Mars as a time machine to Precambrian Earth

Mathieu G. A. Lapôtre1*, Janice L. Bishop2,3, Alessandro Ielpi4, Donald R. Lowe1, Kirsten L.Siebach5, Norman H. Sleep6 and Sonia M. Tikoo6

1 Department of Geological Sciences, Stanford University, Stanford, CA 94305, USA
2 SETI Institute, Mountain View, CA 94043, USA
3 NASA Ames Research Center, Moffett Field, CA 94035, USA
4 Cooperative Freshwater Ecology Unit, Laurentian University, Sudbury, ON P3E 2C6, Canada
5 Department of Earth, Environmental & Planetary Sciences, Rice University, Houston, TX 77005, USA
6 Department of Geophysics, Stanford University, Stanford, CA 94305, USA

© MGAL, 0000-0001-9941-1552; JLB, 0000-0002-6681-9954; AI, 0000-0002-5376-9361; KLS, 0000-0002-6628-6297; SMT, 0000-0001-9524-8284
*Correspondence: mlapotre@stanford.edu

Abstract: As Mars transitioned from an early Earth-like state to the cold desert planet it is today, it preserved a near pristine record of surface environments in a world without plate tectonics and complex life. The records of Mars’ Earth-like surfaces have remained largely untouched for billions of years, allowing space exploration to provide critical insights about the early days of our own planet. Here, we first review what Mars has taught us about volcanic, tectonic and metamorphic processes in the absence of discrete plates, drawing comparisons with the terrestrial and venusian records. Then, we summarize advances in understanding its early surface environments, including impact cratering, hydrological, sedimentary and geochemical processes. Altogether, the martian record provides a picture of early environments that were similar to modern terrestrial ones in many respects, with sediment and geochemical cycling, hydrothermal systems capable of hosting life, but with the exception that topography, sediment and heat sources were provided by volcanoes and impact cratering rather than plate tectonics. Mars thus offers a lens through which one might catch a glimpse of Earth’s infancy, provided exploration efforts continue to refine our understanding of the similarities between Earth and Mars as well as the specificities of each planet.

Received 5 April 2021; revised 11 August 2021; accepted 31 August 2021

Plate tectonics is Earth’s engine, constantly reshuffling rocks at the surface and recycling them into the planet’s interior. Through this process, traces of past environments are progressively erased from the geological record, leaving geoscientists with an increasingly fragmentary puzzle to solve as one looks deeper into geological time (e.g. Spencer 2020; Reimink et al. 2021). Just over a dozen exposures are known to contain Eoarchean or older rocks, many of them occurring as intensely deformed rafts within younger crustal terranes, and few containing zircon grains of Hadean vintage (e.g. Condic 2019). Further adding to the challenge of deciphering Earth’s earliest record, those remaining oldest materials have been thoroughly altered over eons of metamorphism and weathering (e.g. Fedo et al. 2001), such that even resilient time capsules like zircons often experienced alteration that affected their geochemical makeup. As a result, fundamental questions about the early Earth remain unanswered. What did Earth’s surface look like before plate tectonics? What mechanisms controlled crustal deformation in Earth’s early days, and how did they affect sedimentary and (bio) geochemical cycling? Were Earth’s earliest surface environments conducive to life? To date, at least some of the answers to these questions are only partial or non-unique, and solving the remaining mysteries will require a combination of new insights from Earth’s geological record, modelling and observations from extraterrestrial worlds.

Planetary bodies of the Solar System can be used as analogues to the early Earth, as experiments to understand what makes Earth so unique, and as archives of a geological record that was lost on Earth (as summarized in the perspective article of Lapôtre et al. 2020). Specifically, the diversity of planetary bodies in the Solar System offers a golden opportunity to assess how different initial and boundary conditions may affect the long-term evolution of planets. For example, a combination of geodynamic modelling and observations from other planets and moons suggested that differentiated bodies may operate through three endmember tectonic regimes: an active or mobile-lid regime (with or without discrete plates), a sluggish-lid regime (where surface deformation passively responds to mantle convection rather than being self-driven), and a suite of regimes without significant lithospheric deformation (e.g. Lenardic 2018). The last includes a stagnant-lid regime (where most of the heat is transported by conduction with some contribution from plumes; e.g. Solomatov 1995; Sleep and Jellinek 2008), a chemical-lid regime (similar to a stagnant lid but with a chemically buoyant lithosphere; e.g. Sleep and Jellinek 2008) and a heat-pipe regime (where volcanism is the main source of heat transport, thickening the crust by solidification of new lava flows at the planetary surface; e.g. Turcotte 1989). Only under a subcase of active tectonics do multiple discrete plates exist. Importantly, a given planet can episodically transition between any of these regimes, and both stagnant- and sluggish-lid tectonics have been proposed as precursors to plate tectonics on Earth (e.g. O’Neill et al. 2007; Moyen and van Hunen 2012). Venus, Mars and Io are all thought to be single-plate planets operating along the stagnant- to sluggish-lid continuum, whereas only Earth is known to have evolved plate tectonics (e.g. Lenardic 2018; Stern 2018).

The processes by which plate tectonics shape Earth’s crust and surface today, including the generation of bimodal hypsometry (Fig. 1a), are relatively well understood, but the existence and timing of any precursor tectonic regimes are much less constrained. Modern plates operate under a largely bimodal thermal regime, with subduction producing low-temperature–high-pressure (blueschist) facies and backarc related instead to high-temperature–low-pressure (greenschist–amphibolite or even granulite) facies.
Although the appearance of blueschist facies in the Neoproterozoic is often considered as a signature of the onset of modern-like subduction (e.g. Stern 2005), the rock record suggests that a major shift in thermal regime occurred during the Meso- to Neoarchean (Brown 2006; Johnson et al. 2019), and that thermal-regime bimodality gradually arose from the Neoarchean to the present day (Holder et al. 2019). This gradual transition was interpreted as possibly registering a shift from an Archean mode of tectonics (probably stagnant or sluggish lid) to a Proterozoic regime more akin to modern plate tectonics (Brown et al. 2020; Palin et al. 2020; Bruno et al. 2021).

Some evidence for Neoarchean subduction exists in world-class exposures of early crust, such as the Superior Craton of Canada (Percival et al. 2006; Bédard et al. 2013; Mole et al. 2021). The modern-like geochemical diversity of Archean upper continental crust may suggest an even earlier onset of plate tectonics (probably stagnant or sluggish lid) to a Proterozoic regime more akin to modern plate tectonics (Brown et al. 2020; Palin et al. 2020; Bruno et al. 2021).

As a result, the onset of some form of plate tectonics has been inferred to have started as early as the Hadean (e.g. Foley 2018; Mitchell et al. 2022) to as late as the Neoproterozoic (e.g. Piper 2013), a process that could possibly have been kickstarted by plumes (e.g. Gerya et al. 2015; Brown et al. 2020) or even meteor impacts (e.g. Lowe et al. 2014; O’Neill et al. 2017, 2020). Complicating the picture of Precambrian tectonics, most of what we know about the genesis of metamorphic facies relies on empirical evidence from an already cooled Earth, whereas hotter mantle temperatures could have possibly produced different facies through an overall similar process earlier in Earth’s history (Brown 2006). In addition, the likelihood of plate tectonics at any given time during Earth’s history is thought to depend on hydration of the mantle through ocean–mantle interactions, which remains largely unconstrained (e.g. Korenaga 2013; Tikoo and Elkins-Tanton 2017). Although Hadean zircon grains may yet provide invaluable constraints on the initial hydration state of Earth’s mantle (e.g. Harrison 2009), further insights could come from extraterrestrial samples (e.g. Tikoo and Elkins-Tanton 2017).

