developments in the discipline since the publication of Baker’s (1981) paper; thus, revisiting  
37 this work will clearly highlight the impacts of evolving techniques and tools on planetary  
38 geomorphological interpretations. Although the short format of this “classics revisited” paper  
39 does not allow for a detailed analysis of all the advances made in Martian geomorphology  
40 research, we have provided key references throughout this article which the interested readers  
41 can further explore. Instead, here we focus on key facets of Baker’s (1981) work to highlight  
42 the status of our understanding of the Martian geomorphology in the Viking Mission era and  
43 the considerable advancements since then. It is interesting to identify and suitable to  
44 acknowledge, how many of Baker’s (1981) viewpoints still hold relevance, across several  
45 themes within the discipline of Martian geomorphology.

## 46 **II. Planetary geomorphology through terrestrial analogy**

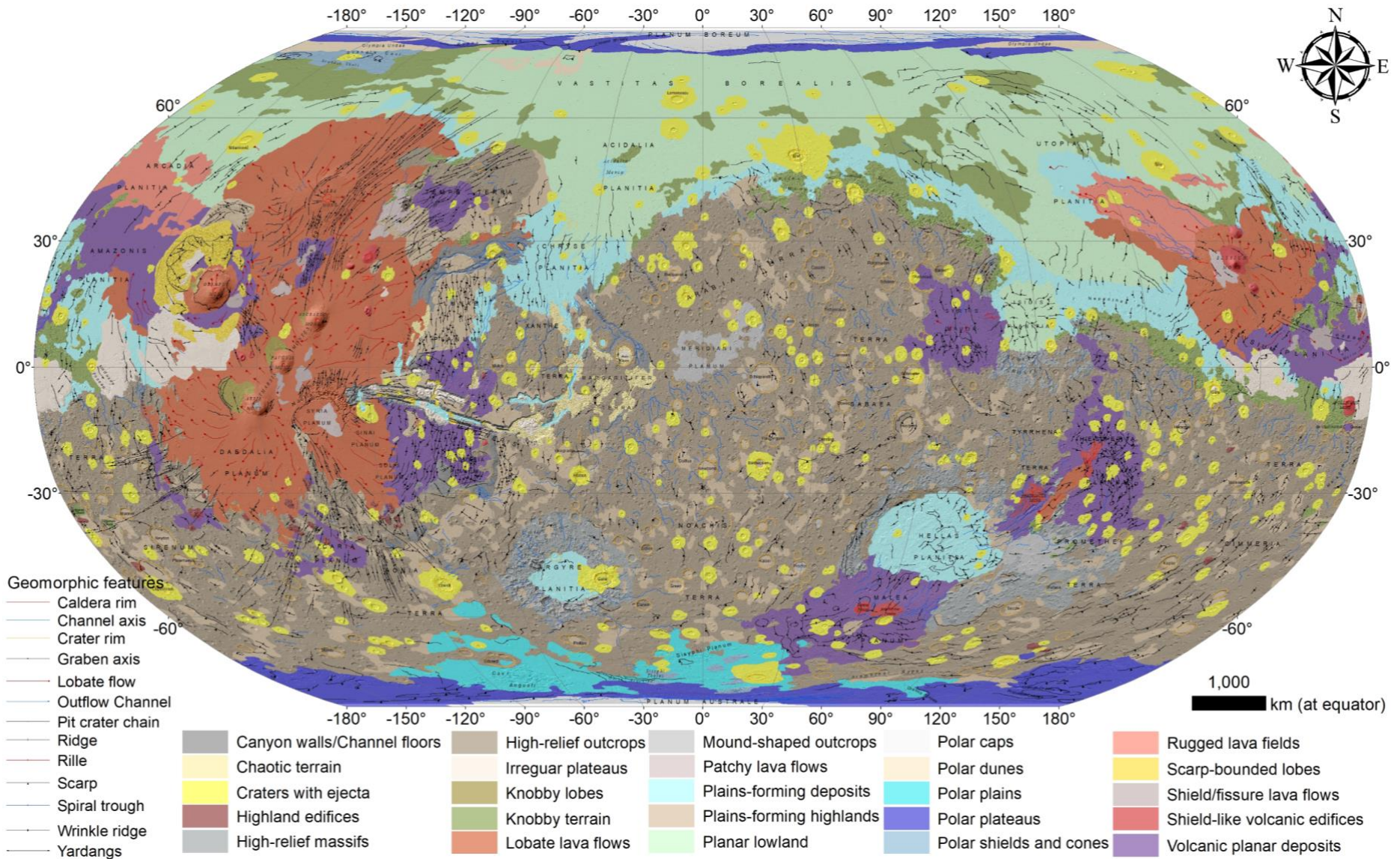
47 Baker starts his paper with an interesting example of the Chief Geologist for the US Geological  
48 Survey, G.K. Gilbert, who had to abandon planned fieldworks after 1892 congressional budget

