CHAPTER

11

The McMurdo Dry Valleys of Antarctica: a geological, environmental, and ecological analog to the Martian surface and near surface

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Abstract

The surface of Mars is universally thought to have experienced widespread cold and dry environmental conditions for at least the last half of its geologic history, with more modern studies suggesting relatively cold and dry conditions early in its geologic history as well. However, the paucity of liquid water and mean annual temperatures well below the freezing point of water do not necessarily mean a complete cessation of all water-related geologic activity at the Martian surface. Over the past several decades, investigations in the McMurdo Dry Valleys (MDV) of Antarctica have revealed a dynamic geological, environmental, and ecological system resulting from locally optimized conditions operating over repeated, albeit brief, intervals during summer months. In this chapter, we compare the hyper-arid and hypo-thermal environments of the MDV and the modern Martian surface and discuss three unique enigmas that demonstrate how the Antarctic is a valuable analog to better understand processes on Mars.

1 Introduction

The McMurdo Dry Valleys (MDV) of Antarctica (Fig. 11.1) are the largest contiguous ice-free region of the Transantarctic Mountains (TAM), located approximately 60 km northwest of McMurdo Station. First explored in November of 1902 by members of Scott's first *Discovery* expedition of Antarctica, the geology, climate, hydrology, and ecology of the MDV have been nearly continuously studied since the International Geophysical Year (1957–58).

Concurrent with the initial geologic mapping and ecological characterization of the MDV, the

Mars Geological Enigmas
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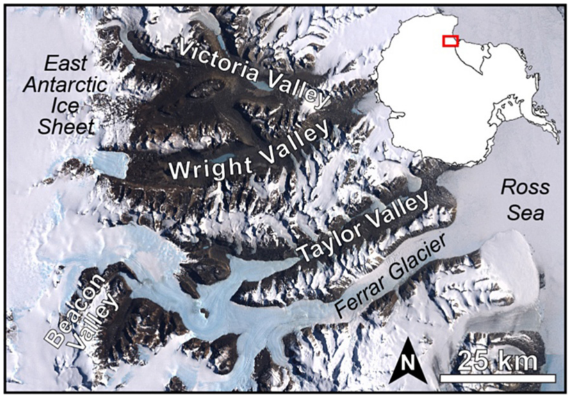

FIGURE 11.1 Context map of the McMurdo Dry Valleys (MDV).

National Aeronautics and Space Administration was also beginning its initial exploration of the Martian surface using landed spacecraft. In 1976 the twin Mars *Viking* landers touched down in Chryse and Utopia Planitia in the flat northern lowlands of Mars, revealing similarly basaltic landscapes dominated by cobble-sized clasts and abundant windblown sediment. The pitted and angular rock surfaces, abundance of dust and other fine-grained materials, primary basaltic surface compositions, and apparent overall absence of liquid water suggested little if any chemical alteration occurred in the modern Martian environment. However, more recent global-scale spectroscopic studies validated through *in situ* exploration suggest that early Mars hosted a more complex and dynamic geologic system than the modern planet would suggest (Fig. 11.2). Ancient rivers, lakes, and potentially oceans eroded and occupied the ancient Martian landscapes for at least millions of years (Irwin et al., 2005; Orofino et al., 2018; Kite, 2019). Substantial groundwater systems were also active on early Mars, as evidenced in the Mineralogical Record (Ehlmann et al., 2011) and the possible deluge of water from Martian chaos terrain that flooded into the northern lowlands (Carr, 1979; Rodriguez et al., 2015a,b).

The bulk of Martian volcanic activity, a potential source of widespread melt-sustaining energy, also dominated the earliest part of Martian history and began to wane concurrent with Martian hydrological processes (Carr and Head, 2010). Since approximately 3.5 Ga, the Martian surface has been dominated by cold, dry, and stable geologic conditions that have preserved the evidence for these earlier habitable conditions at or near the surface (Bibring et al., 2006; Ehlmann et al., 2011; Salvatore et al., 2014). The transition from a more dynamic to the "freeze-dried" planet that we see today was likely driven by cessation of the Martian magnetic dynamo due to internal cooling (Fig. 11.2) (Acuña et al., 1999; Harrison and Grimm, 2002; Ehlmann et al., 2011; Mittelholz et al., 2020). In the absence of a magnetic field the Martian atmosphere could be stripped away by solar winds, resulting in the overall cooling and drying of the Martian near-surface environment. The loss of the magnetic field also resulted in a substantially increased flux of harmful radiation at the surface, which would act to destroy organic molecules and minimize surface habitability.

Despite our improved understanding of Martian environmental evolution and modern surface conditions, many important aspects of Martian surface properties and processes remain enigmatic. Three enigmas continue to plague the Martian scientific community in their quest to understand the evolution of Mars' geologic and environmental systems from its earliest recorded history to its current "freeze-dried" state:

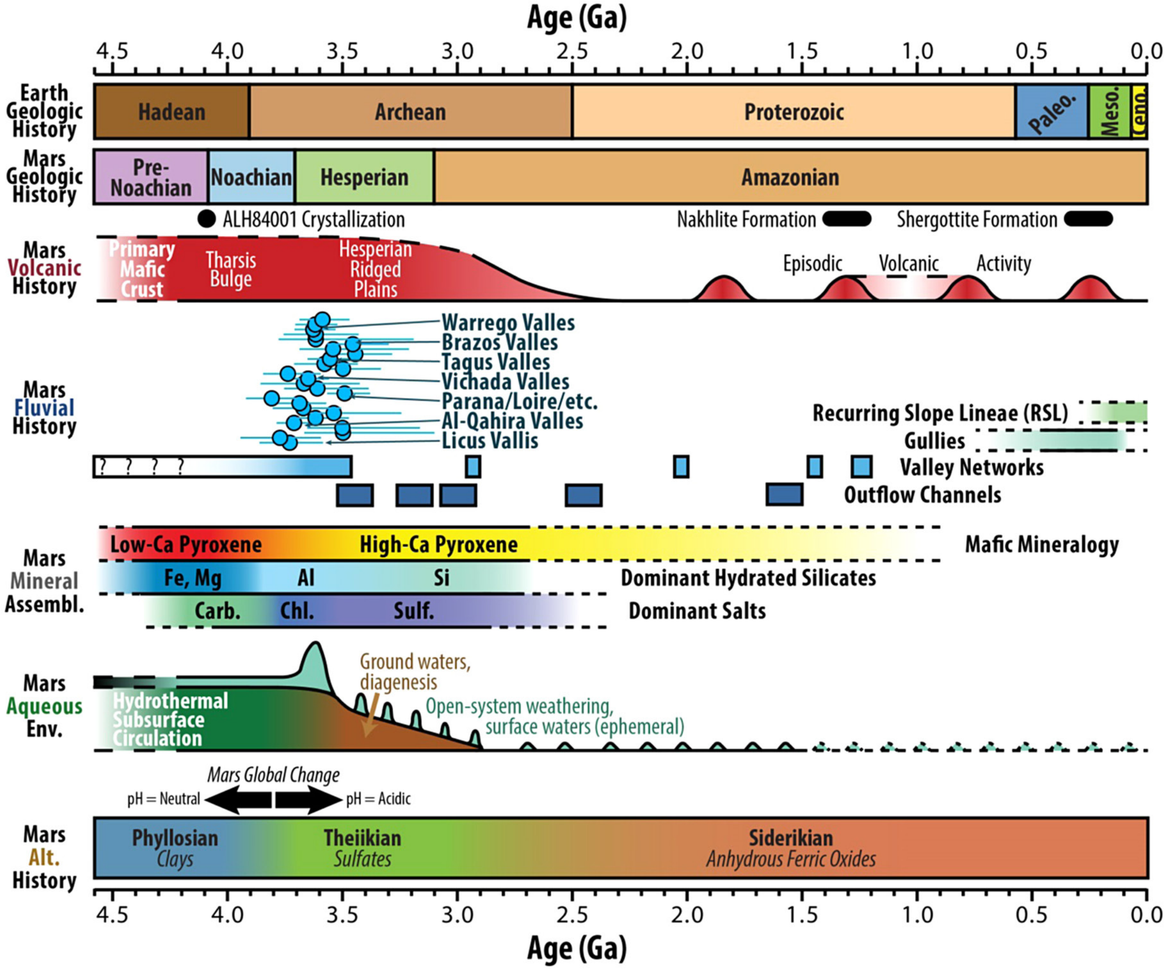

FIGURE 11.2 Geologic, mineralogic, and environmental timeline of Mars. *Modified from Ehlmann et al. (2011, and references therein).*

1. *How can widespread chemical weathering signatures be explained in an environment dominated by physical weathering and cold/dry environmental conditions?*
2. *How can the observed evidence for groundwater- and surface water–related landforms be explained in environments with mean annual temperatures well below freezing?*
3. *What biological mechanisms or environmental adaptations might allow life to persist under cold, dry, salty, and irradiated conditions?*

Debates about how "warm" and "wet" early Mars must have been are fueled by an inability for climate models to produce truly clement conditions even with different atmospheric compositions and thicknesses (Wordsworth et al., 2013, 2015; Wordsworth, 2016). While these models provide critical clues regarding the volatility of climatic conditions and the availability of liquid water on the Martian surface, terrestrial analogs can provide important insight into the resultant geologic, environmental, and astrobiological implications of these different environments.

In the following chapter, we examine these three enigmas and detail the geological, environmental, and ecological processes at work in the MDV and how this terrestrial analog has helped to change our understanding of Martian surface processes. Despite the cold, dry, and stable environmental conditions that dominate the MDV, geologically important processes continue to shape the landscape and to drive complex ecosystems. This analog environment helps us to understand the geologic processes that might be active and omnipresent on recent Mars. However, and perhaps more importantly, this analog environment also provides a glimpse into the hypothesized "cold and icy" early Martian environment where fluvial activity and ecological processes can be fueled by localized environmental optima as opposed to prolonged clement conditions. Such a discussion contrasts with the possible warmer (*see* Davila et al., 2021) and/or wetter (*see* Van Kranendonk et al., 2021), environmental conditions that are alternatively hypothesized and discussed elsewhere in this publication.

2 Background: geologic and environmental context of Mars and Antarctica

2.1 Mars

2.1.1 Ancient Mars: erosion, alteration, and the role of liquid water

Debate currently exists within the Mars community as to whether ancient Mars was once dominated by "warm and wet" or "cold and icy" environmental conditions (Fig. 11.3) (Head and Marchant, 2014; Squyres and Kasting, 1994; Wordsworth et al., 2015; Palumbo et al., 2020). While early studies favored a model dominated by widespread and long-lived rainfall (Craddock and Howard, 2002) to explain the distribution and dominance of mature valley networks, more recent work has shown that colder and drier environments can also generate significant amounts of surface flow resulting from the melting of snow and ice (Scanlon et al., 2013; Head and Marchant, 2014). Fortunately, the relative preservation of the ancient Martian surface and data collected by the armada of Mars orbiters and landers provide us with important clues into this early geologic history and the role of the Martian climate.

Morphologically, ancient Martian landscapes are dominated by many large impact craters and evidence for widespread fluvial and lacustrine activity (Carr and Head, 2010). The majority of Martian valley networks do not show significant hydrological activity since approximately 3.6 Ga, suggesting a cessation of geomorphically significant surface-water discharge around this time (Fig. 11.2) (Fassett and Head, 2008a). Following an intense terminal epoch of aqueous activity (Irwin et al., 2005; Fassett and Head, 2008a,b), water from both the surface and subsurface disappears from the geologic record, resulting in the transition to the modern cold and dry desert environments that we see today (Carr and Head, 2010).

Surface compositions confirm this hypothesis regarding the Martian geologic evolution. While Mars is primarily dominated by primary igneous compositions (Christensen et al., 2000; Mustard et al., 2005), secondary alteration phases are locally widespread and compositionally diverse (Ehlmann and Edwards, 2014). For example, the majority of the ancient Noachian crust on Mars has been shown to contain at least some phyllosilicate minerals (Carter et al., 2013), suggesting ubiquitous interactions with liquid water. In some locations, Al-bearing phyllosilicates overlying Fe/Mg-bearing phyllosilicates are consistent with top-down leaching and pedogenesis often observed in warm and humid terrestrial environments. The identification of carbonate minerals in localized geologic settings (Ehlmann et al., 2008; Niles et al., 2013; Ehlmann and Edwards, 2014)

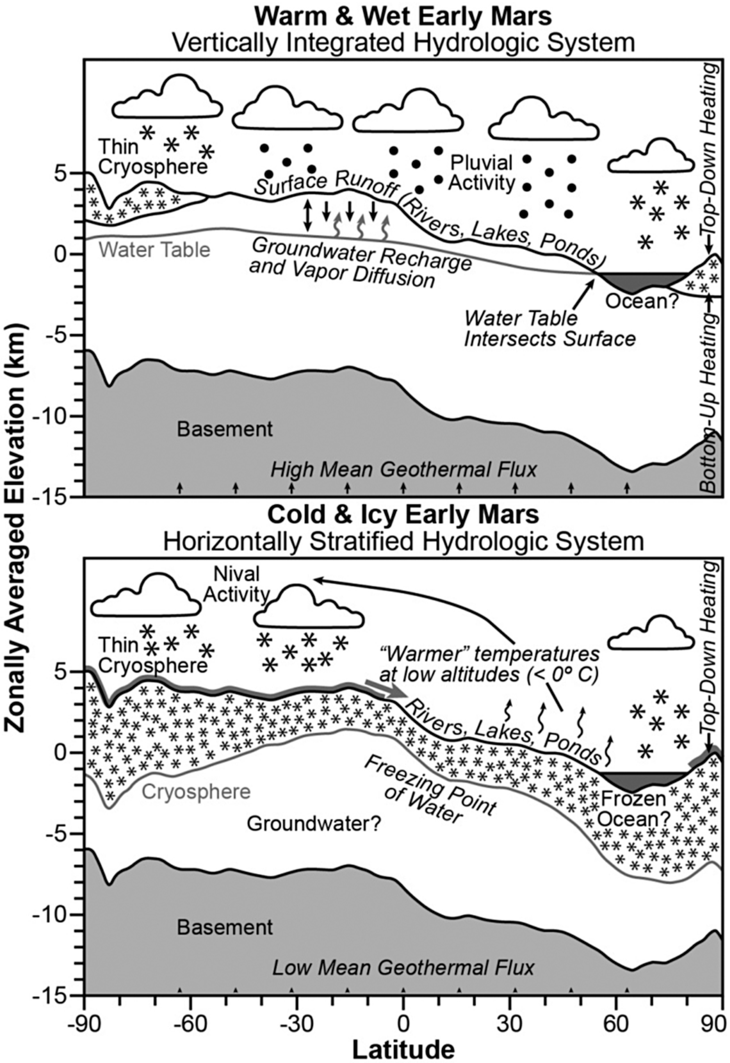

FIGURE 11.3 Schematics of a warm and wet (top) and a cold and icy (bottom) early Martian climate regime. Specifics regarding the nature of the subsurface and the availability of liquid water at and near the surface are both illustrated. *Modified from Head and Marchant (2014).*

suggest long-duration interactions with liquid water at a near-neutral pH.

