Four decades of understanding Martian geomorphology: Revisiting Baker's "The geomorphology of Mars"

Anshuman Bhardwaj[1]*, Lydia Sam[1], Saeideh Gharehchahi[2]

[1]School of Geosciences, University of Aberdeen, Meston Building, King's College, Aberdeen AB24 3UE, UK

[2]Department of Chemistry and Geosciences, Jacksonville State University, Jacksonville, AL 36265, USA

*Corresponding author

Abstract: Owing to multiple successful orbiter and rover missions in the past two and half decades, our understanding of the Martian atmosphere, terrain, and subsurface has continuously evolved. This prompts the need to revisit the first holistic review of Martian geomorphology based on useful images from Viking Mission orbiters, authored by Prof. Victor R. Baker. Several of the remote sensing-based interpretations and recommendations in Baker's (1981) paper are as valid even today as they were four decades back. With an unprecedented focus on Mars exploration in the coming decades, it is important to briefly revisit the advances and prospects in Martian geomorphology research.

Keywords: Mars, geomorphology, Viking Mission, planetary exploration, remote sensing

I Introduction

In our solar system, Mars is the planet with the highest Earth similarity and relative planetary habitability indices, based on various physical and physicochemical determinants (Schulze-Makuch et al., 2011). Being terrestrial planets, the structural and compositional similarities between Earth and Mars are further apparent from the relative geological and geomorphological interpretations (Baker, 1981). The Martian regolith contains minerals and the temperatures are within an acceptable range for the existence of life (as we know it). The moderate Martian gravity can enable future colonization, and the Martian obliquity and the day length are also comparable to Earth, giving the red planet its distinct seasons. Thus, it is not a surprise that the leading space agencies and space companies are investing significant resources in enabling further Mars exploration within the next couple of decades. However, while technological advancements in engineering and computing have certainly bolstered this confidence, the contribution from the vast influx of orbiter and rover observations, in the past two and half decades in facilitating our understanding of the Martian atmosphere, terrain, and subsurface, cannot be ignored (Bhardwaj et al., 2019a).

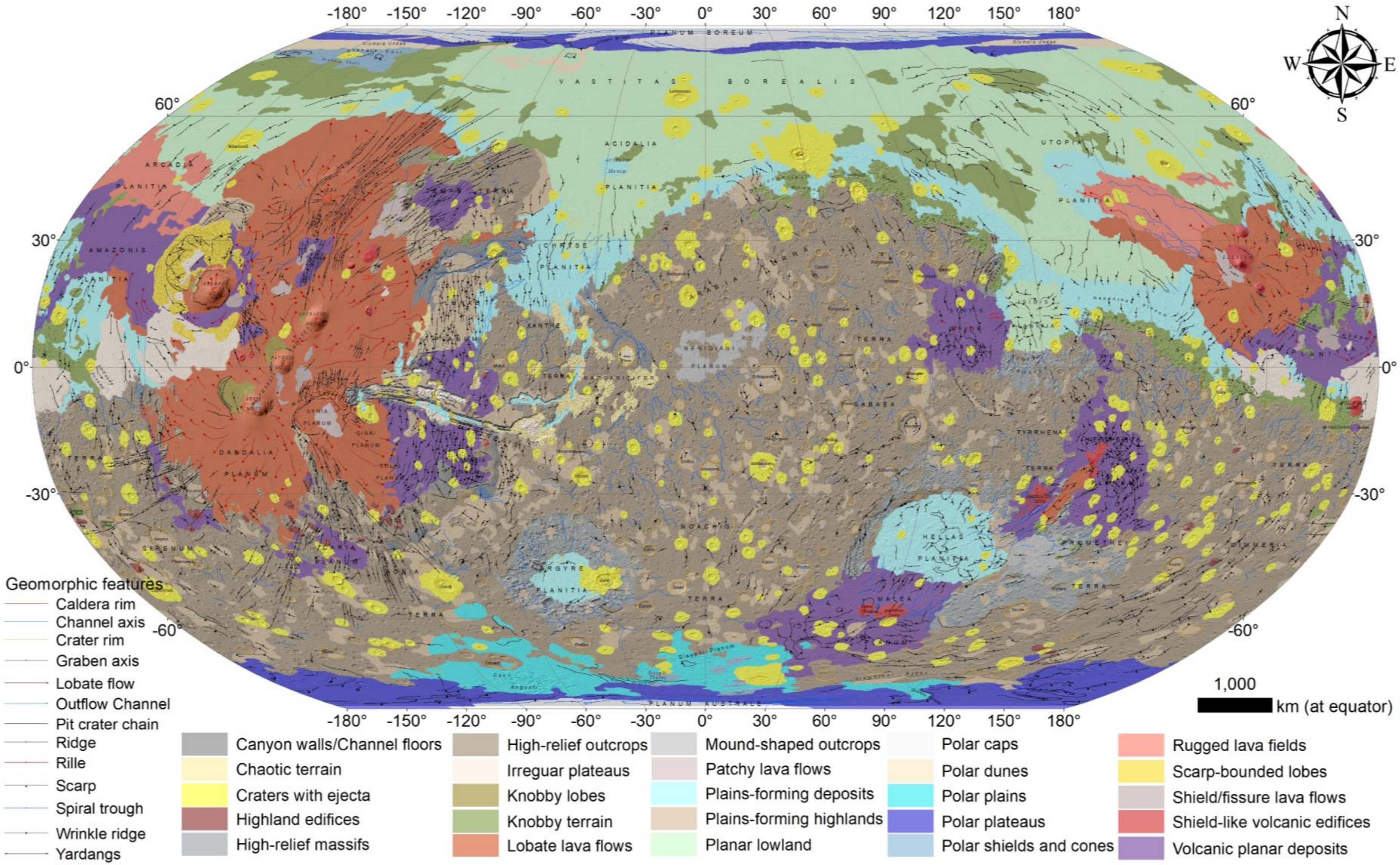
This prompts the need to revisit the first holistic and comprehensive account of Viking Mission-based interpretations of Martian geomorphology, titled "The geomorphology of Mars" and authored by Prof. Victor R. Baker in 1981. Undoubtedly there have been considerable developments in the discipline since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