49 cuts to the Survey. Gilbert channelised this to an opportunity by utilising his time in studying  
50 the moon through the naval observatory telescope in Washington, and thus, publishing one of  
51 the most detailed accounts of contemporary lunar geomorphology (Gilbert, 1893). This  
52 highlights how a scientist trained in terrestrial geomorphology can contribute significantly to  
53 planetary geomorphology. Baker gives some more contemporary examples (e.g., Mutch, 1979;  
54 Sharp 1980) discussing the relevance of analogy-based planetary exploration using remote  
55 sensing images. Starting from the best available spatial resolution of ~10 m/pixel for the Viking  
56 images to as high as ~25 cm/pixel High Resolution Imaging Science Experiment (HiRISE)  
57 camera resolution for Mars today, over these past decades, we have seen numerous similar  
58 analogous interpretations (e.g., Edgett et al., 2003; Irwin et al., 2004; Tsibulskaya et al., 2020;  
59 Wood, 2006) advancing our knowledge of Martian landforms. Interestingly, while mentioning  
60 the ~10 m/pixel resolution Viking images, Baker (1981) writes, “this is better resolution than  
61 is available for portions of Earth”. Coming to the present scenario, the ~25 cm/pixel resolution  
62 provided by the HiRISE camera for Mars is in public domain and we cannot expect such freely  
63 available dataset for parts of Earth. Although the advent of unmanned aerial vehicles (UAVs)  
64 (Bhardwaj et al., 2016; Gaffey and Bhardwaj, 2020) has led to an option of acquiring images,  
65 comparable to HiRISE-resolutions, for Mars analogue research on Earth (e.g., Bhardwaj et al.,  
66 2019b; Sam et al., 2020a; Sam et al., 2020b), the applications of this technique are still limited,  
67 owing to the generally inaccessible nature of the analogue sites. In the subsequent sections,  
68 various relevant references are provided which can be taken as examples of some remarkable  
69 approaches where the knowledge of terrestrial geomorphology was comprehensively  
70 extrapolated to Mars.

### 71 **III. Geomorphic map of Mars**

72 As an important contribution, Baker’s (1981) Figure 1 provides a holistic geomorphic map of  
73 Mars, representing global distribution of various physiographic features. This map was

74 modified from the geological map by Scott and Carr (1978), issued as a US Geological Survey  
75 publication. Baker (1981) classified the heavily cratered equatorial and southern highlands as  
76 cratered uplands, and ejecta and uplifted blocks of ancient terrain caused by large impacts as  
77 mountainous terrain. He further characterised the fretted uplands and isolated mesas along the  
78 boundary between heavily cratered uplands and northern plains as knobby terrain. He also  
79 highlighted three chronological volcanic plains, with Tharsis being the younger lava flows, the  
80 rolling plains constituting the majority of Elysium Planitia as the intermediate age lava flows,  
81 and ridged plains as the older lava plains. Baker (1981) further classified the northern plains as  
82 a “complex lowland showing extensive evidence of ice-contact volcanism, permafrost features,  
83 and aeolian modification”. Chaotic terrain or fractured terrain and valleys were also key  
84 components of Baker’s (1981) Martian geomorphic map. Although with volumes of new  
85 multisensory and higher resolution datasets, the mapping scale has improved severalfold,  
86 undoubtedly, all the major geomorphic units, as presented by Baker (1981), are equally relevant  
87 even today.



**Figure 1.** Global geomorphic map of Mars. This map is modified from the geological map by Tanaka et al. (2014). Data Source: <http://pubs.usgs.gov/sim/3292>.