2.1.2 Transitioning Mars: where did all the water go?

Geologic evidence suggests that Mars underwent a global geologic and environmental transition from "warmer" and "wetter" surface conditions to the cold, dry, and stable desert environment observed today sometime in the ancient past. This transition is thought to have coincided with the cessation of the Martian magnetic dynamo, resulting in the loss of the magnetic field and the exposure of the

Martian atmosphere to stripping by the solar wind (Fassett and Head, 2011). While difficult to predict exactly when the Martian atmosphere thinned, results from the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission support the hypothesis that the Martian atmosphere was heavily influenced by solar wind stripping (Jakosky et al., 2015). Based on morphological evidence, crater retention ages, and global-scale modeling, this major transition is thought to have occurred roughly 3.6 Ga (Fassett and Head, 2008b, 2010; Carr and Head, 2010). At this time, most major Martian valley networks appear to cease hydrologic activity (Fassett and Head, 2008b) while mineralogical evidence for liquid water rapidly becomes scarce and, instead, indicates the removal of liquid water from the surface and near-surface all together. Massive sulfate-bearing layered sedimentary deposits suggest both evaporitic and acidic conditions around a similar timeframe (Gendrin et al., 2005; Roach et al., 2010), potentially sourced from groundwater upwelling as the subsurface began to desiccate as well (Andrews-Hanna et al., 2010). Concentrated chloride salts are also present across the ancient Martian terrain in localized depressions, suggesting a change from overland flow of surface water to groundwater discharge in evaporation-dominated basins (Osterloo et al., 2008, 2010; Glotch et al., 2010).

2.1.3 *Recent and current Mars: surface processes on ice*

Since this global geologic and environmental transition, the Martian surface has largely been dominated by cold, dry, and stable surface conditions similar to those that dominate today. The widespread physical erosion of bedrock, clasts, and sediment results in the removal of fines (clays and silts) from Martian landscapes. In the low-albedo (free of fine-grained dust) landscapes investigated by landed missions, the Martian surface shows clear evidence for the winnowing of the finest sediment size fraction and the preferential accumulation of relatively coarser sediments through surface deflation (Grant et al., 2004; Sullivan et al., 2005). Aeolian abrasion also plays an important role in surface erosion and landscape evolution. The preferential erosion of dolerite clasts in Beacon Valley and the near-complete destruction of sandstone clasts are almost exclusively due to differences in rock hardness and their susceptibility to aeolian abrasion. Measured bedrock erosion rates in the MDV fall between 0.1 and 0.4 m/Ma (Margerison et al., 2005; Morgan et al., 2010), which fall within the measured, modeled, and estimated bedrock erosion rates on modern Mars (10^{-5}–10^{0} m/Ma, Golombek and Bridges, 2000; Farley et al., 2014). The lack of significant and widespread vegetation, the dominance of unconsolidated clastic materials, and the wind-deflated surfaces result in similar appearances between the Martian surface and the MDV, particularly in the Stable Upland Zone (Fig. 11.4).

Modern Mars is dominated by anhydrous oxidative weathering processes (Salvatore et al., 2014), where ferric iron is produced and cations migrate to and from the rock surfaces in response to strong oxidation gradients (Cooper et al., 1996; Salvatore et al., 2013). Evidence for the production of more mature aqueous alteration phases globally waned in conjunction with the observed halting of surface hydrology (Ehlmann et al., 2011; Ehlmann and Edwards, 2014).

Glacial activity on Mars has been shown to dominate landscapes spanning from high (Squyres, 1978) to equatorial latitudes (Head and Marchant, 2003; Fastook et al., 2008). However, the extent to which analogous cyclical glacial process may have shaped bedrock incision on Mars remains largely unknown, owing to uncertainty about the long-term obliquity history of the planet (Laskar et al., 2004) and the absence of evidence for widespread wet-based glacial activity. Nonetheless, evidence for past glaciations can be well preserved in the geologic record, suggesting similarly dramatic environmental transitions on Mars in the recent geologic past (Holt

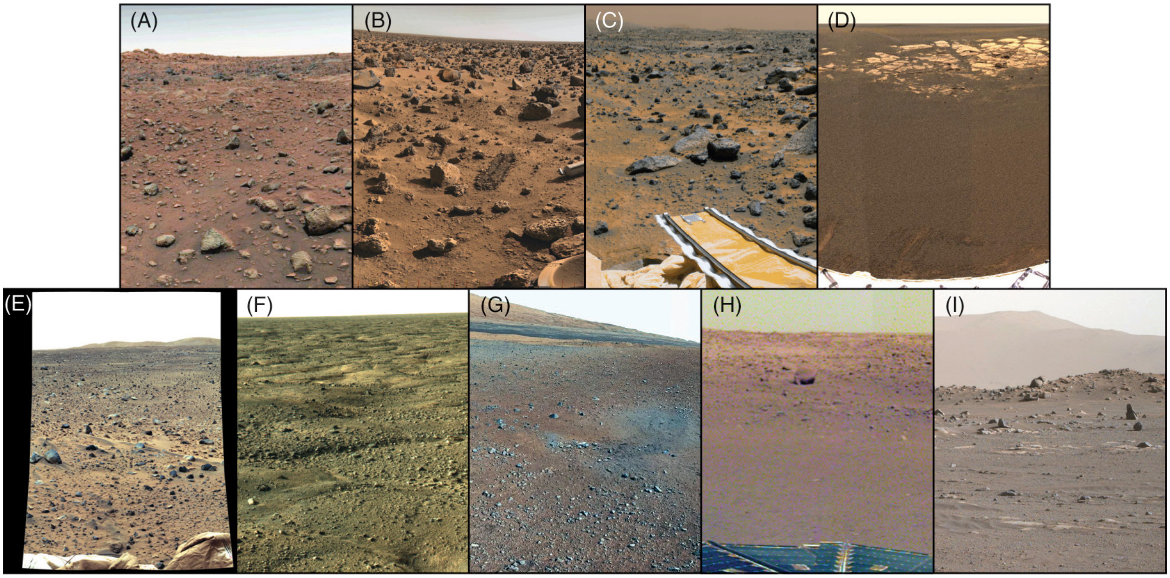

FIGURE 11.4 The Martian surface as observed from all landed NASA missions through 2020, highlighting the cold, dry, desert landscape that lacks evidence for significant modern geologic processing. (A) Viking 1 lander. (B) Viking 2 lander. (C) Mars Pathfinder. (D) Mars Exploration Rover Opportunity rover. (E) Mars Exploration Rover Spirit rover. (F) Mars Phoenix Lander. (G) Mars Science Laboratory Curiosity rover. (H) Mars Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSIGHT). (I) Mars 2020 Perseverance rover. *All images courtesy NASA.*

et al., 2008; Morgan et al., 2009; Head et al., 2010). Shallow subsurface ice is also widespread across Mars (Bandfield, 2007), with landed missions confirming these shallow ice deposits (Smith et al., 2009) and recent work showing significant near-surface exposures down to latitudes of 45° and lower (Vincendon et al., 2010; Dundas et al., 2014; Piqueux et al., 2019). These Martian ice deposits produce similar mesoscale surface morphologies to those identified in the MDV, suggesting similar styles of surface modification (Marchant and Head, 2007; Levy et al., 2009).

Despite surface conditions that are not currently conducive to the long-term stability of liquid water, modern small-scale surface features have been interpreted to indicate possible surface or near-surface hydrological activity. These surface features include gullies and recurring slope lineae (RSL), both of which have been observed to change over the duration of the Mars Reconnaissance Orbiter mission.

The three most commonly accepted models for "modern" Martian hydrologic activity include (1) spin-axis/orbital evolution leading to the remobilization of ice from and deposition in the mid-latitudes, followed by subsequent localized melting (Dickson and Head, 2009); (2) episodic warming and hydrologic activity initiated by punctuated volcanism (Halevy and Head, 2014); and (3) impact-induced short-term ($\lesssim 10^7$ years) global warming leading to the melting of (sub)surface ice deposits (Segura et al., 2002, 2008). While all three models are plausible, recent studies have interpreted the modern activity in both gullies (Dundas et al., 2019) and RSL (Edwards and Piqueux, 2016) to be unrelated to hydrological activity. Nonetheless, the role of liquid water in both the formation and evolution of gullies and RSL remains widely debated, largely because of their spatial distribution and comparison to terrestrial analog landforms.

2.2 Antarctica

The unique cold desert processes operating in the MDV emerge from the interactions between the local/regional geology and the unique cold polar environmental conditions that have operated over the last 10^7 years. Although the cold desert climate processes discussed next largely operated over Neogene timescales, the Dry Valleys have an inherited bedrock history that extends into the Mesozoic (Campbell and Claridge, 1987; Cox et al., 2012). This may mirror modern Martian ice-related geomorphic processes such as mantling and glaciation, which overprint or superpose surfaces of Noachian and Hesperian age (Kreslavsky and Head, 2002; Head et al., 2003). In this section, we describe the local bedrock and environmental conditions in the MDV that give rise to the critically important products and processes analogous to those identified on Mars.

2.2.1 *Bedrock geology*

The MDV are geologically diverse (McKelvey and Webb, 1962; Cox et al., 2012, 2018), with several lithologies that are relevant to those previously observed at the Martian surface. These units are variably exposed throughout the valleys thanks largely to the significant topography of the MDV and the TAM (Fig. 11.5). They also comprise the source materials for glacial tills, soils, and other Quaternary deposits (Bockheim and McLeod, 2008; Bockheim et al., 2008).

The lowermost exposed geologic units throughout the MDV are composed of the Granite Harbor Intrusive Complex, a Precambrian and early Paleozoic plutonic system composed largely of calc–alkalic or alkalic–calcic granitoids (Encarnación and Grunow, 1996; Martin et al., 2015). These igneous and metamorphic units are unconformably overlain by the sedimentary units of the Beacon Supergroup, a Devonian to Triassic mixture of clastic lithofacies ranging in coarseness from conglomerate, to pebbly sandstone, to cross-bedded sandstone,

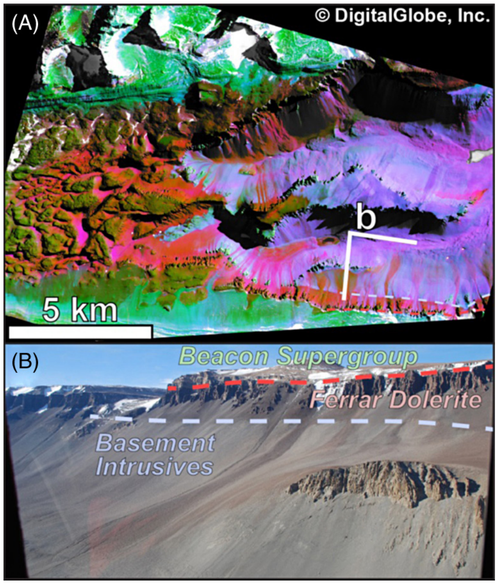

FIGURE 11.5 (A) A multispectral WorldView-2 parameter image of Wright Valley, Antarctica, with different lithologies represented as different colors. *Reds* represent the Ferrar Dolerite, *greens* represent the Beacon Supergroup, and *blues* represent the granitic basement. The *dashed red line* indicates the contact between the Ferrar and the Beacon, while the *dashed blue line* indicates the contact between the Ferrar and the basement intrusives. (B) A perspective view of the southern wall of Wright Valley. *Dashed red* and *blue lines* are analogous to those shown in (A). *(A) Modified from Salvatore (2015).*

and interbedded siltstone/sandstone, with evidence for bioturbation in many exposures (Allen, 1962; Hamilton and Hayes, 1963; Savage et al., 2013; Cox et al., 2018). The Beacon Supergroup is dramatically cross-cut by igneous sills of shallow-intrusive Jurassic-aged Ferrar Dolerite, ranging in age from 176.2 to 177.2 million years old and associated with continental-scale rifting that emerged from a magma source located near the Weddell Sea, some 2500+ km distant (Fleming et al., 1997). These tholeiitic dolerites cut the sedimentary rocks both at the contact with the basal bedrock complex as well as throughout the sedimentary strata, producing sills that can exceed 150 m in thickness and that have even rafted blocks of the country rock into the sills (Webb, 1963). Capping these geologic units is a series of mid-Miocene-aged lacustrine deposits, the most famous of which is present on Mt. Boreas (Lewis et al., 2008). Biostratigraphic evidence suggests that the paleolake present at Mt. Boreas experienced at least one cycle of water level variation from high to low to high, perhaps mirroring water balance mechanisms associated with comparable closed-basin lakes on Mars (Lewis et al., 2008; Goudge et al., 2015).

The paleoenvironmental conditions preserved in the bedrock stratigraphy of the MDV indicate a more clement environment than present. The formation of these units and their subsequent exposure to and preservation in the cold, dry, polar conditions of the MDV provide important insight into similar processes on Mars. The bedrock geology of the MDV sources the substrate upon which modern cold and dry biogeochemical processes act, resulting in distinct hydrological, geochemical, and climatic activity and signatures.

2.2.2 Modern climate

The MDV serve as a unique Mars analog environment in that they combine low temperatures, low precipitation, low relative humidity, and high UV radiation fluxes to produce a cold, dry, irradiated surface environment. They are the only known natural location on Earth that have sites that are fully outside of the climate parameters previously defined for habitability (Rummel et al., 2014) and which, as a consequence, host regions that show no evidence of cellular metabolism and replication (Goordial et al., 2016).