On modern Earth, hydrological, sedimentary and geochemical cycles are intimately tied to both plate tectonics (e.g. Dickinson and Suczek 1979; Ingersoll 1988; McLennan et al. 1993), which currently recycles Earth’s surface at a rate of c. 3 km³ a⁻¹ (Stern and Scholl 2009), and life (e.g. Dietrich and Perron 2006; Lyons et al. 2014). It is unclear, however, how these surface processes operated before the onset of plate tectonics and the evolution of complex life forms. During the Hadean and early Archean, Earth’s surface is thought to have been intensely bombarded by meteors that created...
deep basins in the crust (e.g. c. 800 Chicxulub-sized or larger craters are thought to have formed in the Hadean and Archean; Bottke and Norman 2017), excavated deep crustal and mantle rocks, and spread hot ejecta materials (cumulatively c. 470–700% of Earth’s surface was buried by impact-generated melts since 4.5 Gyr ago; e.g. Abramov et al. 2013; Marchi et al. 2014) that could induce silicate-vapor atmospheres, possibly rendering portions of the surface uninhabitable (e.g. Chyba 1993; Sleep and Zahnle 1998; Abramov et al. 2013; Grimm and Marchi 2018). Yet Hadean detrital zircons suggest that liquid water existed near Earth’s surface (Moizsis et al. 2001; Wilde et al. 2001), raising the question of how Earth’s hydrological and sedimentary cycling operated in a world where topography was not generated by plate motion but by a combination of meteor impacts and a different tectonic regime. Because the rate of surface cooling after impact always outpaced the flux of impactors, at least some fraction of Earth’s surface might have remained habitable at any given time after the Moon-forming impact event (Grimm and Marchi 2018). The subsurface could also have provided shelter against large impacts capable of boiling Earth’s ocean (e.g. Sleep and Zahnle 1998). It thus seems possible, if not likely, that the excavation of mantle rocks and subsequent interactions with surface water in impact-generated hydrothermal systems (e.g. Hagerty and Newsom 2003; Kring et al. 2020, 2021; Simpson et al. 2020) could have produced viable templates for the origin of life on the Hadean Earth (e.g. Sleep et al. 2011; Sleep 2018). Submarine hot springs altering serpentinite rocks are also promising prebiotic locales, providing energy and refuge (e.g. Sleep et al. 2011; Sleep 2018), as well as C, H, N, O, P, S and trace elements required for life as we know it (e.g. Knoll and Grotzinger 2006). If life first evolved when the timescale associated with impacts overtook that of abiogenesis, life on Earth could be as ancient as 4.2–4 Gyr old (if started in deep-marine hydrothermal settings) or 4–3.7 Gyr old (if instead sparked at the surface) (Maher and Stevenson 1988). Some evidence suggests that life might have originated while impacts were still intense and frequent (e.g. Ohtomo et al. 2014; Dodd et al. 2017; Tashiro et al. 2017), which, combined with genetic evidence that the last universal common ancestor might have been thermophilic and lived in a hydrothermal setting (e.g. Nisbet and Sleep 2001; Weiss et al. 2016), raises the question of whether impacts could have facilitated the origin of life rather than frustrated it (e.g. Osinski et al. 2020).

Once impactors became rare and plate tectonics settled into its modern regime, at least one more threshold was to be crossed before surface processes fully evolved to their current modus operandi: that of the evolution of complex life, and in particular, of land plants. The greening of the continents by vegetation is thought to have profoundly affected Earth’s sedimentary pathways, morphodynamic timescales and weathering (e.g. Dott 2003; Istanbulbouluoglu and Bras 2005; Davies and Gibling 2010; Gibling et al. 2014; Ielpi and Rainbird 2016a, b; Ielpi et al. 2016, 2017; McMahon et al. 2017; McMahon and Davies 2018; Ganti et al. 2019, 2020; Santos et al. 2019; Ielpi and Lapotré 2020; Ielpi et al. 2020; Lapotré et al. 2020; Zecher et al. 2021; Ielpi et al. 2022), its geochemical cycles including mineral evolution (e.g. Hazen et al. 2008; Hazen and Ferry 2010; Ibarna et al. 2019; D’Antonio et al. 2020) and its climate (e.g. Boyce and Lee 2017; Dahl and Arens 2020). Earth-like worlds devoid of complex surface life and plate tectonics, such as Mars, offer an unparalleled avenue to explore, by analogy, Earth’s earliest surface environments where life might have first evolved (e.g. Cockell 2020; Sasselov et al. 2020) as well as the mechanics of surface processes throughout the Precambrian (e.g. Lapotré et al. 2020).

Here, we seek to bring extraterrestrial perspectives to the discussion of Precambrian Earth and its mysteries. Specifically, Earth’s planetary neighbours, Venus and Mars, may offer unique insights into the functioning of terrestrial planets under different tectonic regimes and without macroscopic life. After a brief overview of potential lessons from Venus, we review evidence from the topographic, tectonic, igneous and metamorphic records of Mars, which indicate that its geodynamic past was probably akin to that of pre-plate tectonics Earth. Then we discuss what is known about early martian surface environments, with relevance to the potential for abiogenesis as well as hydrological, sedimentary and geochemical pathways in a world devoid of plate tectonics and complex life. Finally, we summarize what the exploration of Mars has taught us to date and what continuing and upcoming missions could reveal in the near future about the dynamics of Earth’s Precambrian surface.

A few words about Venus

Although Mars is the main focus of this review, Venus also represents a promising avenue to explore the dynamics of a pre-plate tectonics world, and possibly, early surface environments and the origins of life. With only a 5% difference in planetary radius, Venus is often regarded as Earth’s twin. However, Venus’ thick CO₂ atmosphere renders observations of its surface challenging. Palin et al. (2020) provided a recent review of how Venus may help us understand the early evolution of Earth, which we summarize and update here. Orbiters mapping Venus with radar instruments have revealed surface features reminiscent of terrestrial tectonic plate margins, such as trench-like landforms that resemble ocean–ocean plate margins, with similar curvatures and asymmetry (Sandwell and Schubert 1992; Schubert and Sandwell 1995), hills along ridges that evoke abyssal hills on mid-oceanic ridges (Head and Crumpler 1987; McKenzie et al. 1992) and transform faults (Ford and Pettengill 1992). Other mapped features appear analogous to the terrestrial intraplate environment, with possible mantle plumes under shield volcanoes (Ernst and Desnoyers 2004; Hansen and Olive 2010), smaller volcanic edifices including silicic volcanic domes (Head et al. 1992; Fink et al. 1993; Stofan et al. 2000) and extensive lava flow fields (Lancaster et al. 1995). Further, the morphology of venusian volcanoes was shown to correlate with elastic thickness (McGovern et al. 2013; Borrelli et al. 2021). Radar emissivity correlates with mapped geological units, perhaps reflecting compositional diversity resulting from specific geodynamic environments or some degree of magma evolution (Brossier et al. 2020). In contrast to Earth, however, Venus’ topography is largely unimodal with only sparse elevated terrains called tesserae (c. 8% of Venus’ surface; Fig. 1a), hinting at fundamental differences between the tectonic styles of Venus and modern Earth (e.g. Arvidson and Gunnis 1982; Head 1990; Rosenblatt et al. 1994; Price and Suppe 1995; Stoddard and Judy 2012). These observations have been interpreted as the signature of vigorous lid tectonics on Venus, with possible plume-induced subduction (e.g. Davaille et al. 2017) and protocontinents (e.g. Romeo and Turcotte 2008), but no tectonic plate (e.g. Bercovici and Ricard 2014); a tectonic regime that may be analogous to Earth’s at some point in its pre-plate-tectonics history. However, the relative density of impact craters within mapped geological units suggests that the intensity of crustal deformation has significantly decreased over time (Basilevsky and Head 1998, 2000, 2002; Ivanov and Head 2011, 2013). In addition, the paucity and apparent randomness of impact craters on Venus suggests a very young surface, with terrains proposed to be c. 750–150 myr old (e.g. McKinnon et al. 1997), and recent estimates even suggest an average crustal age possibly as young as c. 250–130 myr old (Herrick and Rumpf 2011; Le Feuvre and Wieczorek 2011). As a result, it has been proposed that Venus experienced a global resurfacing event c. 500–300 myr ago (e.g. Phillips et al. 1992; Schaber et al. 1992; Strom et al. 1994; Romeo and Turcotte 2010), consistent with the overall random distribution of impact craters on its surface (Riedel et al. 2021). This hypothesis is debated, and putative ancient terrains have also been identified (e.g. Guest and
In contrast to Earth and Venus, the surface of Mars is very old, with Stofan 1999; Hansen and López 2010; Byrne et al. 2020. A counter hypothesis to a catastrophic global resurfacing event that could also reproduce the observed distribution of impact craters is that of continuous magmatism at regional scales under a sluggish-lid regime (e.g. Phillips et al. 1992; Hauck et al. 1998; Bionnes et al. 2012; O’Rourke and Korenaga 2012; O’Rourke et al. 2014). Evidence for a continuous resurfacing scenario includes the possibility of recent or even present-day volcanism, as suggested by fresh surfaces with negligible apparent surface weathering on some lava flows (Smrekar et al. 2010; Campbell et al. 2017; Brossier et al. 2020; Filiberto et al. 2020), the detection of anomalously hot subsurface temperatures (Bondarenko et al. 2010) and, possibly, by time-varying sulfur dioxide concentrations in the atmosphere (Marcq et al. 2013). Whether Venus was catastrophically resurfaced or is continuously rejuvenated, its surface’s overall young age probably represents a significant loss of opportunity to probe its early, more vigorous tectonic regime as well as possibly early habitable surface environments (e.g. Way et al. 2016), as access to ancient terrains is uncertain, possibly sparse and highly localized.