90 As an interesting exercise, we adopted the similar approach as Baker's (1981) and compiled a  
91 geomorphic map of major physiographic regions on Mars (Figure 1) using the data modified  
92 from the most recent and complete geological map of Mars (Tanaka et al., 2014), available  
93 from the US Geological Survey. This global dataset is a derived product of unprecedented  
94 diversity (spectral, topographic, thermophysical, and subsurface), quality (high spatial and  
95 spectral resolutions), and volume of remotely sensed data acquired since the Viking Orbiters.  
96 In particular, the inclusion of precise topographic data such as Mars Global Surveyor (MGS)  
97 Mars Orbiter Laser Altimeter (MOLA) digital elevation model (DEM) (463 m/pixel resolution  
98 at lower latitudes to 115 m/pixel near the poles) (Smith and others, 2001) and the Mars Odyssey  
99 (ODY) Thermal Emission Imaging System (THEMIS) daytime infrared (IR) image mosaic  
100 (100 m/pixel) (Christensen and others, 2004) aided the visual interpretations greatly by  
101 providing 3D terrain and infrared multispectral information (Tanaka et al., 2014). As  
102 mentioned above, the map in Figure 1 is more detailed, understandably owing to the vastness  
103 of the input data, but the close resemblance of the major physiographic classes with the ones  
104 presented in Figure 1 of Baker (1981) are undeniable.

#### 105 **IV. Involvement of geomorphologists in planetary sciences**

106 Baker's (1981) paper was the first review that discussed a very vital contemporary issue (on  
107 Page 476 of Baker, 1981); "Why then have so few geomorphologists become involved in the  
108 study of the fascinating landscapes of Mars?" With inclusion of the first two tables in his article,  
109 Baker (1981) provided two main reasons for this: (1) the limited distribution of journals and  
110 government documents publishing the planetary science papers, and (2) the lack of access to  
111 the planetary surface images which could enable geomorphic interpretations. Baker (1981)  
112 argued how increased involvement of geomorphologists could be great in promoting planetary  
113 sciences as a discipline. There is no denying that in the past four decades, comparative  
114 planetology has advanced as a science and the role of the geomorphological approaches in this

115 advancement has been undisputed. Not only the important themes mentioned by Baker (1981),  
116 such as catastrophic flooding (e.g., Rodríguez et al., 2014), volcanism (e.g., Brož et al., 2020),  
117 impact cratering (e.g., Palumbo and Head, 2018), aeolian erosion (e.g., Williams et al., 2020),  
118 sapping (e.g., Goldspiel and Squyres, 2000), thermokarst (e.g., Dundas et al., 2015), and large-  
119 scale landslides (e.g., Magnarini et al., 2019), have been greatly explored, but also, our  
120 understanding of the effects of reduced gravity (e.g., Jacobsen and Burr, 2016), catastrophism  
121 (Pacifici et al., 2009), and atmospheric processes (e.g., Matsubara et al., 2018) on Martian  
122 landscape evolution has considerably improved. Nevertheless, the internet revolution leading  
123 to digital information dissemination (Feldman, 2002) played a significant role in solving the  
124 two aforementioned issues highlighted by Baker (1981). The online platform not only led to  
125 the increase in the number of planetary journals, but also to the distribution of articles to an  
126 interested reader. Moreover, the World Wide Web and the evolution in computing systems and  
127 geographic information system software enabled easy and efficient data transfers, processing,  
128 and interpretations.

## 129 **V. Major geomorphic features on Mars and conceptual advances**

130 Baker (1981) compiled the information on the geomorphic features on Mars and in the  
131 following sub-sections, we revisit each of them briefly, providing some recent references to  
132 assess the major conceptual advances.