Modern climate conditions in the MDV can be characterized in terms of climate normals, defined by the long-term average climate conditions that are recorded by automatic weather stations located within the valleys (Doran et al., 2002). Air temperatures in the MDV average −14.8° C to −30° C, with the lowest temperatures typically associated with increasing elevation and distance from the coast (although episodic drainage wind events can rapidly raise temperatures inland over daily timescales) (Doran et al., 2002; Fountain et al., 2014). Mean annual conditions in the MDV belie complex seasonal temperature patterns which, importantly, result in short-lived climate optima that drive biogeochemical and geomorphic processes. During the summer months, onshore winds dominate and warm as they progress through the valleys creating a strong linear relationship (r^2 = 0.992) of increasing potential temperature with distance from the coast (0.09° C/km) (Doran et al., 2002). Coupled with dry adiabatic lapse rates, this seasonal warming pattern produces long-term spatial trends in temperature as a function of distance and elevation (Fountain et al., 2014) (see ***Microclimate zones***).

Polar illumination patterns coupled with generally low cloudiness and low relative humidity result in recorded surface temperatures throughout the MDV that are strongly dependent on radiative balance. Site-to-site variation in mean annual solar flux and photosynthetically active radiation (PAR) result from the geography and exposure geometry of each meteorological station, with seasonal and interannual variations at each site likely related to changes in cloudiness (Doran et al., 2002). However, it is notable that annually averaged incoming solar radiation in the MDV has varied by over 20 W/m^2 (20–25% variability) over the past three decades (Obryk et al., 2018). Changing concentrations of stratospheric sulfur dioxide have been inferred to drive this extreme variability in surface energy balance over Antarctica which, in turn, is thought to drive surface melt, runoff generation, and increased soil temperatures (Obryk et al., 2018). However, the overall cause of these energy balance fluctuations remains poorly constrained and requires additional work (Obryk et al., 2018).

Seasonality of insolation also plays a strong role in soil surface and near-surface temperature as a function of time (Fig. 11.6). Low-albedo soils in the MDV rapidly warm under summer insolation (McKay et al., 1998; Guglielmin, 2006),

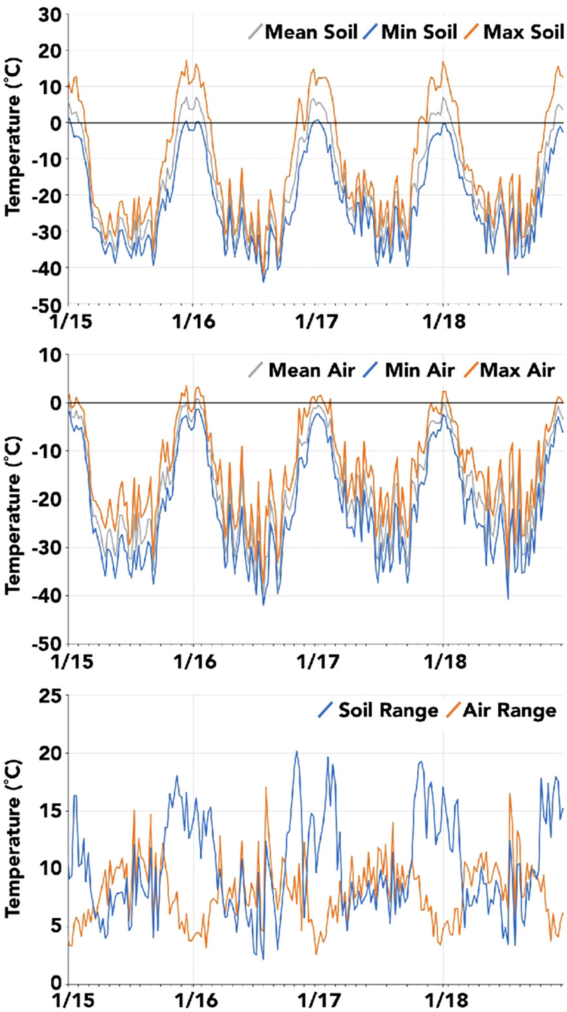

FIGURE 11.6 Lake Hoare, Taylor Valley temperature record showing average, high, and low air (top) and soil (middle) temperatures, aggregated over 1 week periods. Soils are notably warmer than air and achieve greater high/low-temperature ranges in the summer, while air temperatures show a larger range (bottom) during winter drainage wind events.

which transmits heat to the subsurface (Levy and Schmidt, 2016; Linhardt et al., 2019). Intense summer insolation coupled with winter darkness means that soil surface temperatures in the MDV are largely radiatively controlled, with sensible heat playing a minimal role (Linhardt et al., 2019). As a consequence, soils are notably warmer than air in the MDV in the summer, and dark rock surfaces may be even warmer than soils (Fig. 11.6). Soil surfaces regularly exceed freezing temperatures on diurnal timescales during summer months, which may cause organismal stress during freeze-thaw cycling (Walker et al., 2006; Villarreal et al., 2018). These large temperature ranges experienced by MDV soils during summer while air temperatures are relatively uniform are absent in winter, when a lack of persistently oscillating radiative input keeps soil temperatures low and uniform while air temperatures can fluctuate dramatically in response to short-lived drainage wind events (Fig. 11.6).

Precipitation falls entirely as snow (3–50 mm water equivalent annually), most of which sublimates and leads to the characteristic hyper-arid surface conditions present throughout the valleys (Fountain et al., 2009). Annual relative humidity is generally highest near the coast (Doran et al., 2002), although the presence of ice-covered lakes, lake moats, and glaciers provides heterogeneity to the spatial distribution of local humidity conditions. Mean annual wind speed increases with proximity to the polar plateau, as fair-weather up-valley winds from the coast encounter episodic down-valley drainage winds from off the East Antarctic Ice Sheet (EAIS, Nylen et al., 2004). These strong seasonal and gravity-driven winds persist throughout the valleys and play a vital role in the redistribution of both geologic and biological materials.

There remains a significant debate as to whether the MDV or the Atacama Desert is the driest environment on Earth, as determined by the recorded "climate normals." This causes debate as to which environment may be more suitable for studying Mars-relevant biogeochemical processes operating under conditions of extreme aridity. Both sites have meteorological stations that experience ~0 mm of water equivalent precipitation annually (Houston, 2006; Fountain et al., 2009), although Atacama sites have also previously recorded more than 150 mm of mean annual rainfall (Houston, 2006). While both sites experience limited precipitation, atmospheric relative humidity plays a major role at both sites that influences the observed biogeochemical processes (Wilson, 1979; Cáceres et al., 2007; Levy et al., 2012; Gough et al., 2017). Weekly average relative humidity in the Atacama can vary between ~60 and 100%, depending on the site, resulting from local fogs (Cáceres et al., 2007). Relative humidity in the coastal MDV can reach as low as ~6% during gravity-driven drainage wind events and as high as 100% during snowstorms (Doran et al., 2002), with annual average relative humidity in upland sites (see ***Microclimate zones***) averaging 44% (Marchant and Head, 2007). Despite the generally comparable relative humidity ranges, the lower mean annual air temperature in the MDV (−18° C) versus the Atacama (17.3° C) means that, even under identical humidity conditions, average water vapor pressure in the MDV can be more than an order of magnitude lower than average water vapor pressure in the Atacama.

The cold temperatures that dominate the MDV result in pervasive permafrost conditions at the surface, which is another similarity to Mars that sets the MDV apart from other terrestrial locales (Dickinson and Rosen, 2003; McKay, 2009). Permafrost is defined as soils and sediments that exist under permanently frozen conditions over timescales exceeding 2 years, regardless of whether water ice is present or absent (Dickinson and Rosen, 2003). In particular, the dominance of dry permafrost in the high elevations of the MDV serves as an important geological, hydrological, and ecological analog to Martian surface processes (Gilichinsky et al., 2007; McKay, 2009). Other critical environmental parameters that control the presence/absence of ground ice and soil moisture are the water and saturation vapor pressures (Haberle et al., 2001). The water vapor pressure is important because evaporation and sublimation rates are controlled only by the water vapor pressure. This property is instead mostly dominated by the local water/ice sources and atmospheric mixing. Similarly, saturation vapor pressure (which controls relative humidity) is controlled by air temperature and not the total atmospheric vapor pressure, allowing direct comparison between many terrestrial sites, regardless of their mean elevation. In tandem, this earlier work has shown that the environmental and geological conditions present in the MDV are more akin to modern Martian surface conditions, while active hydrological and ecological processes in the MDV help to define their environmental limits. As such, the applicability of the MDV to more ancient Martian environments continues to expand.

2.2.3 *Microclimate zones*

As a result of the interplay between climate normals and seasonal patterns of variability, the MDV experience spatially delimited microclimate zones based on elevation and distance inland (Table 11.1, Fig. 11.7), which drive biogeochemical and geomorphic processes (Marchant and Head, 2007). Fountain et al. (2014) used a summer air temperature model to delimit the

TABLE 11.1 Climatic characteristics of representative locations within the Marchant and Head (2007) microclimate zones.

Location	Beacon Valley	Wright Valley (Lake Vanda)	Taylor Valley (Explorer's Cove)
Microclimate zone[a]	Stable Upland Zone	Inland Mixed Zone	Coastal Thaw Zone
Distance from the coast (km)	75	43	4
Mean annual air temperature (°C)	−22	−19	−20
Mean soil temperature (0 cm depth) (°C)	−22	−20	−19
Mean relative humidity (%)	43	55	74

[a] *As defined by Marchant and Head (2007).*

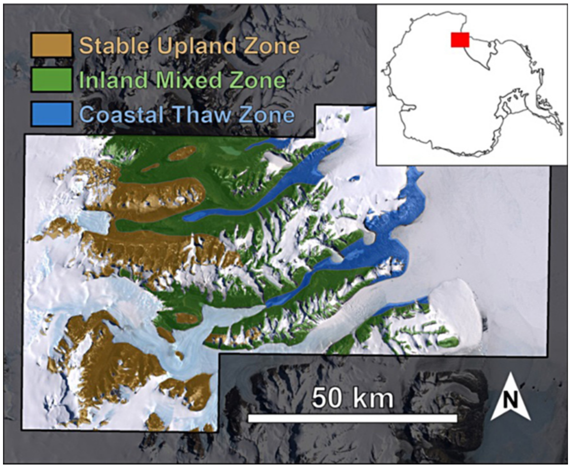

FIGURE 11.7 Microclimate zones of the McMurdo Dry Valleys. *Modified from Marchant and Head (2007).*

geomorphic zones defined by Marchant and Head (2007) by summer temperatures. The Stable Upland Zone occurs where temperatures are $< -10°$ C, the Intermediate Mixed Zone transitional area occurs where temperatures span $-10°$ C to $-5°$ C, and the Coastal Thaw Zone covers areas with temperatures exceeding $-5°$ C (although referred to as "coastal," it should be noted that the coastal zone can extend up to 30 km inland along low-slope valley floors). These microclimate zones generate equilibrium landforms that are diagnostic of meltwater availability, ground ice preservation, and salt action across a range of spatial and geographic extents. Microclimate zonation controls the spatial distribution of macroscale features (such as slope stability and gradient and mass-wasting features such as gullies), mesoscale features (such as polygonally patterned ground types like ice-wedge, sand-wedge, and sublimation-type polygons), and microscale features (such as salt weathering pits, ventifacts, and fully articulated puzzle rocks) (Marchant and Head, 2007).

The microclimate zonation and resultant equilibrium landforms defined and described in the MDV provide a potentially diagnostic view into the interaction between Martian geology and climatology. The plethora of morphologies, erosional remnants, and alteration products generated in these different microclimate zones are sensitive to and diagnostic of very minor changes in environmental conditions. If observed in the Martian geologic record, these products can help to constrain the ancient Martian climate and the nature of its interaction with surface geology. If observed at the modern Martian surface, these products would indicate that local variations in temperature and ice/water/vapor availability are currently playing significant geochemical roles with potential biological implications.

2.2.4 *Climate history*

Prior to 34 million years ago and the shift to icehouse conditions during the Oligocene (Zachos et al., 2008), the Antarctic was largely unglaciated (DeConto and Pollard, 2003). Since then, the MDV (and Antarctica as a whole) have experienced multiple episodes of glaciation (Peters et al., 2010; Liebrand et al., 2017). Even with well-dated paleoclimate proxies and landform assemblages, considerable debate persisted over the long-term stability of the EAIS, which flanks the MDV on its inland border and which drives the drainage wind dynamics that help make the MDV so dry. Sugden et al. (1993) argued that the terrestrial geomorphic evidence of ice sheet overriding of the MDV at ~14 million years ago was consistent with early marine sediment cores that suggested consistent growth of the EAIS during the Miocene and Oligocene, with the persistence of cold and dry conditions in the MDV since then. In contrast, Young et al. (2011) combined marine sedimentary records with subglacial radar measurements and ice flow models to suggest that the EAIS (and other Antarctic ice sheets) likely waxed and waned over 30 times between the inception of the EAIS at 34 and 14 million years ago, generating a series of terrestrial and fjord environments in the coastal Antarctic, including the MDV.

The debate about EAIS minimum extent in and around the MDV can be considered within the context of the maximum advance of ice sheet glacial tongues in the MDV during the Pleistocene. Any coastal MDV fjords that would have developed in response to high sea levels (≳50 m) associated with Pliocene EAIS collapse would have been eroded and overprinted with glacial deposits from Pleistocene glaciations, which filled the MDV with reentrant glaciers to a height of 300–350 m (Stuiver et al., 1981; Hall et al., 2000, 2010). Thicker ice draining through the TAM would fill the Ross Sea during these glaciations, resulting in ice sheet grounding and flooding into the coastal MDV. Intense summer insolation would work on reentrant glacial fronts, producing ice-covered proglacial lakes even during the height of last glacial maximum cooling (Hall et al., 2000; Levy et al., 2013). These now-vanished proglacial lakes may have filled the coastal MDV (such as Taylor Valley) to depths in excess of 300 m, overprinting cold-based glacier tills and drifts with alternating lake ice–rafted sediment (Hendy et al., 2000) and harboring the growth of deltaic deposits where meltwater streams entered at sites now high on the valley walls (Fig. 11.8) (Hall et al., 2000).

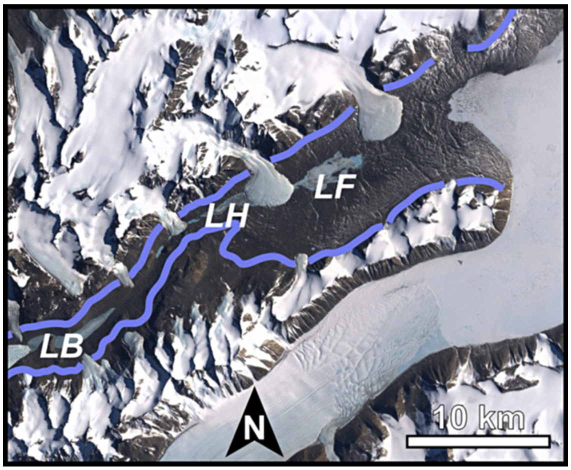

FIGURE 11.8 Maximum possible extent of ice-age glacial Lake Washburn in Taylor Valley (*blue line*). Ancient lake deposits and abandoned deltas demarcate the margin of this lake, which may have risen to a maximum elevation of 336 m above sea level (Hall et al., 2000). Modern lakes Fryxell (LF), Hoare (LH), and Bonney (LB) are also identified.