II. Planetary geomorphology through terrestrial analogy

Baker starts his paper with an interesting example of the Chief Geologist for the US Geological Survey, G.K. Gilbert, who had to abandon planned fieldworks after 1892 congressional budget cuts to the Survey. Gilbert channelised this to an opportunity by utilising his time in studying the moon through the naval observatory telescope in Washington, and thus, publishing one of the most detailed accounts of contemporary lunar geomorphology (Gilbert, 1893). This highlights how a scientist trained in terrestrial geomorphology can contribute significantly to planetary geomorphology. Baker gives some more contemporary examples (e.g., Mutch, 1979; Sharp 1980) discussing the relevance of analogy-based planetary exploration using remote sensing images. Starting from the best available spatial resolution of ~10 m/pixel for the Viking images to as high as ~25 cm/pixel High Resolution Imaging Science Experiment (HiRISE) camera resolution for Mars today, over these past decades, we have seen numerous similar analogous interpretations (e.g., Edgett et al., 2003; Irwin et al., 2004; Tsibulskaya et al., 2020; Wood, 2006) advancing our knowledge of Martian landforms. Interestingly, while mentioning the ~10 m/pixel resolution Viking images, Baker (1981) writes, "this is better resolution than is available for portions of Earth". Coming to the present scenario, the ~25 cm/pixel resolution provided by the HiRISE camera for Mars is in public domain and we cannot expect such freely available dataset for parts of Earth. Although the advent of unmanned aerial vehicles (UAVs) (Bhardwaj et al., 2016; Gaffey and Bhardwaj, 2020) has led to an option of acquiring images, comparable to HiRISE-resolutions, for Mars analogue research on Earth (e.g., Bhardwaj et al., 2019b; Sam et al., 2020a; Sam et al., 2020b), the applications of this technique are still limited, owing to the generally inaccessible nature of the analogue sites. In the subsequent sections, various relevant references are provided which can be taken as examples of some remarkable approaches where the knowledge of terrestrial geomorphology was comprehensively extrapolated to Mars.

III. Geomorphic map of Mars

As an important contribution, Baker's (1981) Figure 1 provides a holistic geomorphic map of Mars, representing global distribution of various physiographic features. This map was modified from the geological map by Scott and Carr (1978), issued as a US Geological Survey publication. Baker (1981) classified the heavily cratered equatorial and southern highlands as cratered uplands, and ejecta and uplifted blocks of ancient terrain caused by large impacts as mountainous terrain. He further characterised the fretted uplands and isolated mesas along the boundary between heavily cratered uplands and northern plains as knobby terrain. He also highlighted three chronological volcanic plains, with Tharsis being the younger lava flows, the rolling plains constituting the majority of Elysium Planitia as the intermediate age lava flows, and ridged plains as the older lava plains. Baker (1981) further classified the northern plains as a “complex lowland showing extensive evidence of ice-contact volcanism, permafrost features, and aeolian modification”. Chaotic terrain or fractured terrain and valleys were also key components of Baker’s (1981) Martian geomorphic map. Although with volumes of new multisensory and higher resolution datasets, the mapping scale has improved severalfold, undoubtedly, all the major geomorphic units, as presented by Baker (1981), are equally relevant even today.