### 133 *1. Impact craters*

134 Baker (1981) highlights how active resurfacing processes on Earth have erased the majority of  
135 the ancient impact craters, making them relatively rare terrestrial landforms to perform  
136 comparative planetology. Nevertheless, in past decades, several terrestrial craters have been  
137 proposed and explored as Mars analogue sites around the globe. For example, Australia's arid  
138 climate, coupled with the low-relief and tectonically stable terrain, has ensured best



139 preservation of several of the craters (West et al., 2010). Undeniably, the majority of these  
140 craters have been identified on constantly improving mid-to-high resolution satellite images;  
141 for example, the 260 m diameter Hickman Crater in Western Australia (Glikson et al., 2008).  
142 Moving further, Baker (1981) provides perspectives on crater densities and ways to enable  
143 relative and absolute dating of Martian surface. He further mentions the morphological  
144 uniqueness of several of the Martian craters, in terms of being surrounded by layered debris  
145 instead of ejecta of ballistic origin, and cites Mouginis-Mark (1979) to imply that the layered  
146 debris might be a consequence of the entrainment of permafrost-melt water into the ejecta.  
147 Now, with years of observational data, numerical modelling, and laboratory experiments, we  
148 know that in addition to the subsurface volatiles, particle size and density, and atmospheric  
149 density and pressure also contribute to the morphology of ejecta blankets (Barlow, 2005).  
150 Moreover, we have further learnt about the astrobiological potential of the numerous small-to-  
151 medium sized impact craters on Mars with clearly defined flat floors containing a possible  
152 sedimentary record (Cockell and Lee, 2002; Lindsay and Brasier, 2006).

## 153 *2. Volcanic landforms*

154 Baker (1981) starts the discussion on volcanic structures by providing dimensional and  
155 contextual information about the highest, i.e., Olympus Mons, and the widest, i.e., Alba Patera,  
156 volcanoes on Mars. He further mentions the possible phreatic (explosive) phases in the early  
157 eruptive history of large Martian volcanoes, owing to the eruptions through water-saturated (or  
158 ice-rich) megaregolith materials (Greeley and Spudis, 1981). These explosive eruptions  
159 probably changed to effusive lava production, constructing prominent shields and domes once  
160 the megaregolith was depleted in water (Baker, 1981). Baker (1981) also cites Reimers and  
161 Komar's (1979) hypothesis on the pyroclastic activity to be a result of volcanic interaction with  
162 an ice-rich permafrost. However, the most recent and comprehensive review on this topic (Brož  
163 et al., 2020) concludes several major points in this discussion of explosive volcanism on Mars.

164 Brož et al. (2020) concur that although, the indications of explosive volcanism have been  
165 identified at various locations on Mars, the evidence is still less common than for effusive  
166 activity. Brož et al. (2020) also infer that the possible explosive eruptions on Mars would have  
167 behaved differently from those on Earth, since the observed edifices are often different in  
168 shapes from their terrestrial counterparts. Baker (1981) mentions the presence of pseudocraters  
169 and pedestal craters in the northern plains of Mars. There still is an uncertainty on the exact  
170 formation mechanism of these landforms. The pseudocraters are now categorised as rootless  
171 cones and both igneous and mud volcano hypotheses are proposed as their formation  
172 mechanism (Czechowski et al., 2020; Dapremont and Wray, 2021). Similarly, the pedestal  
173 craters, even today, are believed to be a result of presence of ice-rich layers during their  
174 formation, when the ejecta formed an erosion-resistant layer shielding the surroundings  
175 (Kenkmann and Wulf, 2018). Baker (1981) cites Hodges and Moore (1979) in proposing the  
176 table mountains of Iceland as a possible analogue for the Martian pedestal craters.

### 177 *3. Aeolian landforms*

178 Aeolian landforms are one of those surficial features on Mars which highlight the effect of  
179 improvement in spatial resolution of the imaging camera on advancing our geomorphic  
180 knowledge. During the 1970s, available coarser resolution images, captured by Mariner 9  
181 (McCauley et al., 1972) and Viking Orbiters (Cutts et al., 1976), revealed large, low albedo  
182 dune masses, now known as large dark dunes (LDDs). Baker (1981) mentions these huge dark-  
183 coloured dunes surrounding the northern polar cap of Mars. With the advent of high-resolution  
184 imagers, such as the Mars Orbiter Camera (MOC) (Malin and Edgett, 2001), High Resolution  
185 Stereo Camera (Neukum and Jaumann, 2004), Context (CTX) camera (Malin et al., 2007), and  
186 HiRISE (McEwen et al., 2007), during the 1990s and 2000s, the captured m-to-cm resolution  
187 images made it possible to observe and study smaller aeolian landforms such as wind ripples,  
188 granule ripples, yardangs, dust devils, ventifacts, and transverse aeolian ridges (TARs)

189 (Bhardwaj et al., 2019c). An updated account of aeolian landforms on Mars can be read in  
190 Bridges et al. (2013).