However, the relative extent and duration of the paleolakes and ice sheet reentrant lobes remains under debate. Early workers traced potential shoreline terraces and widely scattered deltaic deposits as evidence of large, valley-filling lakes occupying much of modern Taylor, Wright, Garwood, and Miers Valleys (Péwé, 1960; Stuiver et al., 1981; Hall et al., 2000). Alternatively, glacier ice may have largely filled the valleys, producing small, marginal fringing lakes in isolated basins that gradually coalesced at lower elevations as the ice melted and retreated from the valley. This "small lakes" interpretation is derived in part from observations of intact lacustrine deltas in proximity to the preserved glacial ice/till dams that generated the paleolakes, which suggests that, in some locations, deltas may have grown to occupy up to a third of the area of the lake basin they grew (Levy et al., 2013). Evidence for such small lakes is supported by soluble salt accumulations in the MDV that would be reset by flooding by large lakes. Toner et al. (2013) found much higher salt concentrations in the inland (western) reaches of Taylor Valley than the coastal (eastern) reach, suggesting that reentrant ice sheet lobes expanded fully into eastern Taylor Valley, damming proglacial paleolakes in western Taylor Valley up to ~300 m elevation.

3 Observations: Antarctic insights into Martian enigmas

3.1 Enigma 1: chemical weathering in cold, dry, and stable environments

Chemical weathering of rock surfaces is a ubiquitous process that occurs in all terrestrial environments. The classical view of chemical weathering has typically suggested that it is the dominant process of rock breakdown in warm and wet environments, while physical erosion dominates when temperatures become colder and/or when liquid water is scarce. Recently, technological advances that allow for the microscale investigation of rock surfaces have revolutionized our understanding of the scale, nature, and extent of chemical alteration in a variety of different terrestrial environments, including cold and dry environments like the MDV of Antarctica (Langworthy et al., 2010; Dorn et al., 2013; Salvatore et al., 2013; Macholdt et al., 2015; Dorn and Krinsley, 2019). As was eloquently stated by Dorn and Krinsley (2019), recent work into the nature and extent of chemical weathering "leads to the inevitable conclusion that it is 'chemical weathering' that truly dominates rock decay in cold climates." But how and why are such processes so fundamentally different in cold and dry environments relative to other terrestrial landscapes, and why is it important to understand these processes when investigating the Martian surface? We address both of these questions and demonstrate why constraining chemical alteration processes in cold and dry environments is relevant to modern Martian investigations.

Terrestrial landscapes are subjected to the competing forces of physical erosion (which breaks material down into smaller components through processes, including abrasion, scouring, plucking, and wedging) and chemical weathering (which results from processes, including dissolution, oxidation, hydrolysis, leaching, and precipitation). Early work on the kinetics of chemical weathering identified that the nature and rate of alteration is related to the temperature and chemistry of the altering environment, the composition and structure of the material being altered, and the duration of environmental exposure (Lasaga, 1984). Lasaga (1984, and references therein) presents several examples of calculated chemical dissolution rates and experimental measurements that confirm the importance of these different variables. Nesbitt and Wilson (1992), Nesbitt and Markovics (1997) and others showed how aqueous alteration under most terrestrial conditions typically results in the initial leaching of alkali and alkaline earth metals followed by the subsequent leaching of other metal phases that are more susceptible to oxidation, which eventually leads to the relative enrichment of structural Si and Al. Low-pH conditions dramatically increase the solubility of Fe^{3+} and Al, which changes these typical terrestrial alteration trends in a predictable manner (Hurowitz et al., 2006).

But how is it possible for chemical weathering to occur where liquid water is scarce or absent? The solution to this enigma may be widely distributed across the surface of Beacon Valley, Antarctica. Beacon Valley is one of the southernmost valleys in the MDV and, at an average surface elevation of roughly 1500 m above sea level, is one of the highest in elevation. This valley is the archetype of the Stable Upland Zone, where the air temperature rarely exceeds 0° C and geomorphic evidence for liquid water on the surface is virtually absent. Instead, the surface is dominated by polygonal cracking resulting from ice sublimation and the annual cooling and contraction of ground ice. The surface is also dominated by large boulders of the Ferrar Dolerite; although the walls of Beacon Valley expose outcrops of both the Ferrar Dolerite and the coarse-grained Beacon Sandstone, the sandstones are extremely friable relative to the dolerites, resulting in their rapid disintegration and a general absence as surface clasts. Sediments underlying the dolerite boulders are dominated by the sand-sized fraction of both the Ferrar Dolerite and the Beacon Sandstone, as finer materials have been largely removed by fair-weather up-valley winds and episodic down-valley gravity-driven winds.

The interaction between the gravity-driven drainage winds and the dolerite boulders highlight an important aspect of chemical weathering in the Stable Upland Zone of the MDV (Campbell and Claridge, 1987; Salvatore et al., 2010). Looking down-valley when standing on the floor of Beacon Valley, the surface appears largely gray in color, which matches the color of the unaltered dolerite that dominates the valley floor. However, when looking up-valley, the surface appears red-brown in color representative of an oxidized surface staining that, while found throughout the MDV, dominates the north-facing (down-valley) slopes of every dolerite clast. This discrepancy in observed clast color is driven by physical abrasion of rock surfaces by saltating sediments during these gravity-driven drainage wind events (Campbell and Claridge, 1987). Typical "fair-weather" up-valley (southward) winds cannot saltate sand-sized particles, which minimize physical erosion on the north-facing sides of clasts. Alternatively, gravity-driven down-valley (northward) winds are able to saltate sand- and even pebble-sized particles, resulting in significant aeolian abrasion on the south-facing sides of clasts.

The nature of the anhydrous oxidative weathering process that dominates the rocks of Beacon Valley is discussed at length in Salvatore et al. (2013) and briefly described here (Fig. 11.9). In short, there is a significant oxidation gradient between the oxidizing atmosphere and the interior of the dolerite clasts, which formed at roughly the quartz–fayalite–magnetite redox buffer. In most terrestrial environments, oxygenated liquid water helps to facilitate the balancing of this gradient through mineral dissolution, the delivery of O_2 to dissolved Fe^{2+}, and the formation of (meta)stable Fe^{3+} compounds. However, in Beacon Valley, liquid water is not readily available to participate in this oxidation process. Therefore, in response to the oxidation gradient, cations in the rock migrate to the free surfaces of the dolerite clasts, a process that is charge-compensated by the inward flux of electron holes (or electron vacancies), which converts Fe^{2+} to Fe^{3+}. This oxidation process then causes an outward flux of electrons to the free surface where, after being transferred to environmental oxygen, they can combine with the previously migrated cations to form metastable and soluble oxide species at the surface of the clast. This process is detailed in Fig. 11.9.

Several lines of evidence support the hypothesis that anhydrous oxidative weathering dominates the alteration of the Beacon Valley dolerites. For example, the surfaces of the dolerites show a systematic depletion in Ca^{2+} and Mg^{2+}, yet a systematic enrichment in K^+ and Na^+, two of the most soluble cations present in these rocks. The depletion and enrichment of divalent and monovalent cations, respectively, are not predicted by

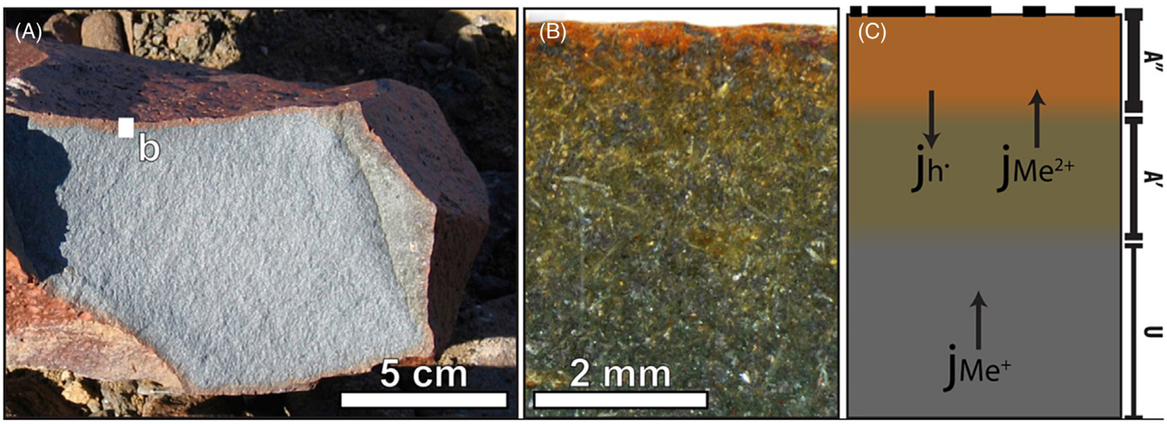

FIGURE 11.9 (A) A dolerite clast from Beacon Valley, showing the red oxidized surface rind and the unoxidized interior. (B) A thick section micro-image of the alteration rind and the uninterrupted transition to the unaltered interior. (C) A diagram of the oxidative weathering process, where divalent cations (j_{Me2+}) migrate to the rock surface, monovalent cations (j_{Me+}) migrate from the rock interior toward the surface, and electron holes ($j_{h\bullet}$) migrate into the rock interior from the surface, resulting in the oxidation of iron. Discrete zones of unoxidized (U), partially oxidized (A′), and heavily oxidized (A″) materials are labeled. Metastable cation-oxide phases form at the rock surface (*black bars*) and are readily removed through erosion and dissolution. *Modified from* Salvatore et al. (2013).

common modes of aqueous alteration. Instead, the preference toward divalent cation removal is electrochemically favorable during anhydrous oxidative weathering (Cooper et al., 1996). The removal of divalent cations results in the inward flux of two electron holes to fill that vacancy, while the removal of monovalent cations results in the inward flux of only one electron hole. Therefore divalent cation removal is favored by a factor of two over monovalent cation removal. This does not, however, mean that monovalent cations are immobile during the oxidation process. Monovalent cations instead respond to the significant charge imbalance by migrating from the rock interior toward the surface, leading to the observed enrichment in Na^+ and K^+ at the surface relative to divalent cations. These zones of cation migration and iron oxidation result in two observed zones of alteration just below the dolerite surface as the abundance of Fe^{3+} exceeds different redox buffers.

Additional evidence that aqueous alteration does not play a significant role in the weathering of dolerite surfaces in Beacon Valley is the absence of more mature alteration phases and the dominance of primary igneous phases at the surfaces of dolerites, which is nearly identical to the mineral assemblages identified in dolerite interiors. This is confirmed by Mössbauer spectroscopy, which shows that the relative abundance of Fe-bearing minerals is the same between the dolerite surfaces and interiors, and that the increased abundance of Fe^{3+} is found in the same phases as the original primary Fe^{2+}. Despite the lack of mineralogical evidence for surface alteration, dolerite surfaces exhibit significantly different reflectance and emission spectral signatures relative to the unaltered interiors. For instance, visible/near-infrared (VNIR) reflectance spectroscopy shows strong Fe^{3+} charge-transfer absorptions at visible wavelengths, followed by an increased blue slope (decrease in reflectance with increasing wavelength) relative to their corresponding interiors. The charge-transfer absorption is consistent with increased Fe^{3+} in the dolerite surface, while the observed blue slope is likely due to the wavelength dependence of light interactions with the most heavily altered portion of the alteration rind (Fischer and Pieters, 1993). Mid-infrared (MIR) emission spectroscopy shows a narrowing of the Reststrahlen features, which is consistent with increased spectral contributions from spectrally amorphous phases and an apparent "standardization" of the Si–O vibrations that correspond to mineral structures (Michalski et al., 2003; Salvatore et al., 2013).

Prior to 2007, this process of anhydrous oxidative weathering had only been observed in laboratory settings using glass beads at high temperatures (Cooper et al., 1996; Smith and Cooper, 2000). The first identification of this process in nature was published by Burkhard and Müller-Sigmund (2007), who identified these signatures at the surfaces of lobes of pahoehoe lava in Hawaii. In this instance the high temperatures enabled this oxidative weathering process to occur quickly, while burial by subsequent pahoehoe flows protected these gradients from destruction by more extensive chemical alteration. Beacon Valley, Antarctica, represents the first known instance where this process and the resultant alteration signatures are preserved subaerially, protected from further weathering and erosion by the low rates of physical erosion, the lack of significant precipitation, and the low temperatures that prevent liquid water from accumulating on rock surfaces that could then play a significant role in the chemical weathering process.

While anhydrous oxidative weathering processes appear to be the dominant mode of surface weathering on fine-grained basaltic and doleritic clasts, compositional analyses from clasts throughout the TAM are inconsistent with anhydrous alteration processes being the dominant mode of surface alteration in sedimentary rocks (Salvatore et al., 2019). While some sedimentary rocks show evidence of with oxidative weathering (Cannon et al., 2015; Salvatore et al., 2019), most instead show a broad array of alteration pathways that are likely dependent on several variables, including the physical properties of the rocks, their composition and susceptibility to chemical weathering, and their physical orientation and exposure histories. Importantly for Mars, the physical properties of the rocks determine their susceptibility to physical erosion, which is in direct competition with surface weathering for determining whether surface alteration is to be observed.