Although modern temperatures and pressures render Venus’ surface inhospitable to life as we know it, the high deuterium–to-hydrogen ratio of its atmosphere indicates that Venus might have hosted a temperate surface ocean in the past (e.g. Ingersoll 1969; Donahue et al. 1982; Way et al. 2016; Way and Del Genio 2020). In principle making it a prime target to explore abiogenesis in the early Solar System (e.g. Cockell 1999; Limaye et al. 2021). The hypothesis of an early ocean on Venus was recently put into question by three-dimensional global climate simulations (Turbet et al. 2021). Given the evidence for abundant volcanic activity, it is likely that the early surface conditions on Venus would have been similar to those of the early Earth if the past existence of an ocean is confirmed (Lunine 2006), with potential hydrothermal systems similar to those thought to have given rise to terrestrial life (e.g. Limaye et al. 2021). NASA’s Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI +), Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) and ESA’s EnVision missions will launch in the next decade to gather a wealth of new data. Notably, these missions will conduct measurements of atmospheric chemistry, map surface emissivity, topography and surface deformation at the global scale, sound the subsurface, and provide high-resolution, high-contrast surface imagery of Venus’ tesserae and other terrain types. Together, these data will shed new light on Venus’ geological and atmospheric history, providing critical answers to fundamental questions such as whether Venus ever hosted a surface ocean, what the nature of Venus’ tesserae is, and when Venus was last geologically active (e.g. Smrekar et al. 2016; Ghail et al. 2017; Garvin et al. 2020). Together, upcoming observations of Earth’s closest neighbour could confirm not only its past habitability, but also the existence and distribution of ancient terrains that could reveal a yet unseen record of habitable surface environments of an Earth-like planet in the early Solar System.

Mars: a pre-plate-tectonics snapshot of Earth?

In contrast to Earth and Venus, the surface of Mars is very old, with >90% of the surface having formed during Earth’s Precambrian and c. 80% of Archean age or older (Fig. 1b), offering the oldest known record of geodynamics and surface environments on any rocky planet in the Solar System. Beyond the Earth, geological time is typically divided based on the density of impact craters within well-defined geological units, an approach that relies on the notion that older surfaces accumulated and preserved more and bigger impacts than younger ones. Following this principle, Mars’ geological history was divided into four main periods (Fig. 1b): the pre-Noachian (any rocks that predate the formation of the Hellas basin (Fig. 2a), visible only in select stratigraphic exposures, c. 4.5–4.1 Ga); Noachian (c. 4.1–3.7 Ga); Hesperian (c. 3.7–3.0 Ga); Amazonian (c. 3.0 Ga–present). The precise boundaries between these periods are uncertain and vary with assumptions related to, for example, the flux of impactors at the Moon (where cratered unit ages have been calibrated with radiometric dates of samples), the Mars/Moon cratering ratio and scaling relationships between impactor and target properties (e.g. Hartmann and Neukum 2001; Ivanov 2001; Hartmann 2005). Mars’ thin CO₂ atmosphere offers a virtually transparent window through which the surface can be mapped in great detail. On Mars, impact spalls generated by meteor impacts into strong bedrock targets are relatively easily ejected to space (e.g. Melosh 1984; Head et al. 2002; Artemieva and Ivanov 2004), and many martian meteorites have been recovered on Earth (identified on the basis of trapped-gas compositions matching the martian atmosphere; e.g. Bogard and Johnson 1983; Ott and Begemann 1985; Ott 1988; and reviews by Swindle 2002; Ott et al. 2019), allowing for petrological and geochemical analyses (e.g. McSween 1994). In contrast, no known venusian meteorites have been found on Earth to date (Dones et al. 2018; Greenwood et al. 2020). Isotopic analyses of martian meteorites reveal that limited mantle mixing occurred after core–mantle differentiation (e.g. Brandon et al. 2000; Marty and Marti 2002; Kleine et al. 2004; Foley et al. 2005; Debaille et al. 2007, 2009; Borg et al. 2016; Barnes et al. 2020), hinting at the lack of vigorous mantle convection, and possibly pointing to a stagnant- or sluggish-lid tectonic regime that may offer similarities to Earth’s Hadean and Archean tectonics. With limited geological activity modifying the martian surface over the past c. 3.8 Gyr (e.g. Golombek et al. 2014), Mars offers an unparalleled opportunity to observe the relic of a pre-plate-tectonics world with our own eyes.

Topography

Mars’ long-wavelength topography (i.e. over horizontal scales of greater than a few hundreds of kilometres) is dominated by a hemispheric dichotomy, where the northern hemisphere sits at a lower elevation than the southern hemisphere (Figs 1a and 2a). Finer-scale topography, in turn, is largely dominated by a myriad of impact craters that are heterogeneously distributed across the surface (e.g. the northern lowlands display fewer and smaller impacts than the densely cratered southern highlands) and range over at least six orders of magnitude in diameter (Fig. 2a). Elevation drops c. 4 km over just a few hundred kilometres at the dichotomy boundary between the northern lowlands and southern highlands. The presence of relatively large, buried impact craters in the northern lowlands suggests that the dichotomy formed early in Mars’ history (Frey et al. 2002; Frey 2006, 2008). This major feature leads to a strongly bimodal hypsometry that is reminiscent of Earth’s low-lying oceanic crust and floating continents (Figs 1a and 2a). This resemblance sparked the hypothesis that the dichotomy could have resulted from plate tectonics and that the northern lowlands were analogous to terrestrial oceanic crust (also bolstered by an arc-like arrangement of the Tharsis Montes volcanoes; Fig. 2a; e.g. Sleep 1994; Lenardic et al. 2004). Several other mechanisms have been proposed to explain Mars’ topographic dichotomy including convection or a superplume, mantle overturn after global magma-ocean formation (e.g. Lingenfelter and Schubert 1973; Wise et al. 1979; McGill and Dimitriou 1990; Zhong and Zuber 2001; Zuber 2001; Ke and Solomatov 2006; Roberts and Zhong 2006; Watters et al. 2007) or, as is currently the prevailing view, one to multiple large impacts or a combination of impact and convection (Wilhelms and Squyres 1984; Frey and Schultz 1988; Andrews-Hanna et al. 2008a; Marinova et al. 2008; Nimmo et al. 2008; Citron et al. 2018b).
Tectonic features

The martian surface hosts a wealth of evidence for crustal deformation, including widespread extensional features (e.g. rifts, horst-and-graben topography) that are found surrounding giant shield volcanoes and large impact basins and volcanic provinces, as well as ‘wrinkle ridges’ interpreted as convergence features (e.g. folds overlying blind thrust faults; Golombek and Phillips 2010; Tanaka et al. 2014b; Fig. 2b). The location and orientation of ancient valley networks indicate that Tharsis (a large volcanic province including several giant shield volcanoes; Fig. 2a) was already loading the crust by the end of the Noachian (Phillips et al. 2001). This is consistent with a Noachian age for about half of the mapped extensional structures (Golombek and Phillips 2010), and the conformity of ancient drainage patterns to modern topography at a variety of spatial scales supports the absence of plate tectonics at the time of valley-network formation (Black et al. 2017). Several mechanisms have been proposed to explain the formation of Valles Marineris, a giant canyon the size of about five Grand Canyons (Fig. 2a), such as large-scale and narrowly distributed strike-slip motion (Yin 2012) or continental-scale salt tectonics (Montgomery et al. 2009), although the prevailing view is that the canyon resulted from a complex interplay between moderate Tharsis-related extension, volcanic intrusion weakening the crust and subsidence (e.g. Schultz 1998; Andrews-Hanna 2012a, b, c). Compressional lobate scarps (curvilinear structures interpreted as thrust faults) and extensional faults associated with the dichotomy boundary indicate later deformation through crustal loading or relaxation of the southern highlands after resurfacing (largely infilling) of the northern lowlands in the Hesperian and Amazonian (Watters et al. 2007). The formation of wrinkle ridges is thought to have peaked in the Hesperian (Golombek and Phillips 2010; Ruj and Kawai 2021), and their distribution is most consistent with compressional stresses resulting from Mars’ secular cooling and contraction (e.g. Tanaka et al. 1991; Watters 1993; Golombek and Phillips 2010; Nahm and Schultz 2011; Andrews-Hanna 2020). Strike-slip motion is relatively rare on Mars, and typically associated with wrinkle ridges or grabens (Andrews-Hanna et al. 2008b; Golombek and Phillips 2010). Recent determinations of the focal mechanism of marsquakes suggest that some deformation still occurs today along normal faults of the Cerberus Fossae graben system, between Gale crater and Elysium Mons (Brinkman et al. 2017).
2021; Fig. 2a). Overall, tectonic features indicate that crustal deformation was dominated by elastic support of Tharsis early in Mars’ history, a volcanically thickening lithosphere, then contraction as the planet cooled (Phillips et al. 2001; Andrews-Hanna et al. 2008b; Golombek and Phillips 2010). Consistently, seismic data from subcrustal marquesques suggest that Mars’ internal structure consists of a 1830 ± 40 km liquid core (Stähler et al. 2021), a thin and sluggishly convecting mantle (Khan et al. 2021) and a thick thermal lithosphere capped by a light and layered crust enriched in heat-producing elements (Khan et al. 2021; Knapmeyer-Endrun et al. 2021).