-180° -150° -120° -90° -60° -30° 0° 30° 60° 90° 120° 150° 180°
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PLANUM BOREUM
VASTITAS BOREALIS
ACIDALIA PLANITIA
UTOPIA PLANITIA
ARCADIA PLANITIA
AMAZONIS PLANITIA
CHRYSE PLANITIA
XANTHE TERRA
MERIDIANI PLANUM
ARABIA TERRA
DAEDALIA PLANUM
TYRRHENA TERRA
NOACHIS TERRA
HELLAS PLANITIA
ARGYRE PLANITIA
MALEA PLANUM
CIMMERIA TERRA
PLANUM AUSTRALE
1,000
km (at equator)
Geomorphic features
Caldera rim
Channel axis
Crater rim
Graben axis
Lobate flow
Outflow Channel
Pit crater chain
Ridge
Rille
Scarp
Spiral trough
Wrinkle ridge
Yardangs
Canyon walls/Channel floors
Chaotic terrain
Craters with ejecta
Highland edifices
High-relief massifs
High-relief outcrops
Irreguar plateaus
Knobby lobes
Knobby terrain
Lobate lava flows
Mound-shaped outcrops
Patchy lava flows
Plains-forming deposits
Plains-forming highlands
Planar lowland
Polar caps
Polar dunes
Polar plains
Polar plateaus
Polar shields and cones
Rugged lava fields
Scarp-bounded lobes
Shield/fissure lava flows
Shield-like volcanic edifices
Volcanic planar deposits

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.

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

IV. Involvement of geomorphologists in planetary sciences

Baker's (1981) paper was the first review that discussed a very vital contemporary issue (on Page 476 of Baker, 1981); "Why then have so few geomorphologists become involved in the study of the fascinating landscapes of Mars?" With inclusion of the first two tables in his article, Baker (1981) provided two main reasons for this: (1) the limited distribution of journals and government documents publishing the planetary science papers, and (2) the lack of access to the planetary surface images which could enable geomorphic interpretations. Baker (1981) argued how increased involvement of geomorphologists could be great in promoting planetary sciences as a discipline. There is no denying that in the past four decades, comparative planetology has advanced as a science and the role of the geomorphological approaches in this advancement has been undisputed. Not only the important themes mentioned by Baker (1981), such as catastrophic flooding (e.g., Rodríguez et al., 2014), volcanism (e.g., Brož et al., 2020), impact cratering (e.g., Palumbo and Head, 2018), aeolian erosion (e.g., Williams et al., 2020), sapping (e.g., Goldspiel and Squyres, 2000), thermokarst (e.g., Dundas et al., 2015), and large-scale landslides (e.g., Magnarini et al., 2019), have been greatly explored, but also, our understanding of the effects of reduced gravity (e.g., Jacobsen and Burr, 2016), catastrophism (Pacifici et al., 2009), and atmospheric processes (e.g., Matsubara et al., 2018) on Martian landscape evolution has considerably improved. Nevertheless, the internet revolution leading to digital information dissemination (Feldman, 2002) played a significant role in solving the two aforementioned issues highlighted by Baker (1981). The online platform not only led to the increase in the number of planetary journals, but also to the distribution of articles to an interested reader. Moreover, the World Wide Web and the evolution in computing systems and geographic information system software enabled easy and efficient data transfers, processing, and interpretations.

V. Major geomorphic features on Mars and conceptual advances

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

1. Impact craters

Baker (1981) highlights how active resurfacing processes on Earth have erased the majority of the ancient impact craters, making them relatively rare terrestrial landforms to perform comparative planetology. Nevertheless, in past decades, several terrestrial craters have been proposed and explored as Mars analogue sites around the globe. For example, Australia's arid climate, coupled with the low-relief and tectonically stable terrain, has ensured best preservation of several of the craters (West et al., 2010). Undeniably, the majority of these craters have been identified on constantly improving mid-to-high resolution satellite images; for example, the 260 m diameter Hickman Crater in Western Australia (Glikson et al., 2008). Moving further, Baker (1981) provides perspectives on crater densities and ways to enable relative and absolute dating of Martian surface. He further mentions the morphological uniqueness of several of the Martian craters, in terms of being surrounded by layered debris instead of ejecta of ballistic origin, and cites Mouginis-Mark (1979) to imply that the layered debris might be a consequence of the entrainment of permafrost-melt water into the ejecta. Now, with years of observational data, numerical modelling, and laboratory experiments, we know that in addition to the subsurface volatiles, particle size and density, and atmospheric density and pressure also contribute to the morphology of ejecta blankets (Barlow, 2005). Moreover, we have further learnt about the astrobiological potential of the numerous small-to-medium sized impact craters on Mars with clearly defined flat floors containing a possible sedimentary record (Cockell and Lee, 2002; Lindsay and Brasier, 2006).