The most obvious and widespread product of chemical weathering on the Martian surface is readily represented by its ubiquitous red coloration, caused predominantly by nanophase iron oxides that have oxidized through interactions with the Martian atmosphere (Singer et al., 1979; Morris et al., 2000). This red coloration is primarily the result of the globally distributed fine-grained dust, which spectroscopic studies have shown to be dominated by plagioclase with lesser amounts of other primary and hydrated mineral phases (Bandfield et al., 2003; Ruff, 2004; Hamilton et al., 2005). Even where dust is absent or has been mechanically removed, Martian surfaces appear to be significantly oxidized (Morris et al., 2004), suggesting that some sort of oxidative weathering has kept pace with physical erosion. Burns (1993) and Burns and Fisher (1993) provide a comprehensive list of possible oxidative weathering mechanisms to explain the oxidation observed on the Martian surface, yet all of these mechanisms require the presence of liquid water to facilitate mineral dissolution and the conversion of Fe^{2+} to Fe^{3+}. *If oxidative weathering is somehow keeping pace with physical erosion in the "modern" Martian environment, how could liquid water play a substantial role in the generation of these oxidative weathering products?*

Beacon Valley dolerites share several key characteristics with Martian basalts and regional/global spectral provinces. For example, major elemental trends observed in Beacon dolerites are wholly consistent with those identified from both the surface and interior of the rocks Adirondack and Humphrey studied in Gusev crater by the Mars Exploration Rover (MER) *Spirit* (Salvatore et al., 2013). Both of these basaltic clasts exhibit significant increases in Na^+ and K^+ at their surfaces relative to their interiors with no corresponding enrichment in SiO_2. These observations are inconsistent with aqueous alteration, whether at near-neutral or acidic conditions. Instead, the data are most consistent with anhydrous oxidative weathering being the dominant alteration process influencing these surfaces.

MER *opportunity* also identified surface alteration products that were consistent with anhydrous oxidative weathering in the sedimentary environment of Meridiani Planum (Cannon et al., 2015), indicating that the landscape in Meridiani Planum is sufficiently stable to create and preserve oxidation rinds. However, definitive evidence to suggest that oxidative weathering is the primary surface alteration process in Gale crater does not exist based on analyses by the Mars Science Laboratory *Curiosity* rover (Salvatore et al., 2019). The discrepancy between Meridiani Planum and Gale crater may result from differences in long-term erosion rates (Golombek and Bridges, 2000; Golombek et al., 2014; Farley et al., 2014), which may be due to a plethora of potential geologic processes that include enhanced aeolian abrasion in Gale crater (due to local topography), differences in rock strength, composition, and/or burial and exhumation histories to name a few.

Despite the influence of physical erosion on the preservation of anhydrous oxidative weathering processes, spectral signatures consistent with anhydrous oxidative weathering are also apparent in orbital data at both the regional and global scales. For instance, Acidalia Planitia in the Martian northern lowlands exhibits both a blue slope at VNIR wavelengths as well as a narrowing of the Reststrahlen features at MIR wavelengths (Salvatore et al., 2014). Many investigators have variably interpreted these MIR emission signatures as the result of compositions more enriched in andesite (Bandfield et al., 2000), smectites (Wyatt and McSween, 2002), or weathered glass (Horgan and Bell, 2012). However, the spectra associated with anhydrous oxidative weathering is the only hypothesized process that is consistent with both the observed MIR and VNIR signatures.

The preservation of anhydrous oxidative weathering signatures on the surface of Mars has several implications for Martian surface conditions as well as our ability to investigate the Martian surface from orbit. Outside of the Stable Upland Zone in the MDV, oxidative weathering can be readily overshadowed by more intense chemical alteration processes because of the availability of liquid water over significant portions of the austral summer. For example, ephemeral glacial melt streams in the Coastal Thaw Zone can result in more mature chemical alteration products and the destruction of oxidative weathering signatures (Marchant and Head, 2007). Therefore the presence of oxidative weathering signatures across the Martian surface that are consistent with anhydrous processes provides a qualitative insight into the maximum temperature and water availability on Mars over the time period that these products formed. In addition, anhydrous oxidative weathering products in Beacon Valley exhibit significant spectral differences relative to their unaltered interiors, yet the chemical effects of these processes are relatively small and the mineralogical effects are virtually nonexistent. For these reasons, sampling rock interiors on Mars through grinding or drilling is a critically important capability. In addition, identifying analytical capabilities that are able to differentiate between different modes of surface alteration can help to constrain the environmental history of Mars.

3.2 Enigma 2: surface and subsurface hydrology in cold deserts

Despite mean annual air temperatures well below 0° C, the MDV have been shaped by a range of hydrological processes at both the surface and in the subsurface. Determining how these hydrological systems interact, their drivers, and how they shape the biological and geochemical features of the MDV have progressed as different geochemical, geophysical, and remote sensing tools have been brought to bear to address the following questions: (1) *Where does liquid water in the MDV come from—what are its sources and sinks?* (2) *What is the hydro-period of MDV hydrological activity—when is it active, for how long, and how do salts moderate this period of activity?* (3) *Is the MDV hydrological system vertically integrated or horizontally stratified (Head and Marchant, 2014)—can water move across the base of the permafrost?*

The dominant paradigm for understanding hydrological activity in the MDV focuses on the major water sources, transport paths, and sinks operating primarily in the Coastal Thaw Zone. In this model, summer glacier melt is the dominant runoff source; it flows through seasonally active stream channels and ultimately arrives at perennially ice-covered lakes (Fig. 11.10) (Chinn, 1981, 1993). These lakes are perennially ice-covered but do form open "moats" around the margins during summer months. Soil–water interactions in this model are minimal. Meltwater interacts with soils only in the hyporheic

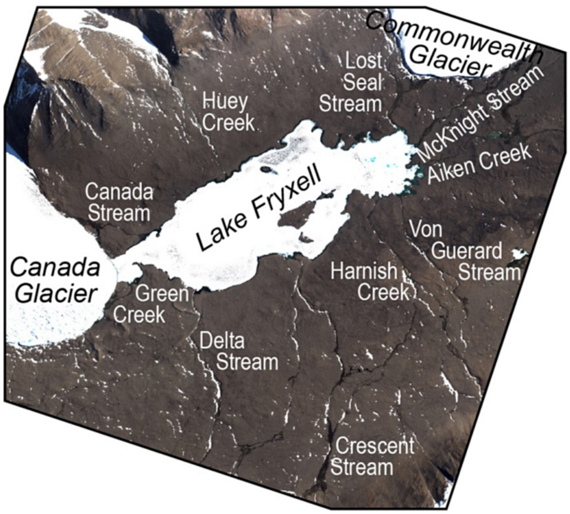

FIGURE 11.10 A map of ephemeral stream channels in the Fryxell basin of Taylor Valley. The Fryxell basin is one of the most hydrologically active areas of the MDV.

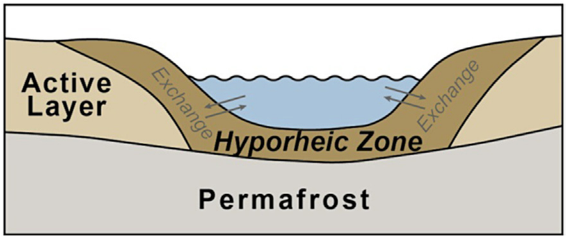

FIGURE 11.11 An illustration of the hyporheic zone of Antarctic streams. Chemical weathering of rocks and soils occurs as water migrates from the channel into the hyporheic zone, where it can then reenter the channel and transport weathered materials downstream.

zones of streams (Fig. 11.11), where water enters thawed stream banks, weathers stream bank soils, and returns to the stream channel (McKnight et al., 1999; Gooseff et al., 2002, 2003).

For several weeks each year, surface temperatures increase to near-freezing temperatures while perpetual sunlit conditions lead to the melting of glacier surfaces. This supraglacial meltwater flows downhill and cascades off of the glacier, where it first saturates the loosely consolidated soils before transitioning to overland flow. Stream channels develop along the valley walls and along the floor through the repeated melting of glaciers, saturating of the soils, and overland flow along the top of the shallow and impenetrable permafrost layer. They vary from less than 1 km to several kilometers in length. All major streams debouche into the margins of one of the perennially frozen lakes along the valley floors. All of the major MDV lakes lack outlets to the ocean and instead serve as closed basin lakes, the inputs of which are balanced by a combination of surface evaporation, freezing, and ablation, and shallow groundwater losses. Toward the end of the melt season as melting begins to wane, water is primarily lost either through freezing or evaporation, as penetration deeper into the subsurface is prevented by the shallow impermeable permafrost.

Under this Glaciers–Streams–Lakes paradigm, surface-water hydrological features are controlled largely by the interplay between geological legacies, climate history, and modern climate processes (Lyons et al., 2000). The solutes in the lakes may owe a legacy to the Pleistocene-aged paleolakes that occupied the valley. High salinity pools at the bottom of MDV lakes may represent evaporitic drawdown events from early Holocene high stands (Lyons et al., 2000). Modern lake locations are controlled in large part by the location of bedrock ridges and sills that resulted from interactions between bedrock hardness and glacial overprinting by the EAIS when it overtook the MDV from the west. Lake location is also dependent on modern glacier position and flow rate; lakes Hoare and Fryxell in Taylor Valley would merge if not for the dam provided by the intervening Canada Glacier. The modern large MDV lakes like Fryxell, Hoare, Bonney, and Vanda are almost entirely fed by glacial runoff minus evaporative losses from transport downstream and infiltration into stream channels, which can surpass available runoff in some streams during some years (Gooseff et al., 2016). Melt generation on MDV glaciers is controlled by a combination of sensible heat (Doran et al., 2008), variable insolation (Conovitz et al., 1998), and englacial "greenhouse" warming that traps the incoming shortwave (Hoffman et al., 2014). Microclimate factors, including temperature, insolation, and wind intensity and direction, control both the inputs to the lakes (in the form of glacial melt) and lake losses (in the form of evaporation of open water and sublimation of overlying ice), which cause lake levels to be extremely sensitive to climatic processes in the MDV. As a consequence, it is intriguing that lake levels have been persistently rising in the MDV since the early 1900s (Bomblies et al., 2001), a trend that has accelerated since 2002 (Gooseff et al., 2017).

While the Glaciers–Streams–Lakes paradigm largely explains the basin-scale hydrology of the MDV, it neglects the smaller hydrological systems that operate at the hillslope scale in soils and interfluves. These smaller hydrologic processes likely play important roles in solute cycling and water budgets for smaller ponds and watersheds. Early workers in the MDV noticed the widespread distribution of wetted soils, marshy wetlands, and other groundwater features present between the ground surface and the top of the permafrost (the seasonally thawed active layer) (Cartwright and Harris, 1981). Today, these small-scale soil moisture features are recognized as "water tracks," comparable to headwater channels in arctic and alpine catchments (Fig. 11.12) (Levy et al., 2011). Water tracks route snowmelt, ground ice melt, and deliquescent salt brines downslope, where they are transported over the ice table and discharged as "seeps" (Harris et al., 2007). These seeps intersect the ground surface at breaks in slope or where melt generation exceeds soil infiltration capacity, resulting in solute-rich springs. These water tracks can vary from brief, ephemeral, seasonal melt streams resulting from the localized melting of windblown snow (Langford et al., 2015) or as formidable landscape features that occupy eroded ice table channels, stretching for kilometers and persisting over decades or longer (Levy et al., 2013).

Cartwright and Harris (1981) recognized and described how the hydrology of the MDV operates at a range of magnitudes and scales. They estimated the largest flux of water into/out of the MDV come from atmospheric processes: the deposition of snow, its sublimation, and, in some cases, its melting and evaporation, constituting a large flux of ~10^9 m^3/year. They suggested that perennial glacier-fed streams, representing the dominant element of the Glaciers–Streams–Lakes paradigm, are the next largest, transporting ~10^7 m^3/year. Groundwater, including water tracks, was believed to be volumetrically insignificant, involving only ~10^5 m^3/year. This wide range in fluxes suggests that the impact of hydrological activity in the MDV on landscape evolution and biological processes could be understood on the basis of

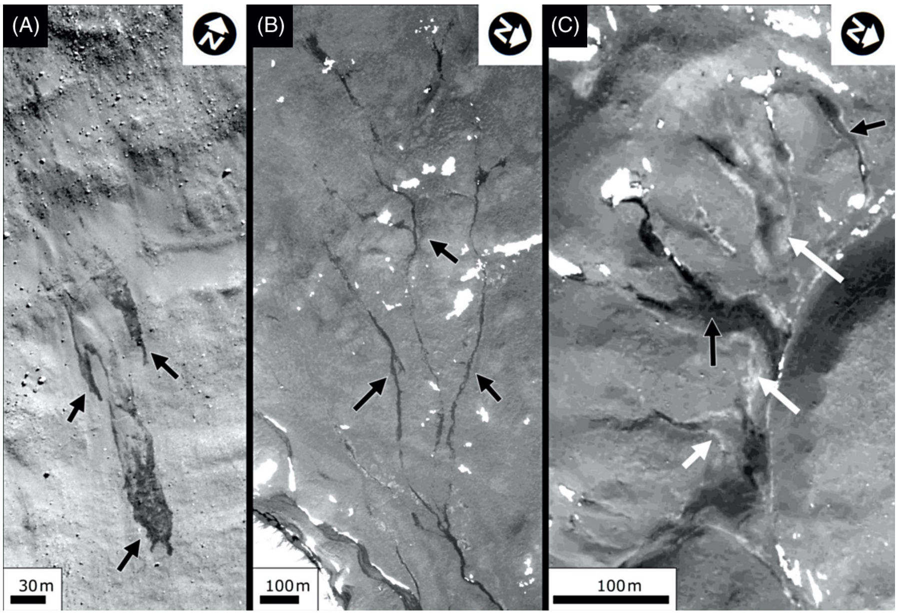

FIGURE 11.12 Examples of water tracks from (A) the Lake Bonney basin, (B) the Lake Fryxell basin, and (C) the Explorer's Cover region of eastern Taylor Valley. Digitate and dendritic water tracks are marked with *black arrows*. *White arrows* indicate bright salt efflorescences, fringing the edges and termination points of water tracks. *Data courtesy DigitalGlobe, Inc., and provided by the Polar Geospatial Center (PGC).*

the how much water moved through hydrological systems (magnitude of discharge) coupled with the persistence of these water sources on the landscape. This pairing of hydrological magnitude and persistence constitutes a complement to the Glaciers–Streams–Lakes paradigm: the hydrological continuum model (Levy, 2015). Three major classes of hydrological landform were considered in this model: (1) perennial glacier-fed streams, (2) water tracks, and (3) gullies. Gullies are an intermediate landform that incises steep hillslopes in the MDV. They are not necessarily perennial and are typically snow-fed rather than glacier-fed (Dickson et al., 2019).