In addition to faults and folds, evidence for crustal deformation is corroborated by intense but localized magnetic anomalies in the Noachian southern highlands. Early work identified strips with alternating magnetic polarity in this region (Acuña et al. 1999; Connerney et al. 2005), but more recent magnetic mapping of remanent crustal magnetism suggests that magnetization within the previously identified strips may instead be nonuniform in direction (Langlais et al. 2019). In the absence of a global magnetic field today, these magnetic anomalies are thought to be the signature of remanent magnetization of the martian crust under an ancient geodynamo (Acuña et al. 1999), although uncertainties surrounding the magnetic mineralogy (e.g. serpentinization-derived magnetite; Quesnel et al. 2009) and the geometries (lateral extent, depth and thickness) of crustal magnetic sources render the determination of palaeo-field strength challenging (Ehilmann et al. 2016; Alfantooobi et al. 2021). No magnetic anomalies are detected in the terrains surrounding the Hellas basin, leading to the hypothesis that the impact that formed the basin c. 4.1–3.9 Gyr ago postdated the demise of the martian geodynamo (Werner 2008; Lillis et al. 2013). Carbonate-hosted magnetite in the ALH 84001 meteorite suggests Earth-like surface magnetic field intensities (Weiss et al. 2008), although it is possible that ALH 84001 recorded a strong remanent crustal field from an earlier time rather than a field produced by an active dynamo c. 4.1–3.9 Gyr ago (Borg et al. 1999; Lapen et al. 2010). However, recent evidence for remanent magnetization co-located with 3.7 Gyr old rocks suggests that the martian dynamo may have lasted longer than previously thought; that is, until after the formation of the Hellas basin (Mittelholz et al. 2020). The martian geodynamo could have been intermittently interrupted by large impacts, possibly explaining the absence of magnetic anomalies around Hellas and other large basins (e.g. Roberts et al. 2009; Arkani-Hamed and Olson 2010; Arkani-Hamed 2012). By analogy with magnetic anomalies in Earth’s oceanic crust, the martian magnetic strips were initially interpreted by some as a record of plate divergence (Connerney et al. 1999), but possibly broader than their terrestrial counterparts owing to slower spreading rates (Breuer and Spohn 2003). Anomalies in the Eridania basin appear to be associated with hydrothermal assemblages, possibly supporting the hypothesis of an ancient spreading seafloor (Michalski et al. 2017), although metamorphic assemblages are commonly associated with impact structures as discussed below. Nimmo and Stevenson (2000) showed that plate tectonics, if it ever occurred on early Mars, could have efficiently transported heat from the core so as to maintain core convection and thus a dynamo. However, models invoking plate tectonics cannot explain the spatial distribution of martian magnetic anomalies, whereas a simple stagnant- or sluggish-lid regime with plumes can (Breuer and Spohn 2003; Citron and Zhong 2012).

Volcanic landforms and igneous processes

The martian surface hosts a multitude of volcanic landforms, from the giant shield volcanoes of Tharsis and Elysium to smaller volcanic cones, extensive lava flow fields and some pyroclastic deposits (e.g. Squyres et al. 2007; Hauber et al. 2009; Xiao et al. 2012; Grott et al. 2013; Fig. 2b). Volcanic activity is thought to have been widespread in the late Noachian and into the Hesperian, but its intensity decreased through time to become progressively confined to the Tharsis and Elysium regions throughout the Amazonian (e.g. Werner 2009; Robbins et al. 2011), with evidence for plain volcanism as recently as the last few tens of million years (Hauber et al. 2011). Martian volcanic edifices range over two orders of magnitude in size, including the largest known volcano in the Solar System, Olympus Mons, a 23 km high and 600 km wide shield located in the Tharsis region (Fig. 2a). The Tharsis bulge constructed by Tharsis Montes and Olympus Mons is thought to be the surface expression of a core–mantle plume (e.g. Harder and Christensen 1996; Roberts and Zhong 2004; Golombek and Phillips 2010). In addition to widespread effusive volcanism, explosive eruptions are also thought to have occurred (e.g. Hynek et al. 2003; Squyres et al. 2007; Kerber et al. 2011; Bröz et al. 2021; Whelley et al. 2021), with an inferred transition from an explosive volcanism-dominated regime to an effusive one during the Hesperian, possibly driven by crustal dehydration over time (Robbins et al. 2011; Banfield et al. 2013; Kremer et al. 2019).

Most of our knowledge of crustal composition in Noachian terrains comes from orbiting and landed spacecraft data, and notably, from visible–shortwave infrared (VSWIR) and thermal infrared (TIR) spectrometers. Because felsic phases lack distinctive absorption features in the VSWIR wavelength range and TIR spectrometers orbiting Mars have relatively coarse (c. 100 m per pixel) spatial resolutions, it is challenging to detect more felsic compositions on Mars today. With globally widespread spectral signatures of mafic minerals such as pyroxenes and olivines (e.g. Ody et al. 2012), the surface of Mars appears to be largely basaltic to basaltic andesite in composition (e.g. Christensen et al. 2005; McSween et al. 2009), but some igneous diversity has been recognized on Mars despite instrumental limitations. Notably, TIR spectra acquired near Syrtis Major are suggestive of compositions ranging from low-Si basalts to high-Si dacite (Christensen et al. 2005), although the latter might be associated with hydrated silica rather than implying a dacitic magma (Christensen et al. 2005; Skok et al. 2010). Carter and Poulet (2013) identified potential anorhotic terrains from VSWIR spectra, which they interpreted to be consistent with an Earth-like, localized plutonic origin. Wray et al. (2013) detected spectral signatures that are consistent with Fe-rich plagioclase in three different locations, including one situated near a dacite detection. They argued that any significant presence of mafic phases would obscure the identified plagioclase features, and thus they interpreted the detections as representative of evolved felsic volcanic rocks, although they could not rule out an anorhotic composition instead. This interpretation was countered by Rogers and Nekvasil (2015), who argued that TIR observations of the same locations are not consistent with felsic (>65% Si) compositions. Instead, they found the detections to be more consistent with either basaltic or anorhtotic rocks, although the geological context (including volcanic flows and embayment relationships) does not support a plutonic origin. Rogers and Nekvasil (2015) thus favoured the hypothesis of basaltic eruptive products enriched in large plagioclase crystals, formed through fractional crystallization at the base of a thick crust and subsequent crystallization of the residual liquid at low pressure. The origin of these detections remains debated, as the coarse spatial footprint of TIR spectra may lead to sub-pixel mixing of mafic regolith and feldspar-rich bedrock, and the spectral unmixing in the VSWIR range is more consistent with high (>80%) feldspar abundances (Eggers et al. 2021). The lack of widespread felsic rocks is consistent with a tectonic regime where no large-scale tectonic processes conspired towards the crystallization of large swaths of evolved crustal rocks.
An important caveat for orbiter-based compositional studies is the uncertain petrology of target surfaces. A planet dominated by basaltic parent rocks, when subjected to water flows and winds, will form sedimentary rocks of basaltic composition, with diversity driven by compositional sorting rather than reflecting true source diversity (e.g. Lapôtre et al. 2017a; Siebach et al. 2017). It is in fact possible that a significant fraction of bedrock exposures on Mars reflect clastic lithologies (including pyroclastic, impact-generated and detrital sedimentary rocks) that were enriched in mafic or felsic phases during transport or after diagenesis through deflation (Rogers et al. 2018). Thus, samples analysed in situ by landers orrovers as well as meteorites are critical to deciphering Mars’ igneous evolution.