2. Volcanic landforms

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

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

3. Aeolian landforms

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

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

4. Hillslopes and mass movement

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

Interestingly, one of the possible mass movement features, which Baker (1981) refers to as lobate debris deposits and discusses towards the end of this section, are extensively investigated in the past two decades. These lobate debris deposits resemble terrestrial glaciers, with valleys filled with debris, in some instances originating from cirque-like heads, and locally marked by prominent longitudinal ridges. Squyres (1978; 1979) correlated the lobate debris deposits with regions of probable high frost deposition and proposed their possible analogy with terrestrial rock glaciers (Baker, 1981). All these glacial-type formations on Mars, displaying evidence of viscous flow, are now characterised within an umbrella term called Viscous flow feature (VFF) (Souness et al., 2012). Four major types of VFFs are identified and studied (Hubbard et al., 2011; Souness et al., 2012; Squyres, 1978, Squyres, 1979; Squyres and Carr, 1986): (1) lobate debris aprons (LDA), (2) lineated valley fill (LVF), (3) concentric crater fill (CCF), and (4) glacier-like forms (GLF). Interested reader can find an updated account of VFFs in Berman et al. (2021). Koutnik and Pathare (2021) recently presented an informative and updated account of LDA and GLF in terms of their analogy with terrestrial debris-covered glaciers. Their review can be helpful in providing a holistic account of analogy between debris-covered glaciers on Earth and dust and debris-covered ice on Mars.

5. Periglacial and permafrost features

Although morphologically, VFFs qualify to be characterised as permafrost landforms often observed in periglacial landscape on Earth, Baker (1981) at the very onset of this section, defines “periglacial” as a geomorphic environment categorised by very low annual temperatures, freeze-thaw episodes, and strong wind action. Baker (1981) further defines the term “permafrost” as used in comparative planetology. Although “permafrost” refers to frozen ground, irrespective of its water content, in planetology, the term is often used as a synonym for “ground ice” (Baker, 1981). Baker (1981) starts by discussing polygonal fracture patterns which are typical of permafrost terrain. For the initially observed fractures in Martian northern plains, the two most probable proposed mechanisms were permafrost ice wedging, and cooling-contraction cracking in lava flows. However, the massive dimensions of these cracks (hundreds of metres wide with average spacings of 5-10 km) put constraint on both these hypotheses. Terrestrial ice-wedge polygons generally vary from 1-100 m in diameter (Baker, 1981), and with HiRISE images, today many regions on Mars have been identified with polygons comparable in dimensions to their terrestrial counterparts (Soare et al., 2021). Baker (1981) further discusses thermokarst landforms and scalloped terrain on Mars and highlights the contemporary views of thermokarst landforms being a result of melting ground ice. However, in the past couple of decades, both sublimation (e.g., Dundas et al., 2015) and melting (e.g., Soare et al., 2008), have been investigated as the formation mechanisms for these thermokarst landforms on Mars.

6. Polar terrains

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

7. Channels and valleys

Baker (1981) starts this section by highlighting the excitement that was linked with the discovery of channels, valleys, and related features of possible aqueous origin on Mars. However, like any other hypothesis of possible liquid water on Mars, this discovery was also not without controversies, and soon, in addition to water, lava flow, wind, glacial ice, liquefaction of crustal materials, debris flows, liquid carbon dioxide, and liquid alkanes were suggested as other possible channel-carving agents (Baker, 1981). To characterise the widely variable channel morphologies, Masursky (1973) adopted a broader context and proposed four classes: (1) broad large-sized channels originating from chaotic terrain, (2) narrow intermediate-sized channels, (3) small valleys across the heavily cratered terrain, and (4) volcanic channels (Baker, 1981). Sharp and Malin (1975) proposed an additional category called fretted channels, in addition to Masursky's categories (Baker, 1981). Using high-resolution MOC images of channels and valleys, Malin and Edgett (2003) provided geomorphic evidence for aqueous sedimentation on early Mars. Mangold et al. (2004) interpreted the geomorphic characteristics, especially the high degree of branching, of the valleys in Valles Marineris region, to propose atmospheric precipitation during 2.9 to 3.4 billion years as their formation mechanism. However, a recent paper (Galofre et al., 2020), puts a constraint on entirely precipitation and surface water runoff-based hypotheses for valley formations on Mars and proposes subglacial and fluvial erosion as the predominant mechanisms.

VI. Summary

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

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