These hydrological landforms vary widely in terms of their discharge and landscape impact, as measured by incision rate. MDV streams typically have mean discharges of 10s–100s of L/s, while gullies peak at 20 L/s based on channel geometry (Levy, 2015). Gullies are difficult to gage because of their small size, episodicity, and wide range of measured discharge that can span orders of magnitude. Water tracks have the smallest discharge of any water flowpath in the MDV, typically 5–100 mL/s. The nature of erosion caused by overland flow in these systems also varies between the three landforms. Levy (2015) estimated rates of erosion based on channel incision through paleolake delta deposits or tills that had been radiocarbon dated. Even though their discharge is roughly comparable, MDV streams are much more erosive than gullies, downcutting 10^{-4} m/year on average for streams versus 10^{-6} m/year for gullies (Levy, 2015). Water track discharge is too small to move sand-sized particles, although silt and clay can move through water tracks along with high solute loads (total dissolved solids load for MDV streams is 10^1–10^2 mg/L, while water tracks span 10^2–10^5 mg/L, Levy et al., 2011).

What causes this difference in landscape impact between these different hydrological features? Stream erosion may be two orders of magnitude higher than gully erosion because incision depends not just on mean discharge, but on the intensity and duration of peak-discharge events. Glacier-fed streams can have more high-discharge events under the same insolation forcing because they accumulate runoff from broad expanses of melting alpine glacier surfaces (Fountain et al., 1999; Hoffman et al., 2008); 1 mm of surface melt from across the full drainage surface of a large alpine glacier toe greatly exceeds 1 mm of surface melt from a group of scattered snowbanks. Water track flow is even more regulated than stream or gully flow, being limited by the infiltration capacity of the soil and its hydraulic conductivity (Schmidt and Levy, 2017). Despite the potential for much more rapid incision by glacier-fed streams, even they are limited by their persistence of their glacial melt sources. Changes to glacier shape or drainage patterns can result in the abandoning of once active channels. As a result, only ~50% of Dry Valleys stream channels are currently occupied by active streams (McKnight et al., 1999). Therefore, even at its most active, the MDV near-surface hydrological system is both spatially and temporally constrained.

This hydrological gradient plays a role in shaping the depositional behavior of fluvial systems in the MDV at their sink, controlling the distribution of sedimentary landforms that can be used to infer past changes to hydrological activity. There is a strong relationship between water discharge and sediment deposition patterns. Large glacier runoff fluxes typically exceed in-stream evaporation rates and infiltration rates, whereas comparatively small snowbank runoff fluxes in gullies do not (Gooseff et al., 2016; Dickson et al., 2019). This is the guiding reason why glacial streams discharge in ponds—they serve as reservoirs for excess runoff—and produce deltaic deposits comparable to those generated in paleolakes earlier in the history of the MDV. In contrast, gullies lose their water to infiltration and evaporation, causing them to terminate subaerially as alluvial fans (Dickson et al., 2019). Water tracks, when inactive, can only be identified on the basis of subtle topographic dips in the ice table and ground surface and by the presence of digitate salt efflorescences marking their evaporative boundaries (Levy et al., 2013).

The widespread role of salts in MDV hydrological systems has led to the development of a third major paradigm for understanding water-related processes operating at or near-freezing temperatures: a freshwater/saltwater paradigm. This approach to understanding hydrological activity connects surface and near-surface waters more directly with the atmosphere and subsurface. Cartwright and Harris (1981) recognized that saline groundwater discharges in a handful of locations in the MDV, most notably at Don Juan Pond (DJP) where a saturated $CaCl_2$ brine forms the saltiest natural body of water on Earth (Fig. 11.13A) (Meyer et al., 1962). A groundwater source for DJP brines was inferred on the basis of artesian discharge from a borehole drilled through the permafrost and into the flanks of DJP basin by the Dry Valley Drilling Project (Talalay and Pyne, 2017). However, the origin of the concentrated $CaCl_2$-rich brines in DJP is controversial. Based on time-lapse imaging of surface water and water track flows, Dickson et al. (2013) concluded that water levels in DJP are largely controlled by the influx of surface water. Alternatively, using geochemical modeling, Toner et al. (2017) concluded that DJP is a localized upwelling site for a regional groundwater flow-through system in which evaporatively enriched brines in DJP are recycled back into the subsurface. In order to balance evaporation in either case, DJP needs to discharge ~30 m^3/day on average (Harris and Cartwright, 1981), resulting in a large, $CaCl_2$-dominated salt pan.

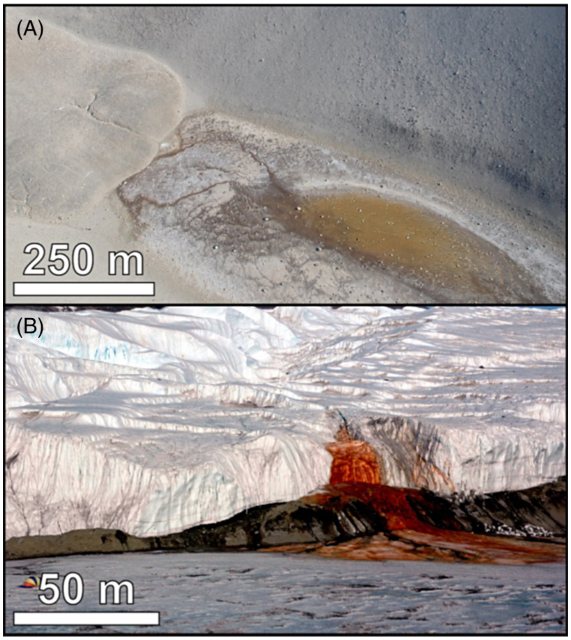

FIGURE 11.13 (A) An aerial image of Don Juan Pond in Wright Valley. (B) Blood Falls emanating from Taylor Glacier in Taylor Valley. *Photo courtesy (A) MRS and (B) Wiki Commons.*

In contrast to the chloride-dominated DJP, sub-glacial and sub-permafrost discharge is observed in neighboring Taylor Valley at a location known as "Blood Falls," where iron, sulfate, and silica-rich groundwater discharges from beneath Taylor Glacier (Fig. 13B) (Mikucki et al., 2004, 2015; Toner et al., 2013). Blood Falls is so named because the abundance of oxidized iron results in a unique bright red color. Discharge from Blood Falls is inferred to be microbially modified seawater trapped beneath Taylor Glacier during fjord conditions that occurred during past interglacials, and which discharges in response to pressurization by the overlying glacier (Badgeley et al., 2017). Discharge volumes from Blood Falls are smaller than from DJP, although Blood Falls remains ungaged owing to the microbial sensitivity of the site.

While both Blood Falls and DJP produce easily observable groundwater discharge at the surface, it is only recently that the potential of these systems to be connected to more widespread sub-permafrost hydrological systems has been recognized. The high salinity of DJP solutions means it has a eutectic freezing temperature below −50° C, preventing DJP from freezing under modern conditions in Wright Valley, even during the winter months. Icings have been detected on the pond during summer when freshwater floats form from gully runoff into the margin of the pond, but these are not brine freezing events (Dickson et al., 2013). High salinity groundwater systems may persist beneath and within MDV permafrost. Recent airborne transient electromagnetic induction surveys of the MDV have revealed zones of low subsurface resistivity beneath Taylor Valley, including in the Blood Falls region (Mikucki et al., 2015). Researchers interpret these observations to indicate that a liquid with sufficiently high salinity to resist freezing exists in pore spaces within the permafrost. The inferred brines are widespread within permafrost and extend below Taylor Valley glaciers and lakes.

Persistent unfrozen brines are also present at the soil surface across the MDV, though at a smaller spatial scale than those generated by deep groundwater brines. Isolated saline soil “wet patches” (Levy et al., 2012) dot the surface across Taylor and neighboring valleys, producing isolated soil moisture anomalies (~3% by mass vs. <1% by mass for typical MDV soils) composed of highly concentrated saline solutions (total dissolved solids >500 g/L). These chloride-dominated brine pockets have low water activities, allowing atmospheric water vapor to deposit directly into the brine through deliquescence and growing the solution volume. The origin of wet patches remains unknown; however, they share similarities with both water track composition as well as brines that form along the fringe of DJP. These marginal DJP brines are formed when crystalline $CaCl_2 \cdot 6H_2O$ (Antarcticite) deliquesces under high humidity conditions, forming episodic brine sheets along the lake margin. Similar salt compositions between wet patches, water tracks, and salinas suggest that wet patches may be remnant water track–fed ponds or evaporative remnants of pond margins. The longevity of these soil brines in response to evaporation and/or freezing is unknown. However, their ionic strength is comparable to that of DJP, suggesting that they may persist as pockets of surface moisture even during Antarctic winter.

Together, these large and small surface and subsurface brine systems constitute a saltwater hydrological system operating in the MDV that integrates both atmospheric and deep groundwater moisture sources. In contrast, the surface waters in the MDV are overwhelmingly fresh and are derived almost exclusively from glacier and snowmelt, carrying only a small load of marine-derived salts and glaciogenic calcite (Green et al., 1988; Nezat et al., 2001). The different salinities of these two systems result in markedly different hydrological behavior. The surface freshwater system is largely horizontally stratified (Head and Marchant, 2014)—it provides connectivity across the landscape from glaciers, to streams, to lakes, and through water tracks, as it integrates hillslope watersheds into lake and stream processes (Gooseff et al., 2011; Wlostowski et al., 2016). However, the freshwater system operates exclusively during summer months, and from the ground surface to the base of the active layer. This limits its longevity as well as its ability to provide water to biogeochemical reactions in the soil and rock. In contrast, the saltwater system at work in the MDV is solute-rich, resists freezing, and, as a consequence, is vertically integrated (Head and Marchant, 2014). Flow of brines can occur through permafrost and glacial barriers, providing a long-lived and potentially habitable environment in which water and solutes are present. The high salinities of these systems may limit the extent to which weathering reactions occur (i.e., they are in many cases saturated) and may have water activities too low to support microbial metabolisms (Beaty et al., 2006). However, they represent a potentially long-lived model for vertically integrated hydrological activity under cold climate conditions that resist freezing and evaporation, and that can provide connectivity from the atmosphere, through the soil, to the subsurface.

The development and evolution of streams and lakes throughout the MDV where mean annual temperatures are well below freezing suggest that local climatic optima may be an important driver in Martian hydrology. Such local and short-lived climatic drivers support the prediction that Martian surface hydrology experienced punctuated and spatially localized activity (Andrews-Hanna and Lewis, 2011). Such relationships between local climatic optima and hydrological activity have significant influences on the distribution, activity, and magnitude of fluvial and lacustrine processes in the MDV (Fig. 11.14). For example, direct precipitation-fed hydrologic systems require immediate communication between the environment and fluvial and lacustrine activity. Such a scenario would mean that near- or above-freezing temperatures would need to be present at the surface in order to produce the observed flow and ponding of water. Alternatively, stores of frozen water can be deposited as snow and ice and preserved at the surface at temperatures well below the freezing point of water. These stores can remain indefinitely until climatic conditions lead to their melting and the generation of fluvial and lacustrine activity at the surface. Such storage and subsequent melting during climatic optima define the hydrologic cycle of the MDV, where seasonal melting of large stores of ice drive the fluvial activity discussed previously. This model may also be relevant to a "cold and icy" early Mars climate scenario (Head and Marchant, 2014), which may alleviate the need for long durations of warm and wet conditions at the Martian surface during the Noachian epoch. Large stores of ice can also serve to impound water into long-lived yet temporary lakes. Such processes have been shown to play important roles in both the modern and legacy hydrology of the MDV (Doran et al., 1994) and have been predicted to occur on Mars as well (Burr, 2010).

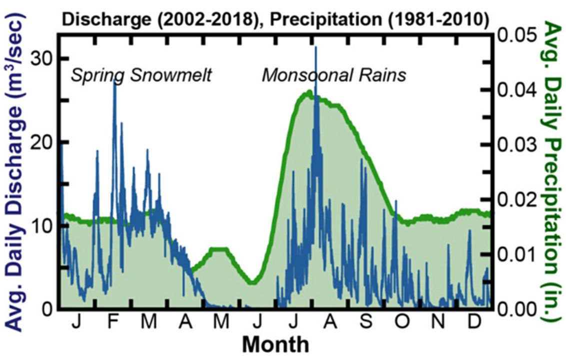

FIGURE 11.14 Hydrograph (*blue*) and climatological (*green*) data from the Little Colorado River near Winslow, AZ. Direct precipitation-fed discharge can be seen during the summer months associated with monsoonal rainfall. During the winter months, equally intense discharge is observed with relatively little consistent precipitation, as the majority of this flow is due to snowmelt from further upstream. This illustrates how fluvial activity can be related to both direct atmospheric inputs as well as long-term water storage as past frozen precipitation. *Stream gage data courtesy the USGS and climatological data courtesy the NWS.*

This temporally discontinuous hydrological model not only influences the mobility of liquid water across the surface but also significantly influences the local geology. Large stores of water (e.g., lakes, seas) grow and shrink as the balance between their inputs (i.e., groundwater, surface flow) and outputs (i.e., evaporation, discharge as impoundments are removed) change. In addition to the obvious influences related to fluvial incision or abandonment, geochemical legacies of these ancient hydrological processes can be preserved across the landscape as well. For example, the biogeochemical legacies of ancient lacustrine systems are still preserved in the MDV tens of thousands of years after lake level modification (Doran et al., 1998; Barrett et al., 2010). Where solutes are particularly concentrated in the geologic system (e.g., regions of continuous groundwater upwelling or multiple episodes of lake refill and evaporation), thick accumulations of salts and other evaporites can develop. We see these types of deposits in the MDV in places like DJP, as well as on the Martian surface as chloride deposits in topographic lows, interpreted as possible salinas (Osterloo et al., 2008).