Significant variations in both major and minor elements seen by the Curiosity rover at Gale crater indicate at least two magmatic sources (e.g. Stolper et al. 2013; Grotzinger et al. 2015a; Le Deit et al. 2016; Mangold et al. 2016; Cousin et al. 2017; Siebach et al. 2017; Udry et al. 2018; Payré et al. 2020), including an alkali basalt sufficiently evolved to contain nearly pure sanidine (Treiman et al. 2016). The surprising detection of tridymite in a mudstone by Curiosity is most probably an indication that silicic volcanism took place (Morris et al. 2016; Payré et al. 2021), although the general lack of more than c. 2% quartz in all drilled samples shows that such evolved volcanism was rare (Ranpe et al. 2020). Some light-toned float rocks found by Curiosity have also been interpreted as feldspar-rich rocks. Sautter et al. (2015) conducted a petrological analysis of these rocks and found similarities to terrestrial Archean trondhjemitetoanlitegranodiorite (TTG) suites (Johnson et al. 2019). However, further analyses by Udry et al. (2018) demonstrated that, for all major elements, the Gale crater samples are statistically more similar to Earth’s oceanic intraplate volcanoes located far away from continental terrains than to Archean TTG suites and that, overall, evolutionary trends of martian magmas display remarkable similarities to those associated with terrestrial intraplate volcanism (e.g. McCubbin et al. 2008). Similarly, Payré et al. (2020) found that the range of igneous mineral chemistries measured in the Gale crater floor rocks could be formed via fractional crystallization of mantle melts with different degrees of partial melting.

The meteorite record is inherently biased towards unweathered igneous rocks as mechanically weaker rocks are more prone to breakdown upon impact and impact into regolith decreases ejection speed. It is thus unsurprising that the vast majority of martian meteorites found on Earth to date sampled very young lava flows, with most meteorites found to be only a few million years old (e.g. Head et al. 2002). Of particular interest, the NWA 6963 shergottite is a martian gabbro containing a quartz–alkali feldspar intergrowth of late-stage granitic-melt composition (e.g. Filiberto et al. 2018). However, these relatively young samples are not representative of the ancient Noachian crust (e.g. McSween et al. 2009; Udry et al. 2010) and only a handful of meteorites (including ALH 84001 and NWA 7034; Borg et al. 1999; Lapen et al. 2010; Nyquist et al. 2016; Costa et al. 2020) are older than 1.3 Ga (e.g. Nyquist et al. 2001; McSween 1994; Park et al. 2009). The NWA 7034 meteorite (and its paired samples) is a polymict breccia that has similar VSWIR properties to average Noachian crust (e.g. Humayun et al. 2013; Cannon et al. 2015). It contains igneous clasts of varied compositions (e.g. basalt, mugearite, trachyandesite, norite, gabbro and monzonite; e.g. Hewins et al. 2017) that had not been found among martian meteorites before. It notably includes at least one clast that has the same composition as a basaltic sample observed at Gusev crater by the Spirit rover (McCubbin et al. 2008; Udry et al. 2014, 2020). Zircon grains from NWA 7034 and its pairs span c. 4.2 Gyr in crystallization ages, with two main age groups around 4.4 and <1.5 Ga, respectively (Costa et al. 2020). The first, older group is thought to reflect a period of intense bombardment by meteor impacts, as suggested by the sample’s unradiogenic initial Hf-isotope composition, whereas the younger group is probably the signature of late Tharsis and Elysium volcanism (Costa et al. 2020). The Hf-isotope composition of the zircon grains is chondritic-like, and consistent with an early geodynamic regime driven by convection of the asthenospheric mantle under a depleted lithospheric mantle and enriched crust (Costa et al. 2020).

In summary, martian igneous samples analysed to date are more consistent with fractional crystallization of basaltic parent magmas within intraplate environments than Earth-like TTG suites. Magmas evolved to generate a wide array of igneous compositions and even produce small amounts of felsic rocks, possibly facilitated by greater water abundances on early Mars (e.g. McCubbin et al. 2010; Udry et al. 2020). The martian igneous record is most consistent with the hypothesis that Mars was dominated by stagnant- to sluggish-lid tectonics throughout its history (Costa et al. 2020), with a convective mantle, possibly thermo-chemical mantle plumes, fractional crystallization and assimilation at crustal depths (Grott et al. 2013; Payré et al. 2020; Udry et al. 2020).

**Low-temperature metamorphism and hydrothermalism**

The composition of putative metamorphic rocks on Mars can be estimated from the composition of parent igneous rocks as determined from meteorites and rover observations (e.g. McSween et al. 2015; Semprich et al. 2019; Semprich and Filiberto 2020). It was shown that, depending on thermophysical conditions, martian basaltic rocks should primarily produce mineral assemblages containing chlorite, actinolite, albite and opaline silica, with laumontite, pumpellylite, prehnite, or serpentinite and talc (McSween et al. 2015; Semprich et al. 2019). Ultramafic rocks, in turn, should produce serpentine, talc and magnesite (McSween et al. 2015; Semprich et al. 2019). Comparing these predictions with actual mineral detections allows us to constrain the thermophysical conditions, and thus, possibly, the tectonic regime that created the observed metamorphic assemblages. To date, no global survey of metamorphic phases has been conducted on Mars, but VSWIR data suggest the presence of distinctive assemblages that are heterogeneously distributed across the planet’s surface (Ehlmann et al. 2010, 2011a; Bultel et al. 2015; Viviano-Beck et al. 2017; Amador et al. 2018; Fig. 3a). Specifically, Ehlmann et al. (2011a) identified assemblages of prehnite–chlorite–silica, analcime–silica–(Fe,Mg) smectite–chlorite, chlorite–illite/muscovite and serpentinite. Thus, most anticipated metamorphic phases were identified, with the notable exception of laumontite and pumpellylite, although both phases are spectrally similar to zeolites and other phyllosilicates (which have been detected) in the VSWIR wavelength range. The specific assemblages identified on Mars to date are not consistent with high-grade metamorphism. Given the absence of evidence for significant tectonic uplift or deep erosion, the excavation of metamorphic phases was probably driven by impacts with excavation depths ~8 km as estimated from crater diameters (McSween et al. 2015). Thus, metamorphic assemblages are thought to reflect alteration through diagenesis and low-grade, sub-greenschist metamorphism, or hydrothermal or fumarolic activity at relatively low temperatures (~400°C; Ehlmann et al. 2011a) under a ~20°C km⁻¹ geothermal gradient (McSween et al. 2015; Semprich et al. 2019). Such a steep geothermal gradient exceeds what is expected solely from radiogenic elements, requiring another heat source. Current observations of patchy, low-grade assemblages are thus largely consistent with the excavation of mafic rocks by impacts and subsequent alteration by post-impact hydrothermal systems (e.g. Oskiniski et al. 2013; McSween et al. 2015) rather than at high temperatures and pressures deep in the crust.
Mars to envision Earth’s surface before macroscopic life

With evidence for impact-driven hydrothermal activity and the absence of plate tectonics, Mars constitutes a prime exploration target in the search for early life in the Solar System (e.g. Cockell and Barlow 2002; Michalski et al. 2018; Onstott et al. 2019; Sasselov et al. 2020). On Mars, and potentially on early Earth, meteors would have exerted a dominant control on topography, acting as sources (crater rims) and sinks (crater basins) for sediments and bio-essential elements (e.g. McLennan et al. 2019). Here, we discuss how the martian record may help geologists understand Earth’s earliest surface environments, where life first thrived, as well as the dynamics of Earth’s barren Precambrian landscapes following the waning of surface bombardment and before the advent of complex life on land.