#### 191 *4. Hillslopes and mass movement*

192 In his comprehensive and interesting review, Brunsten (1993) appropriately highlighted the  
193 complexity involved in discussing mass movement as an isolated discipline. Studying mass  
194 movements mandatorily needs an interdisciplinary approach involving geomorphology,  
195 geology, hydrology, geophysics, and soil mechanics (Brunsten, 1993). This makes  
196 understanding the nature of mass movements even more complex for the places (e.g., Mars)  
197 where sufficient multidisciplinary data are unavailable. Nevertheless, Baker (1981) relatively  
198 effectively uses published contemporary examples of the Valles Marineris system (e.g.,  
199 Lucchitta, 1979; Sharp, 1973) to highlight the typical “spur-and-gully topography” (Lucchitta,  
200 1978) defining numerous steep escarpments and hillslopes on Mars. Such complex topography  
201 is prone to produce an immense array of mass movement features (Baker, 1981), some of which  
202 are difficult to interpret and characterise even today (e.g., Bhardwaj et al., 2019a; Bhardwaj et  
203 al., 2019d). Undeniably, the unavailability of high-resolution multisource datasets for the  
204 majority of the Martian terrain makes the interpretations even more speculative. Baker (1981)  
205 also compiled published examples to emphasise the relatively massive dimensions of mass  
206 movements on Mars, undetected on Earth.

207 Interestingly, one of the possible mass movement features, which Baker (1981) refers to as  
208 lobate debris deposits and discusses towards the end of this section, are extensively investigated  
209 in the past two decades. These lobate debris deposits resemble terrestrial glaciers, with valleys  
210 filled with debris, in some instances originating from cirque-like heads, and locally marked by  
211 prominent longitudinal ridges. Squyres (1978; 1979) correlated the lobate debris deposits with  
212 regions of probable high frost deposition and proposed their possible analogy with terrestrial

213 rock glaciers (Baker, 1981). All these glacial-type formations on Mars, displaying evidence of  
214 viscous flow, are now characterised within an umbrella term called Viscous flow feature (VFF)  
215 (Souness et al., 2012). Four major types of VFFs are identified and studied (Hubbard et al.,  
216 2011; Souness et al., 2012; Squyres, 1978, Squyres, 1979; Squyres and Carr, 1986): (1) lobate  
217 debris aprons (LDA), (2) lineated valley fill (LVF), (3) concentric crater fill (CCF), and (4)  
218 glacier-like forms (GLF). Interested reader can find an updated account of VFFs in Berman et  
219 al. (2021). Koutnik and Pathare (2021) recently presented an informative and updated account  
220 of LDA and GLF in terms of their analogy with terrestrial debris-covered glaciers. Their review  
221 can be helpful in providing a holistic account of analogy between debris-covered glaciers on  
222 Earth and dust and debris-covered ice on Mars.

### 223 *5. Periglacial and permafrost features*

224 Although morphologically, VFFs qualify to be characterised as permafrost landforms often  
225 observed in periglacial landscape on Earth, Baker (1981) at the very onset of this section,  
226 defines “periglacial” as a geomorphic environment categorised by very low annual  
227 temperatures, freeze-thaw episodes, and strong wind action. Baker (1981) further defines the  
228 term “permafrost” as used in comparative planetology. Although “permafrost” refers to frozen  
229 ground, irrespective of its water content, in planetology, the term is often used as a synonym  
230 for “ground ice” (Baker, 1981). Baker (1981) starts by discussing polygonal fracture patterns  
231 which are typical of permafrost terrain. For the initially observed fractures in Martian northern  
232 plains, the two most probable proposed mechanisms were permafrost ice wedging, and cooling-  
233 contraction cracking in lava flows. However, the massive dimensions of these cracks (hundreds  
234 of metres wide with average spacings of 5-10 km) put constraint on both these hypotheses.  
235 Terrestrial ice-wedge polygons generally vary from 1-100 m in diameter (Baker, 1981), and  
236 with HiRISE images, today many regions on Mars have been identified with polygons  
237 comparable in dimensions to their terrestrial counterparts (Soare et al., 2021). Baker (1981)

238 further discusses thermokarst landforms and scalloped terrain on Mars and highlights the  
239 contemporary views of thermokarst landforms being a result of melting ground ice. However,  
240 in the past couple of decades, both sublimation (e.g., Dundas et al., 2015) and melting (e.g.,  
241 Soare et al., 2008), have been investigated as the formation mechanisms for these thermokarst  
242 landforms on Mars.