Gullies in Antarctica have been observed to form primarily through the melting of snowpacks present in their alcoves (Fig. 11.15)

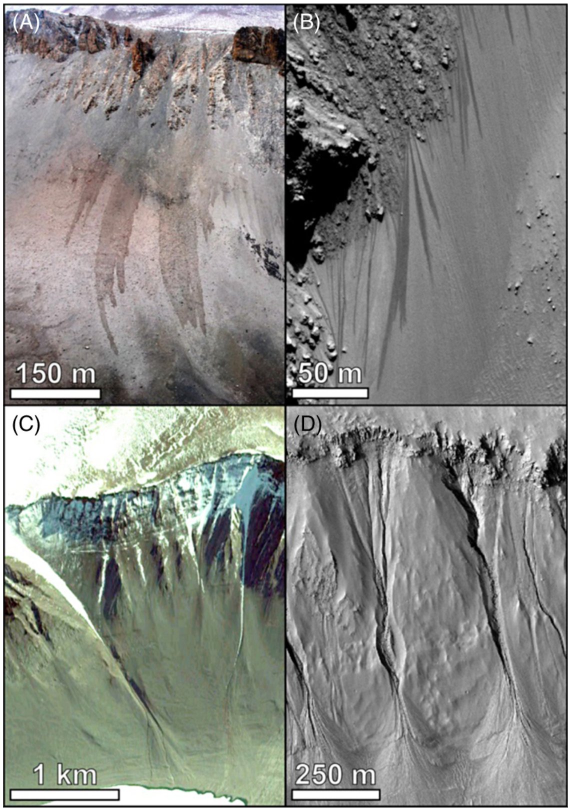

FIGURE 11.15 Water tracks (A) and recurring slope lineae (B) in Wright Valley, Antarctica, and on Mars, respectively. Gullies along steep valley and crater slopes in Wright Valley, Antarctica (C), and on Mars (D), respectively. *(A) Courtesy MRS, (B) is HiRISE image ESP_022256_1475, (C) Google Earth, (D) is HiRISE image ESP_011727_1490.*

(Dickson et al., 2019). While more recent investigations have favored water-free mechanisms to explain the observed modern changes in gully morphology on Mars (Dundas et al., 2019), their global distribution and strong regional and local preferences that optimize microclimatic conditions may still indicate a hydrological origin for these features (Dickson and Head, 2009). Similarly, RSL were originally thought to indicate the seasonal deliquescence of liquid water along crater walls due to high concentrations of salts (Fig. 11.15) (Chevrier and Rivera-Valentin, 2012). While recent thermophysical studies have suggested that neither liquid water nor surface salts can be present in substantial quantities and still satisfy the thermal properties of the observed RSL (Edwards and Piqueux, 2016), these features are remarkably similar in appearance to water tracks and wet patches in the MDV (Levy et al., 2011, 2012). Levy et al. (2012) showed that wet patches contain an average gravimetric water content of ~3%, which is comparable to the soil moisture detection limit discussed by Edwards and Piqueux (2016) in reference to Martian RSL.

These comparisons are meant to highlight the plausible relationship between observed hydrological features in the MDV of Antarctic and both the ancient and modern hydrological signatures and features observed on the Martian surface. While by no means meant to serve as a unique solution to all Martian hydrologic, fluvial, and lacustrine environments, understanding the similarities and differences between the Antarctic and Martian landscapes will help to further constrain the geologic and paleoenvironmental properties of Mars throughout its history.

3.3 Enigma 3: Livin' on the edge: fueling ecosystems in cold and barren environments

Despite mean annual temperatures well below the freezing point of water, months of perpetual darkness, and a scarcity of liquid water available for biological processes, the MDV have been shown to host a diversity of cyanobacteria, mosses, algae, chemoautotrophic bacteria, lithophiles, and microscopic invertebrates, including rotifers, nematodes, and tardigrades (McKnight et al., 1999). These organisms make use of whatever source of liquid water may be available, including seasonal melting of snow and glaciers and the thawed margins of perennially frozen lakes. They have been found to develop unique characteristics that allow them to survive the harsh Antarctic conditions and to seek refuge when environmental conditions are unsustainable. These biological communities of the MDV and the conditions to which they are able to adapt help address one of the most prominent enigmas in modern Martian science: Is it possible for life as we know it to exist at or near the surface of Mars at any point in its history?

The barren, cold desert soil surfaces of Taylor Valley are emblematic of the harsh environmental conditions that dominate the MDV and reveal the mechanisms by which near-surface ecosystems function under cold, dry, salty, and irradiated climate conditions. The majority of the valley floor consists of loose sand-sized sediments or cobbles and boulders of local bedrock composition. The dominance of sand-sized sediment in most locations results from the loss of finer materials to the strong winter katabatic winds, which deflates fine-grained surfaces and deposits dust and silt into the Ross Sea. Ice-cemented permafrost is typically found at less than 1 m depth below the surface at a depth at which peak annual temperatures never exceed 0° C—dry frozen permafrost is present where diffusive loss of ground ice to the atmosphere is particularly intense, such as on valley walls (Hagedorn et al., 2007).

The glacier-fed ephemeral stream channels provide two forms of microbial habitat, supporting stream channel microbial mats and hyporheic zone communities. Streams originating near the valley bottom are dominated by sand and silt. This loosely consolidated and frequently replenished bed precludes the establishment and sustenance of mature microbial ecosystems, while boulder and cobble-floored streams with coarse sediment supplies provided by valley wall talus have stable beds on which microbial mat communities can become established (McKnight et al., 1999).

The wetted hyporheic zones surrounding these active stream channels are also areas where significant exchange of cations between the soil and the water occurs (Lyons et al., 2003). The dissolution of pre-existing salts and the chemical weathering of rocks and soils provide the nutrients necessary for microbial growth as water flows into and out of the stream bank soils during its downstream migration (through a process known as hyporheic exchange; McKnight et al., 2004).

3.3.1 *Stream ecology*

The stream channels themselves host the highest standing terrestrial biomass by area in the MDV (McKnight et al., 1999). The microbial communities present in these ephemeral streams can be broadly classified by their dominant pigment color, which also helps to predict their relative locations within the stream channels (Fig. 11.16) (Vincent et al., 1993; Alger et al., 1997; Kohler et al., 2015). The most spatially extensive microbial communities associated with ephemeral stream channels are black cyanobacteria mats dominated by the genus *Nostoc*. These black mats can be found in a variety of different morphologies, from spongy carpet-like mats to organizations of leaf-like polyps. Black mats are found almost exclusively along the wetted margins of stream channels or in shallow stagnant or slow-moving reaches and can extend for hundreds of square meters (Kohler et al., 2015). Their diagnostic black color is the result of dark sunscreen pigments that serve to protect the more sensitive photosynthetic pigments from bleaching by UV-B radiation (Alger et al., 1997). These dark pigments are what enable these communities to exist subaerially or in shallow water. Underlayers containing these darker pigments are often lighter layers that appear more green in color due to the decreased abundance of sunscreen pigments and the dominance of chlorophyll.

Orange mats dominated by genera *Oscillatoria* and *Phormidium* almost exclusively occupy deeper and faster moving waters near the channel thalweg, although they can be found along the margins of the channel where standing pools are present (Kohler et al., 2015). Orange mats contain higher proportions of carotenoid pigments

FIGURE 11.16 Photos highlighting the diversity of microbial communities present in ephemeral stream channels. (A) Subaerially exposed *black mats*. (B) Submerged *orange mats* in a channel thalweg. (C) Small tufts of *green mat* in small, deep, fast-moving pockets. Note the *green moss* along the channel margins. (D) An example of the complex assemblages possible due to channel microtopography. Visible are *black*, *orange*, and *green mats*. All scale bars represent 25 cm. *Photos courtesy MRS.*

relative to sunscreen pigments, making them naturally more susceptible to damage from UV-B radiation than *Nostoc*. Instead of these natural protective pigments, orange mats rely on the UV-absorbing properties of liquid water to minimize damage by UV-B radiation. The two dominant morphologies possessed by orange mats include thick and continuous carpet-like mats and thin, filmy, translucent coatings of pebbles and cobbles on streambeds (Kohler et al., 2015). Communities of the same or similar genera that are more pink in color, sparsely distributed, and clumpy and rubbery in nature are often referred to as red mats (Alger et al., 1997).

Green, filamentous, and "stringy" mats of the genera *Prasiola* are sparsely populated yet commonly occurring within the channel of well-established streams with high biomass. The high relative abundance of chlorophyll relative to other ancillary and sunscreen pigments means that *Prasiola* are highly susceptible to UV-B damage if and when exposed to direct sunlight. As a result, as glacial meltwater flows subside, these green filamentous streamers often settle into cracks between pebbles and rocks, which both increase the duration they are able to remain wet while simultaneously protecting them from intense insolation and aeolian abrasion or remobilization.

Lastly, red and green mosses can be found along the margins of many stream channels. These mosses are patchy in their distribution and are typically found in damp yet unsaturated portions of the stream margin (Kennedy, 1993). In some instances, moss can grow on top of black *Nostoc* mats that are more bulbous, carpet-like, and dry to damp (Schwarz et al., 1993). These moss communities act to stabilize the stream margins wherever present, as they are one of the few biological communities in the MDV with root systems. Moss also serves as an important habitat for other microorganisms, including nematodes and tardigrades (Schwarz et al., 1993).

3.3.2 Soil ecology

The soils of the MDV are a classic biogeochemical example of the rich getting richer and the poor getting poorer. Unless located along stream margins, in wet patches (Levy et al., 2012), or in water tracks (Levy et al., 2011, 2014), the vast majority of soils in the MDV never experience significant abundances of liquid water or biogeochemical cycling. As a result, biological materials are unable to accumulate in these soils as their growth cannot be supported. Oppositely, soils that are frequently saturated experience nutrient cycling driven by evaporation and capillary migration. Legacy ecological communities and microorganisms that are transported by the wind take advantage of these favorable conditions, where they can accumulate on multi-annual timescales (Barrett et al., 2010).

Nematodes sit atop the soil food web in the MDV as the dominant soil grazers, feeding on bacteria and algae that are common throughout the valleys (Takacs-Vesbach et al., 2010). Bacteria are, by far, the most abundant organisms both by mass and diversity. Other less studied members of soil communities include rotifers, tardigrades, and archaea (Courtright et al., 2001).

3.3.3 Glacier and lake margin ecology

Both cryolakes and cryoconite holes are present within the ablation zones of glaciers throughout the MDV, both of which host microorganisms and serve as local refugia within the ice (Tranter et al., 2010). Cryolakes are large pools of meltwater atop the surfaces of glaciers. They accumulate windblown materials, which darken the floor of these lakes and promote additional melting through increased absorption of insolation, resulting in a positive feedback (Bagshaw et al., 2010). Continued melting can cause the lake bottom to sink significantly into the glacier's surface, forming steep ice cliffs surrounding the cryolakes.

Cryoconite holes are small (typically less than one meter in diameter) cylindrical melt pools that grow into the surfaces of glaciers in their ablation zones (Fig. 11.17). Like cryolakes, a positive feedback process leads to the continued growth and deepening of these holes. Unlike cryolakes, however, cryoconite holes are often isolated environments that rarely interact with the atmosphere,

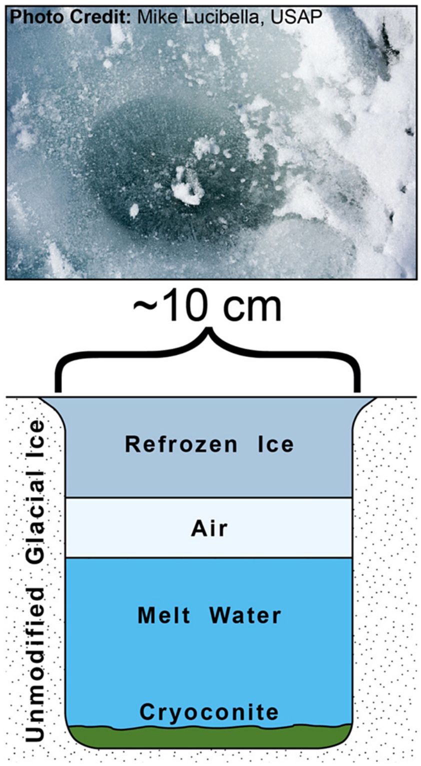

FIGURE 11.17 (Top) A photograph of a cryoconite hole on Canada Glacier, Antarctica. (Bottom) The structure of a cryoconite hole. *Adapted from Fountain et al. (2004).*

as their surfaces can often remain perennially frozen (Fountain et al., 2008). Internal melting at the cryoconite-ice contact leads to the formation of meltwater and head space (as total volume is reduced during thawing), which then refreezes during the autumn and winter months. Inorganic ion dissolution and reprecipitation are also common as water undergoes these seasonal transformations (Fountain et al., 2004).

The basal materials of both cryolakes and cryoconite holes are made of a combination of inorganic dust and sediment in addition to microorganisms, including cyanobacteria, fungi, and algae. Once seeded with the basal materials, these ecosystems are almost completely self-contained. Nutrients are provided by the inorganic materials, photosynthesis is possible through the transparent ice lids, and the generation of meltwater facilitates these biological processes (Tranter et al., 2010). Water from both cryolakes and cryoconite holes is able to drain through fractures in the glacier and reemerge atop and along the face of the glacier. Chemical evidence for both the biological and inorganic processes taking place can be identified in this meltwater through, for example, enrichments in dissolved solutes and organic carbon (Porazinska et al., 2004).

While the majority of environments in the MDV experience biological productivity that is limited by the availability of liquid water, the permanent valley bottom lakes represent one of the few environments where access to water is essentially unlimited. The subsurfaces of all perennially frozen lakes in the MDV remain unfrozen during the Antarctic winter, although Lake Vida represents an anomaly in that it is only unfrozen at the very base where a hypersaline slurry is present (Doran et al., 2003). In all lakes, only a small fraction of PAR is able to penetrate through the lake ice and into the unfrozen waters below, which puts significant limitations on the amount of photosynthesis that can occur under the lake ice (Hawes and Schwarz, 1999). Basin topography and lake bathymetry also play important roles in determining the amount of light that can reach the lake bottom. For example, Lake Bonney is narrow, deep, and steep-sided, while Lake Fryxell is broad and shallow with gently sloping walls. The diversity of illumination conditions, bathymetry, and water chemistry lead to a diversity of biological communities as well, ranging from oxygenic and anoxygenic photosynthesis to archaea (Wharton et al., 1983). Variations in each of these important properties can lead to unique ecosystems that are well adapted to the specific environmental conditions.

3.3.4 *Adaptation to harsh environmental conditions*

The MDV represent an unusual ecological landscape that is limited in many dimensions that are critical for life. They are hyper-arid, hypo-thermal, high-salinity, and strongly irradiated by ultraviolet light. Few other terrestrial ecosystems are faced with the same number and magnitude of challenges as those presented in the MDV. Two primary modes of adaptation are required for ecosystems to persist in such a harsh environment. The first is through the development of physiological, chemical, and biological adaptations to combat specific unfavorable conditions. In nearly all instances, biology is limited by at least one of the several environmental factors described previously. The second mode of adaptation is the ability to suspend all metabolic functions in the face of truly inhospitable conditions, followed by the ability to rapidly "awaken" and efficiently take advantage of favorable environmental conditions once they are available. This suite of environmental adaptations provides exciting clues into how extraterrestrial ecosystems may adapt to conditions that are unfavorable for life as we know it.