Meteor impacts and the origin(s) of life

In addition to possibly delivering relevant chemical compounds, meteors impacting planetary surfaces had the potential to generate the energy, chemical gradients and habitats required for life to emerge. A comprehensive review on this topic was recently offered by Osinski et al. (2020); here, we briefly summarize and expand upon their findings in the context of utilizing Mars to explore the potential cradles of life on the early Earth. Although the subsurface would have probably been sterilized in the close vicinity of an impact owing to locally scorching temperatures and crushing pressures, empirical evidence suggests that bio-essential elements and even living bacteria can survive an impact event in highly shocked rocks and near-impact melts (e.g. Pontefract et al. 2012; Hazaël et al. 2017). Furthermore, these initial high-pressure–high-temperature conditions dissipate within minutes after impact (e.g. Gault et al. 1968; Osinski et al. 2020), creating new spaces within fracture networks that are shielded from UV and cosmic radiation (e.g. Boston et al. 1992; Osinski et al. 2020), and giving way to conditions conducive to hydrothermal circulation (e.g. Abramov and Kring 2005; Kirsimoné and Osinski 2012). Temperatures within such hydrothermal systems may take up to hundreds of thousands of years to cool sufficiently to become habitable (e.g. Kring et al. 2020).
Groundwater upwelling associated with central uplifts within impact craters could have sustained alkaline lakes on early Mars (e.g. Michalski et al. 2013a). Together, impact-generated hydrothermal springs and surficial lakes created environments on Mars that are analogous to those found around black and white smokers on Earth, which are often referred to as the most likely systems to have catalysed abiogenesis. There, interactions between excavated ultramafic rocks and heated fluids could have provided the energy and chemical gradients required for abiogenesis (e.g. Ramkissoon et al. 2021) through, for example, chemical reactions such as serpentinization (e.g. Schulte et al. 2006; Russell et al. 2010). Several impact craters in the southern highlands of Mars were found to display spectral signatures consistent with serpentine in their central peaks, walls and ejecta (Ehlmann et al. 2010), thereby constituting promising astrobiological targets (e.g. Osinski et al. 2020). The Spirit and Opportunity rovers explored sites associated with volcanic and impact-driven hydrothermal activity at Gusev and Endeavor craters (e.g. Squyres et al. 2008; Ruff and Farmer 2016), respectively, suggesting that such environments may have been common on the early Martian surface. The inferred near-surface environments of early Mars thus appear to have been suitable for life as we know it, leading some geoscientists to suggest that abiogenesis could have occurred on Mars (under an Earth-like magnetic field), and perhaps even transferred to Earth by travelling through space in a martian meteoroid (e.g. McKay et al. 1996; Sleep and Zahnle 1998; Mileikowsky et al. 2000; Thomas-Keprta et al. 2000; Weiss et al. 2000; Nisbet and Sleep 2001; Artemieva and Ivanov 2004; McKay et al. 2004; Kawaguchi 2019).

**Hydrological, sedimentary and geochemical cycling**

Hydrological and sedimentary cycling on Mars have been significantly affected by the planet’s long-term atmospheric evolution, starting with a comparatively thick (>0.5 bar) CO₂ atmosphere in the Noachian followed by significant atmospheric loss, the exact pace and timing of which is poorly constrained (e.g. Jakosky et al. 2017; Kite 2019; Jakosky 2021). As a result, abundant surface water flowed through well-integrated watersheds early in the planet’s history (mid- to late Noachian), and became sparser 3.0–3.5 Gyr ago, with only episodic outburst floods at the surface throughout the Hesperian and Amazonian (e.g. Fassett and Head 2008b). For a state-of-the-art overview of Mars’ climate history, we refer the reader to the review of Wordsworth (2016). For the sake of this review, it suffices to keep in mind that, although Mars’ atmospheric trajectory diverged from that of Earth, Noachian and early Hesperian surface environments may serve as analogues to Earth’s at various points in its history (Lapôtre et al. 2020). For example, even if early Mars was generally cold with only episodic warm periods (Bishop et al. 2018; Wordsworth et al. 2021), it could possibly serve as a point of comparison to understand how Earth entered and recovered from Proterozoic snowball states as well as their associated surface environments.

Evidence for ancient sedimentary systems on Mars includes dendritic valley networks in the Noachian highlands (Fig. 3b; e.g. Pieri 1976; Baker et al. 1992; Carr 1996; Irwin et al. 2005, 2008; Lasue et al. 2019) indicating contributions from both precipitation-driven and groundwater sources (e.g. Carr and Malin 2000; Mangold et al. 2004; Lapôtre and Lamb 2018; Seybold et al. 2018). Water–rock interactions were also recorded by Mars’ diverse surface mineralogy (Fig. 3a; e.g. Bibring et al. 2006; Ehlmann and Edwards 2014), including abundant Fe–Mg clays in Noachian terrains thought to have formed through weathering, hydrothermal or deuteritic processes (e.g. Poulet et al. 2005; Mustard et al. 2008; Meunier et al. 2012; Ehlmann et al. 2016). Detection of carbonates, sulfates and chlorides are indicative of open-system weathering as well as spatially and temporally varying aqueous chemistry (Ehlmann and Edwards 2014; Rapin et al. 2019).

In addition to a clear erosional and mineral record of past water–rock interactions, a wide variety of lithified sedimentary rocks have been identified on Mars (e.g. Malin and Edgett 2000) despite the paucity of evidence for significant basin subsidence (Grotzinger and Milliken 2012; Davis et al. 2021). Sedimentary deposits display a variety of bedding styles and thicknesses (e.g. Stack et al. 2013), simple to complex geometries (Dromart et al. 2007) and evidence for burial depths up to several kilometres (e.g. Milliken et al. 2010; Zabrisky et al. 2012; Bennett and Bell 2016; Caswell and Milliken 2017; Schieber et al. 2017; Day and Catling 2020), including exhumed impact craters that had been previously buried (e.g. De Hon 1987; Pain et al. 2007). Observations of extraformational sedimentary clasts within sedimentary layers by the Curiosity rover further suggest that ancient sedimentary rocks were recycled (multiple times in places, as evidenced by clasts within clasts; Edgett et al. 2020), as is common on Earth (e.g. Cox and Lowe 1995).

Significant geomorphological work was done by surficial liquid flows on ancient Mars. Fluvial ridges, formed through preferential erosion of floodplain materials relative to more resistant channel fills, highlight the geometry of ancient martian channel belts (Fig. 3b; Burr et al. 2010; DiBiase et al. 2013; Williams et al. 2013b; Kite et al. 2015; Davis et al. 2016, 2019; Cardenas et al. 2018; Dickson et al. 2020; Zaki et al. 2021). Channelized and sheet-like fluvial deposits have been observed from the ground and from orbit (Williams et al. 2013a; Edgar et al. 2016; Salese et al. 2020). Observations of fluvial landforms and deposits to date suggest that ancient martian rivers spanned a wide range in sizes, displayed varied planform geometry (e.g. both single- and multi-thread) and transported a variety of gravel- to sand-grade sediment (Lapôtre et al. 2019). Given Mars’ lower gravity, it has been proposed that supercritical bedforms could have been more common on early Mars than on Earth (Konsoer et al. 2018; Lapôtre and Ielpi 2020). Because some such systems are preserved in both planform and stratigraphic exposures in places, they could provide critical new information about the morphodynamics and deposits of pre-vegetation rivers on the Earth (Ielpi and Lapôtre 2019, 2020; Lapôtre et al. 2019). Both closed- and open-basin lakes have been inferred in many impact craters (Fassett and Head 2008a; Goudge et al. 2012, 2015; Stucky de Quay et al. 2020), and lacustrine deposits were observed by Curiosity, including extensive thinly laminated mudstones, the deposits of plunging river plumes and evidence for near-shore mudcracks (Grotzinger et al. 2015b; Stein et al. 2018; Stack et al. 2019). Potential marginal carbonates were detected along the inferred shoreline of a palaeolake in Jezero crater (Horgan et al. 2020). Notably, many deltas and sublacustrine fans are found in impact craters and along the dichotomy boundary (e.g. Wood 2006; Metz et al. 2009; Di Achille and Hynek 2010; Palacis et al. 2016; Goudge et al. 2018; Rivera-Hernández and Palacis 2019; Lapôtre and Ielpi 2020). Alluvial fans are also common along the walls of impact craters and grabens (Fig. 3b; Moore and Howard 2005; Palacis et al. 2014; Wilson et al. 2021). In addition to its alluvial, fluvial, deltaic and lacustrine geomorphological and depositional records, Mars also displays evidence for many other sedimentary environments found on the Earth. Numerous aeolian deposits are observed on Mars, both from orbit (e.g. Milliken et al. 2014; Day et al. 2019; Chojnacki et al. 2020) and in situ with rovers (e.g. Grotzinger et al. 2005; Lapôtre et al. 2016; Banham et al. 2018, 2021; Rubin et al. 2022). Sandstones possibly as old as c. 3.7 Ga were formed by sand dunes migrating over groundwater-fed playas (e.g. Grotzinger et al. 2005), as evidenced by the presence of current ripples in interdune deposits.
(e.g. Lamb et al. 2012) and sub-equal parts of evaporative salts and clastic material (McLennan et al. 2005). Because aeolian bedforms form in concert with winds, their deposits may hold clues about the past martian atmosphere. Notably, a type of aeolian bedform not seen in Earth’s sandy deserts forms ubiquitously under Mars’ modern low atmospheric density (Lapôtre et al. 2016, 2018). Although their formation mechanics are debated (e.g. Durán Vincent et al. 2019; Sullivan et al. 2020), the bedform size correlates with atmospheric density (Lorenz et al. 2014; Lapôtre et al. 2016, 2017a, b), empirically suggesting that their stratification may serve as a proxy to reconstruct atmospheric density through time (Lapôtre et al. 2016, 2021; Rubin et al. 2022). In addition to aeolian deposits, ghost palaeo-dune fields were identified from dune casts (Day and Catling 2018) and many yardangs are found around Mars’ surface and are probably still undergoing morphogenesis today (e.g. Ward 1979; Zimbelman and Griffin 2010). More recent glacier-like forms have also been identified (e.g. Hubbard et al. 2014). In addition, because of the antiquity of its surface (Fig. 1b), Mars has the potential to preserve impact-related strata from the early bombardment era (e.g. Grotzinger and Milliken 2012; Scheller and Ehlmann 2020), a record that has long been erased from Earth’s surface. Overall, the vast majority of Earth’s sedimentary processes occurring on land are thought to have likewise occurred on Mars (e.g. Grotzinger et al. 2013), such that the martian sedimentary archive recorded similarly complex spatial and temporal shifts in depositional environments (e.g. Grotzinger et al. 2005, 2015b; Lowe et al. 2020), with impact craters serving as prominent sedimentary sinks (including to this day; e.g. Day et al. 2019; Day and Catling 2020; Roback et al. 2020; Dom and Day 2020; Gunn et al. 2022).