#### 243 *6. Polar terrains*

244 Baker (1981) starts this section with describing Mariner and Viking observations of Martian  
245 polar caps. Based on the temperatures observed by the infrared radiometers of the Viking  
246 orbiters, Baker (1981) asserts that the “northern cap must be water ice”. Subsequent  
247 multisensory observations have validated the residual ice caps to be primarily consisting of  
248 water ice. A recent paper (Ojha et al., 2019) placed compositional constraint on the polar  
249 silicate-rich basal unit below the ice-rich north polar layered deposit, by modelling its gravity  
250 signature in both spatial and spectral domains. These estimates suggest that even the silicate-  
251 rich basal unit below the polar layered deposits may contain  $55\pm 25\%$  water ice, corresponding  
252 to  $\sim 1.5$  m global water equivalent, making it one of the largest reservoirs of water-ice on Mars  
253 (Ojha et al., 2019).

#### 254 *7. Channels and valleys*

255 Baker (1981) starts this section by highlighting the excitement that was linked with the  
256 discovery of channels, valleys, and related features of possible aqueous origin on Mars.  
257 However, like any other hypothesis of possible liquid water on Mars, this discovery was also  
258 not without controversies, and soon, in addition to water, lava flow, wind, glacial ice,  
259 liquefaction of crustal materials, debris flows, liquid carbon dioxide, and liquid alkanes were  
260 suggested as other possible channel-carving agents (Baker, 1981). To characterise the widely  
261 variable channel morphologies, Masursky (1973) adopted a broader context and proposed four

262 classes: (1) broad large-sized channels originating from chaotic terrain, (2) narrow  
263 intermediate-sized channels, (3) small valleys across the heavily cratered terrain, and (4)  
264 volcanic channels (Baker, 1981). Sharp and Malin (1975) proposed an additional category  
265 called fretted channels, in addition to Masursky's categories (Baker, 1981). Using high-  
266 resolution MOC images of channels and valleys, Malin and Edgett (2003) provided  
267 geomorphic evidence for aqueous sedimentation on early Mars. Mangold et al. (2004)  
268 interpreted the geomorphic characteristics, especially the high degree of branching, of the  
269 valleys in Valles Marineris region, to propose atmospheric precipitation during 2.9 to 3.4  
270 billion years as their formation mechanism. However, a recent paper (Galofre et al., 2020), puts  
271 a constraint on entirely precipitation and surface water runoff-based hypotheses for valley  
272 formations on Mars and proposes subglacial and fluvial erosion as the predominant  
273 mechanisms.

## 274 **VI. Summary**

275 As evident from revisiting Baker's (1981) paper, the relevance and impact of geomorphology  
276 as a discipline in progressing comparative planetology in general, and Mars landscape research  
277 in particular, are indisputable. The timely compilation and survey of contemporary literature  
278 following Viking Missions, and raising the awareness of geomorphology community on Mars  
279 exploration, are the highpoints of this first holistic review of Martian geomorphology presented  
280 by Baker (1981). With nearly the entire Martian terrain covered at ~6 m/pixel CTX resolution,  
281 and continuously increasing volume of submeter HiRISE data, undoubtedly, the prospects for  
282 performing comprehensive local-scale geomorphic analyses have considerably improved.  
283 Moreover, the operational rovers on Mars are also providing stereoscopic and multispectral  
284 images. In fact, the perceived success of the first unmanned aerial vehicle on Mars, in the form  
285 of a mini-helicopter named Ingenuity onboard the recently landed Perseverance Rover, as an

286 image capture platform can really transform the next stage of exploring Martian  
287 geomorphology.

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289 The author(s) declared no potential conflicts of interest with respect to the research, authorship,  
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