For simplicity, the harsh environmental conditions present in the MDV can be broken into five primary categories. First, air temperatures in the MDV rarely exceed the freezing point of water. Second, while liquid water is largely absent from the landscape, brief and spatially localized deluges are possible as a result of the melting of glaciers and snowpacks. Third, geochemical cycling and the mobility of critical bioavailable nutrients are both (1) severely limited by the relative absence of liquid water, yet (2) quickly removed before they can be locally utilized during these punctuated deluges. Fourth, sunlight for photosynthesis is seasonally controlled and, when present, relatively low in the sky. Lastly, when sunlight is present, potentially lethal UV-B fluxes are present due to polar depletions of stratospheric ozone. While it may be possible to readily adapt to some of these harsh environmental conditions elsewhere across the planet, the MDV represent one of the few locations where ecosystems must adapt to all five conditions in order to persist and grow.

Even during the warmest summer months, environmental conditions that fuel ecosystems can be fleeting. For example, cloud-free conditions and calm winds can result in significant glacial melt, runoff, and stream activity. This activity can fuel microbial mat communities while the clear conditions can promote rapid photosynthesis. Within minutes, however, cloudy conditions can cause air temperatures to decrease, which can retard glacial melting and cause surface waters to freeze. The cloudy conditions also cause a significant reduction in PAR. In order to survive these severe and rapid environmental swings, especially during the season where environmental conditions that promote ecosystem growth should be the norm, these communities must develop effective adaptation strategies.

As mentioned previously, microorganisms in the MDV have developed effective means of minimizing exposure to and damage from increased UV-B fluxes. Mobile microorganisms, including nematodes and tardigrades, can migrate below the surface to reduce exposure. Microbial mat communities have adapted through preferential habitation; mats containing an abundance of sunscreen pigments can more readily survive in shallow water or along the wetted margins of stream channels. Mats without sunscreen pigments, however, must occupy deeper waters where the water itself provides shielding from UV-B radiation.

In the hyper-stable landscapes of the MDV, the migration of nutrients and ions is driven by the migration of liquid water through soils along the margins of stream channels and lakes or downward through the soil during episodic, ephemeral snowmelt events. Barrett et al. (2009) demonstrated that microbial activity correlates with these marginal biogeochemical processes. Not only does this biogeochemical cycling provide the nutrients necessary to support active microbial processes, but it also determines the distribution of legacy carbon throughout the landscape, which determines where ecosystems have flourished in the past and where they may potentially flourish in the future.

While radiation fluxes and nutrient cycling are important biological and ecological considerations, they are secondary to the primary limitations caused by long stretches of cold, dry, and dark conditions. To combat these hardships, the primary mode of adaptation that is adopted by many of the ecological communities present in the MDV is cryptobiosis, where metabolic processes temporarily cease when faced with unfavorable environmental conditions. Nematodes and other microscopic invertebrates present in the soils of the MDV undergo anhydrobiosis, where more than 95% of their body water is lost and all metabolic activity ceases in the face of hyper-arid and hypo-thermal conditions (Treonis et al., 2000). These organisms are then able to rehydrate and emerge from this anhydrobiotic state within just a few hours (Womersley et al., 1998; Treonis et al., 2000). Similarly, microbial mats will desiccate and enter a freeze-dried state when exposed to inhospitable conditions, allowing them to persist over long durations without undergoing photosynthesis. These freeze-dried mats can either remain in place, which results in relatively high standing biomass within stream channels and along lake margins where perennially hospitable conditions may be found, or they can be remobilized by strong winds, continuing their migration until they find a new favorable location to inhabit. Both field observations and experimental data suggest that these microbial mats are able to reanimate and begin photosynthesizing within tens of minutes after exposure to liquid water, even after decades of inactivity (Fig. 11.18) (Vincent and Howard-Williams, 1986; Hawes et al., 1992; McKnight et al., 1999, 2007). Where microbial communities are encased in glacial ice or permafrost, viable microbial cells can persist and emerge as culturable populations over considerably longer timescales, potentially spanning 10^5–10^7 years (Gilichinsky et al., 2007; Bindle et al., 2007). It is entirely possible that we have not yet identified the oldest viable microbial cells, suggesting that microbes are able to essentially survive indefinitely under stable MDV-like environmental conditions.

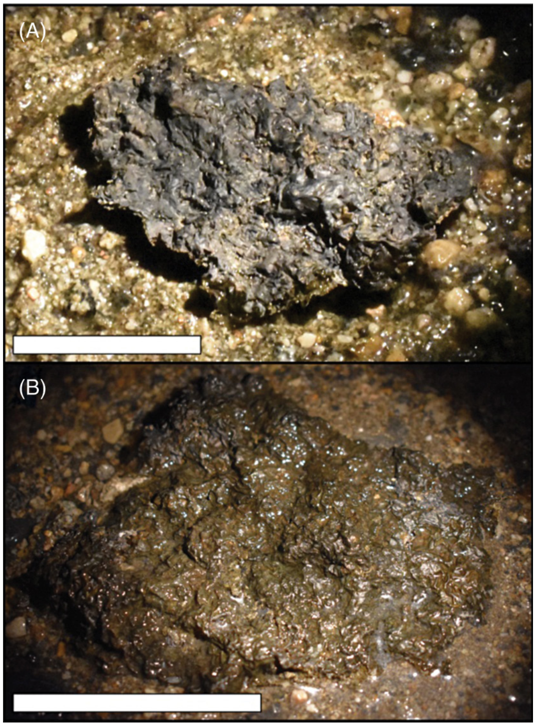

FIGURE 11.18 Experimental rewetting of a desiccated section of *black microbial mat* from Crescent Stream, Taylor Valley. (A) The desiccated *black mat* showing a matte appearance and brittle texture. (B) The rewetted *black mat*, which turns slimy and flexible shortly after rewetting. Scale bars represent 1 cm. *Photos courtesy MRS.*

The adaptations that keep Antarctic ecosystems alive through long expanses of unfavorable environmental conditions provide an interesting look into possible adaptations that might be employed by potential Martian organisms, should ecosystems have ever formed and been preserved or persist in isolated refugia. Despite all evidence to suggest that ancient Mars was likely wetter, potentially warmer, and certainly more geologically active than it is today, the Martian surface might still present habitable environments where Martian ecological communities can survive and bide their time until conditions become optimal. Whereas habitable conditions dominate the vast majority of terrestrial landscapes, Antarctic ecosystems must take advantage of local climate optima to emerge from refugia, reactivate, and to grow. Antarctica, therefore, has demonstrated how persistently unfavorable average conditions are just one aspect of a complex ecological picture. Instead, more hostile conditions simply mean that habitable environments shrink in extent and duration. These adaptations that prolong survivability under hostile environmental conditions, therefore, are critical under such extreme environmental conditions.

One important consideration in the distribution of life throughout the MDV is the presence and abundance of “legacy” organic and inorganic components. Over time, portions of the landscape have accumulated biogeochemically important ions, nutrients, and organic carbon as a result of lake level expansion or locally fueled microhabitats that have since become inhospitable. This biogeochemical legacy present within the soils allows for the future identification of past habitable environments and an understanding of their key ecosystem characteristics.

They also provide important seed materials for the generation of modern ecosystems and play an important role in their distribution throughout the present-day landscape. Biogeochemical legacies on Mars might be observed in the modern geologic record, preserving the signatures of ancient ecosystems that were once present but have since succumbed to the modern inhospitable surface and near-surface environment.

This ability for microbial communities in the MDV to remain in a desiccated state for decades before reanimating and photosynthesizing within an hour demonstrates the versatility necessary to survive under such harsh conditions. On Mars, it is quite possible that habitable environmental conditions might not persist for tens of thousands of years or more before briefly becoming available for the blink of a geologic eye. As we see in the MDV, any organisms waiting for such conditions to arise must be able to take advantage of these short climatic and environmental excursions when they do present themselves.

For example, imagine a scenario where warmer and wetter conditions dominated the earliest history of Mars, creating habitable environmental conditions that led to the formation of microbial ecosystems at or near the Martian surface. Environmental transitions during this earliest phase of Martian geologic history, driven by widespread volcanism, meteorite impacts, and the slow yet unrelenting trend toward colder, drier, and more acidic surface conditions, would have led to the evolution of ecosystems that are capable of surviving rapid and harsh transitions. Eventually, as liquid water becomes essentially absent from the surface, these ecosystems enter a cryptobiotic state where they lie in waiting for the next excursion into habitable environmental conditions. Eventually, conditions may become locally favorable for the production of liquid water, at least for enough time to perform some minimal amount of geologic work. Such conditions may be brought on by the same geologic events that were widespread early in Martian history—volcanism, impact cratering, etc. Even though global conditions may still be largely inhospitable, a combination of latitude, topography, surface composition, the presence of subsurface ice, or any other surface property may lead to local conditions that are favorable for water to exist. If so, and if cryptobiotic microbiota have been waiting for such favorable conditions to arise, it is possible that the surface of Mars could quickly host microbial life.

4 Discussion

The MDV serve as a valuable analog to several important processes that were, are, and/or might be relevant to the Martian surface. As discussed previously, this analog environment has provided clear insight into how geochemical alteration, hydrological systems, and ecological communities can develop in extremely cold environments where liquid water is both spatially and temporally limited. While critically valuable, this analog is also limited in that warmer and wetter conditions have not been present in the geologically recent past. As a result, we must turn to other environmental analogs for comparison and contrast.

For example, the warmer and wetter environments recorded in both the Atacama Desert of northern Chile (*see* Chapter 12: The Atacama Desert: A Window into Late Mars Surface Habitability?) and in the rocks of the Pilbara Craton in Western Australia (*see* Chapter 13: Life analog sites for Mars from early Earth: Diverse habitats from the Pilbara Craton and Mount Bruce Supergroup, Western Australia) provide unique insight into the adaptability and preservation of life under significantly different environmental conditions. The Atacama Desert and its current environmental gradients can help to better understand the controls on the distribution and activity of ecological communities, shedding important light on surface and near-surface habitability during the global environmental transitions that occurred early in Mars' history (Fletcher et al., 2012; Wilhelm et al., 2018). Australia's Pilbara region contains a wide variety of ancient habitats preserved in a combination of sedimentary and volcanic ash deposits, helping to decipher the biopreservation potential of several Mars-relevant lithologies (Noffke et al., 2013; West et al., 2010). Both of these analog sites provide interesting glimpses into ancient Martian habitability and the preservation of biological signatures, while the MDV help to understand the colder/drier range of environmental, geological, and ecological conditions that may have been present on Mars throughout much of its geologic history. Each of these analog environments, in addition to the countless additional environments that provide their own unique views of Mars-relevant surface conditions, serve important roles in shaping our understanding of terrestrial planets and their habitability.

5 Summary and conclusions

The MDV of Antarctica are a uniquely cold, dry, geologically stable, and environmentally harsh setting on Earth that can shed important light on Martian surface processes. We have specifically highlighted and discussed how the MDV are unique in terms of their geology, hydrology, climatology, and ecology. As a potential analog to both a "cold and icy" early Mars climate scenario and the more modern Martian environment, the MDV serve as an important setting for continued comparative planetology. In particular, as the emphasis of Martian surface investigations moves toward the search for habitable environments and ancient/modern life, the ecology of the MDV and its geologic and environmental drivers becomes all the more scientifically relevant and important. As such, the MDV have and will continue to play an important role in addressing some of the most enigmatic questions remaining in Martian science.

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MARS GEOLOGICAL ENIGMAS

From the Late Noachian Epoch to the Present Day

Edited by Richard Soare, Susan Conway, Jean-Pierre Williams, & Dorothy Oehler

Key Features

- Presents a transchronological perspective on disparate and long-standing geological/geomorphological Martian enigmas
- Comprises thematic nodes that compare and contrast these enigmas from multiple points of view
- Identifies questions and queries that remain outstanding

Mars Geological Enigmas: From the Late Noachian Epoch to the Present Day focuses on many of the outstanding geological/geomorphological questions left unanswered by years if not decades of thoughtful inquiry about the Red Planet. The result is a robust, multi-angled and comprehensive discussion that reaches beyond the future to the past

About the Editors

Richard Soare is a physical geographer specializing in periglacial (cold-climate, non-glacial landscapes. Through the last twenty years he has spent considerable time off-planet, intellectually, i.e. identifying landscapes on Mars present or past possibly molded by the freeze-thaw cycling of water. His work spans the red planet geographically, ranging from the plains of Utopia Planitia in the northern hemisphere and the Moreux impact- crater at the Mars dichotomy through to the Argyre impact-crater in the southern hemisphere. Recently, he co-edited *Dynamic Mars: Recent and Currrent Landscape Evolution on the Red planet and a special issue of Icarus: Current and Recent Landscape Evolution on Mars*.

Susan Conway is a CNRS research scientist hosted by Laboratoire de Planétologie et Géodynamique based at the University Nantes in France. She is Vice President of the International Association for Geomorphologists (IAG) and has run the Planetary Geomorphology session at the European Geoscience Union since 2011. She is a team member on the High Resolution Imaging Science Experiment (HiRISE) instrument on NASA's Mars Reconnaissance Orbiter and Guest Investigator on the ESA Trace Gas Orbiter mission to Mars, specifically focused on the CaSSIS camera. Her work focuses on glacial, periglacial and fluvial landforms on Mars, encompassing field, remote sensing and laboratory simulation data, with a specialty in analysis of 3D terrain data.

Jean-Pierre Williams is a researcher at the University of California in Los Angeles (UCLA). He received his PhD in Geophysics and Space Physics from UCLA and was a research scientist at the California Institute of Technology before returning to UCLA. His work focuses on the geology and physics of the inner planets. He is the author/co-author of over 50 peer-reviewed publications and is currently the Deputy-PI of the Diviner Lunar Radiometer Experiment on the Lunar Reconnaissance Orbiter.

Dorothy Oehler is a planetary geologist and Precambrian paleontologist seeking ways to identify biosignatures of potential, past life on Mars and predict optimal locations in which to search for biosignatures. She obtained her Ph. D. from the University of California at Los Angeles (UCLA), then spent several years in petroleum research focusing on methane in the subsurface of the Earth. She now applies that background to investigations of methane on Mars. Dr. Oehler spent the years from 2003 to 2016 at Johnson Space Center and was a member of the 1st Mars Science Laboratory (Curiosity Rover) Science Team. Currently, she continues her work on methane on Mars, earliest life on Earth, and potential biosignatures on Mars. In 2012, Dr. Oehler was named Distinguished Alumna from the Department of Earth, Planetary, and Space Sciences at UCLA.

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