The presence of oceans in the northern lowlands was proposed based on mapping of putative palaeoshorelines from orbiter-based imagery (Parker et al. 1993), although it was found later that mapped palaeoshorelines do not follow equipotential surfaces. The distribution of deltas, valley networks and inverted fluvial ridges along the martian dichotomy could support the ocean hypothesis (e.g. Di Achille and Hynek 2010; DiBiase et al. 2013; Cardenas et al. 2018) if crustal deformation occurred after fluvial activity (e.g. Perron et al. 2007; Chan et al. 2018; Citron et al. 2018a), although a detailed analysis of deltas along the dichotomy in the Gale crater region indicates that their distribution is more consistent with formation within distinct, enclosed lakes rather than a connected ocean (Rivera-Hernández and Palucis 2019). A systematic search for evaporitic phases in the stratigraphy or ejecta of impact craters within the northern lowlands did not reveal widespread evaporitic strata as might be expected from the evaporation of a large ocean (Pan et al. 2017). Early estimates of Mars’ water budget seemed inconsistent with an ocean’s worth of water (Carr and Head 2015) but a significant amount of water, not accounted for in previous estimates, could be trapped within hydrated minerals and possibly account for an early ocean (Mustard 2019; Scheller et al. 2021; Wernicke and Jakosky 2021). In fact, water volumes equivalent to a five times thicker than the upper Al-rich phyllosilicates and poorly crystalline phases in altered outcrops at Mawrth Vallis also suggests that acidic conditions reigned for a short period of time following longer-term neutral–alkaline environments (Loiseau et al. 2010; Bishop et al. 2020; Lowe et al. 2020). Further, the c. 200–250 m
thick Fe-rich smectite unit displays consistent spectral features over thousands of kilometres around the Mawrth Vallis region (Bishop et al. 2008; Noe Dobrea et al. 2010), whereas the upper materials exhibit regional variability in the detection of jarosite, acid-altered phyllosilicates, montmorillonite, kaolinite, opal and poorly crystalline phases similar to allophane (Bishop et al. 2008, 2020; McKewon et al. 2009; Bishop and Rampe 2016).

In contrast to the early view of global acid-sulfate conditions, one might expect ground fluids on early Mars to have largely been neutral–alkaline given the great buffering efficiency of basaltic crust (e.g. Zolotov and Mironenko 2007; Tosca and McLennan 2009; Schwennen et al. 2016; McLennan et al. 2019). Notably, the widespread occurrence of Fe/Mg-smectite across Mars (e.g. Murchie et al. 2019) is consistent with neutral–alkaline waters (e.g. Harder 1976; Schwennen et al. 2016; Bishop et al. 2020). The detection of phases that are incompatible with acidic fluids at both Meridiani and Gale crater (e.g. Cino et al. 2017; Morrison et al. 2018; McLennan et al. 2019) and other indications that freshwater with neutral–alkaline pH was stable for prolonged episodes at Gale crater (e.g., Grotzinger et al., 2014, 2015b; McLennan et al., 2014, 2019; Schwennen et al., 2016) further contradict the view of global acidic conditions. The lack of detectable carbonates in mudstones at Gale crater (Ming et al. 2014; Vaniman et al. 2014) suggests that any CO₂ in ground fluids was efficiently neutralized prior to diagenesis (e.g. Fairén et al. 2004; Niles et al. 2009; Schwennen et al. 2012a, b; Melwani Dwawani et al. 2016; Schwennen et al. 2016) or that atmospheric pCO₂ was low at the time of diagenesis (Bristow et al. 2017). In summary, it appears likely that, rather than reflecting global acidic conditions, jarosite could have originated from late diagenesis (e.g. Tosca et al. 2008) and that evidence for acidic conditions instead reflects local redox processes (e.g. Hurowitz et al. 2010, 2017; McLennan et al. 2019).

Alternatively, inferred early martian surface and near-surface environments are thought to have been conducive to the origin of life and capable of supporting a variety of metabolic pathways. Fe-bearing smectites have been proposed as a candidate system for the origin of life on Earth (e.g. Odom et al. 1979; Lawless 1986) because of the convenient reaction template provided on smectite interlayer surfaces for organic molecules and the potential for Fe to bind with organic compounds. Organic reactions on smectite surfaces have even been shown to catalyse formation of RNA and other precursor molecules necessary for the origin of life (e.g. Ferris et al. 1989; Franchi et al. 2003; Ferris 2006). It is unknown if organic compounds were widely incorporated into Fe/Mg-smectites on Mars, but some organic matter was detected in mudstones at Gale crater (Eigenbrode et al. 2018). Rover observations at a site containing a thick sequence of Fe/Mg-smectite-rich beds (e.g. McAdam et al. 2021) or possibly even altered clays associated with sulfates (Bristow et al. 2021) could reveal the presence of organic compounds in such systems. A multitude of bio-essential elements were detected in martian materials in addition to S, including H, C, N, O, Mg, P, Mn and Fe (McLennan et al. 2014; Ming et al. 2014; Vaniman et al. 2014), some of which could have supported the metabolism of putative early martian life through redox reactions (e.g. Nealon and Conrad 1999; Nixon et al. 2013; Cockell 2014; King 2015; Price et al. 2018; Macey et al. 2020; Sasselev et al. 2020). However, a quantitative understanding of elemental cycling on early Mars remains to be formulated (McLennan et al. 2019) and will require more data to be acquired by rovers and samples to be returned to Earth from the martian surface (Beaty et al. 2019).

Conclusion: parsing through analogies and differences

Modern plate tectonics defines many aspects of Earth’s functioning. By uplifting mountains, it generates thermodynamically and gravitationally unstable source materials that, after erosion and transport as sediments or solutes, accumulate in subsiding terminal depositional basins. Sediments and precipitates are ultimately recycled within Earth’s interior or re-emerge to the surface after exhumation, via sedimentary and geochemical cycles largely driven by plate tectonics. In addition, planetary heat escapes Earth’s interior at a rate (and following surface patterns) dictated by plate tectonics, generating hydrothermal systems when interacting with surficial water that regularly supply energy and geochemical gradients to life. Life in turn has geoengineered Earth’s surface through physical and chemical feedback that promotes environmental stability, affecting the Earth system in a myriad of ways, from atmospheric, soil and water chemistry to sedimentary morphodynamics (e.g. Lovelock 1967; Lovelock and Margulis 1973; Gurnell 2013; Ielpi and Laporte 2020). The degree to which plate tectonics and life affect geological and atmospheric processes today is profound, and envisioning how the surface of our planet operated before the advent of plate tectonics and life is one of the geosciences’ greatest challenges. Further complicating this task, eons of crustal recycling and biological co-evolution have altered the record of Earth’s earliest surface environments, leaving behind scarce clues about how similar or different Earth was in the Precambrian. Earth’s neighbouring planets, Venus and Mars, could be keys to filling this fundamental knowledge gap.

Venus might be the most Earth-like planet in the Solar System, but major mysteries remain regarding its geological and atmospheric evolution that currently hinder its use as an analogue to the early Earth. Upcoming missions to Venus have the potential to change this paradigm if they reveal that Venus was once habitable, as has been proposed before, and that a surface record of its habitable prime exists and is accessible. In contrast, Mars’ exceptionally ancient and well-preserved record offers a unique window into the early surface environments of an Earth-like world that did not evolve plate tectonics or complex surface life, and thus, could help us to better understand the dynamics of Earth’s Precambrian surface. Without the vigorous crustal deformation generated by plate motion, intuition dictates that Mars’ topographic evolution should have largely been unidirectional, with landscapes diffusing through time as a result of erosion of topographic highs and infilling of topographic lows. In addition, it is unclear whether hydrothermal systems potentially conducive to abiogenesis could have existed on early Mars if planetary heat was largely lost by conduction through a thick crust and large but isolated mantle plumes.

Perhaps defying expectations, data from Mars paint a picture of early surface environments that, in many respects, bear surprising resemblance to those of modern Earth. Mars hosted a wide spectrum of environments that were interconnected by complex hydrological, sedimentary and geochemical pathways despite the absence of plate tectonics. Notably, and in addition to limited crustal deformation caused by crustal loading and secular cooling, volcanoes and impact craters generated topography, providing sediment sources and sinks, forming a sedimentary cycle capable of extraformational recycling. Interactions between surficial water and heat from impacts created hydrothermal environments thought to have been habitable over biologically relevant timescales, and that could have therefore served as a refugium for an origin of life. Despite the lack of macroscopic life rooting into sediments and baffling flows and winds, a wide diversity of sedimentary environments has been recognized, including single-thread meandering rivers with relatively stable banks prone to lateral accretion and migration. Without land plants, floodplain mud probably played a major role in stabilizing riverbanks. The apparent abundance of aeolian deposits on Mars could reflect a true preponderance of aeolian processes in unvegetated landscapes, although their true proportions relative to coeval fluviolacustrine deposits remain to be evaluated.
Some igneous evolution occurred on early Mars, but martian surface materials are overall geochemically, mineralogically and petrologically different from those of modern Earth. Although differences in bulk composition of the two planets may exist, the dominance of mafic minerals on Mars is largely attributed to the lack of crustal differentiation operated by plate tectonics. As a result, the measured compositions of martian sedimentary rocks provide unique insights into how the composition of source rocks affects sedimentary processes, from erosion to transport, deposition, diagenesis and alteration. Notably, the polymetallic nature of martian sediments led to compositional sorting at a variety of spatial scales. The basaltic nature of martian sediments also affects the mineralogy and chemistry of weathering products and ground fluids. Ground measurements of rock compositions by rovers have led to significant advances in our understanding of geochemical cycling on Mars, although more work is needed to frame these measurements into a spatiotemporal model for elemental cycling on a pre-plate-tectonic and barren terrestrial planet.

Because similar conditions are likely to have been achieved on Hadean–Archean Earth to those on early Mars, the nature of sedimentary successions on Mars displays unprecedented potential to disclose critical knowledge about sedimentary and geochemical pathways (and timescales) on Earth before the Paleozoic greening of the continents. It is important, however, to also acknowledge fundamental differences that limit the scope of any analogy between the two planets, such as their different acceleration of gravity and divergent climate trajectories. Specifically, resolving outstanding questions about early martian environments, such as the nature of its climate and geochemical cycles, is currently hindered by the paucity of ground data as well as significant age uncertainties associated with crater counting. Just as our knowledge of the early Earth is limited by the fragmentary nature of Earth’s Precambrian record, and despite Mars being one of the most explored planetary bodies beyond the Earth, our understanding of early martian environments is limited by the sparcity of ground-truthed geological data and absolute stratigraphic tie-points. A continued, global exploration effort of Mars will be required to solve remaining fundamental mysteries about the planet’s early days, and in doing so, to better understand the scope and limits of Mars as a time machine to Precambrian Earth.

Acknowledgements The authors thank D. Regis for editorial handling of this paper and are grateful for the insightful reviews provided by S. Schwenzer and K. S. Morgan.

Author contributions MGAL: conceptualization (lead), data curation (lead), writing – original draft (lead), writing – review & editing (lead); JLB: conceptualization (supporting), data curation (supporting), writing – original draft (supporting), writing – review & editing (supporting); DRJ: conceptualization (supporting), data curation (supporting), writing – original draft (supporting), writing – review & editing (supporting); AI: conceptualization (supporting), data curation (supporting), writing – original draft (supporting), writing – review & editing (supporting); HLS: conceptualization (supporting), data curation (supporting), writing – original draft (supporting), writing – review & editing (supporting); SMF: conceptualization (supporting), data curation (supporting), writing – original draft (supporting), writing – review & editing (supporting)

Funding This work was funded by the Natural Sciences and Engineering Research Council of Canada (RGPIN-2016-5720). A.I. is supported by a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada.
McKown, N.K., Bishop, J.L. et al. 2009. Characterization of phyllosilicates observed in the central Mawrth Vallis region, Mars, their potential formational processes, and implications for past climate. Journal of Geophysical Research: Planets 114, https://doi.org/10.1029/2008JE003001

McKinon, W.B., Zahnle, K.J., Ivanov, B.D. and Melosh, J.J. 1997. Cratering on Venus: models and observations. In: Bougher, S.W., Hunten, A.D.M. and Phillips, R.J. (eds) Venus II. Arizona University Press, Tucson, 969–1014.

McLennan, S.M. et al. 2009. Sedimentary processes on Mars. SEPM Special Publication, 102, 119–138, https://doi.org/10.2113/70.112.119.138

McLennan, S.M. and Grotzinger, J.P. 2008. The sedimentary rock cycle of Mars. Geological Association of Canada, St John’s Newfoundland.

McLennan, S.M., Anderson, R.B. et al. 2019. The Martian surface – Composition, Mineralogy, and Physical Properties. Cambridge University Press, Cambridge.

McLennan, S.M., Hamming, S., McDaniel, D.K. and Hanson, G.N. 1993. Geochemical approaches to sedimentation, provenance, and tectonics. Geological Society of America, Special Papers, 284, 21–40, https://doi.org/10.1130/0091-760X(1993)284<0021:GAPSPA>2.3.CO;2

McLennan, S.M., Bell, J.F. et al. 2005. Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars. Earth and Planetary Science Letters, 240, 95–121, https://doi.org/10.1016/j.epsl.2005.09.041

McLennan, S.M., Anderson, R.B. et al. 2014. Elemental geochemistry of sedimentary rocks at Yellowknife Bay, Gale crater, Mars. Science, 343, 1244734, https://doi.org/10.1126/science.1244734

McLennan, S.M., Grotzinger, J.P., Hurowitz, J.A. and Tosca, N.J. 2019. The sedimentary rock cycle on Early Mars. Science, 365, 6031, https://doi.org/10.1126/science.aan4660

McLennan, S.M. and Grotzinger, J.P. 2008. The sedimentary rock cycle of Mars. Geological Association of Canada, St John’s Newfoundland.

Milliken, R.E., Grotzinger, J.P. and Thomson, B.J. 2010. Paleoclimate of Mars as captured by the stratigraphic record in Gale crater. Geology, 38, 1091–1094, https://doi.org/10.1130/G26307.1

Miner, G. 1956. The Martian surface. In: The Martian Surface – Composition, Mineralogy, and Physical Properties, Cambridge University Press, Cambridge.

Miles, K., Kukek, A., Gehrels, T. et al. 2014. Phyllosilicates in the Martian surface: implications for past climate 4,300 Myr ago. Nature, 409, 178–181, https://doi.org/10.1038/3505155

Mole, D.R., Thurston, P.C., Marsh, J.H., Stern, R.A., Ayer, J.A., Martin, L.A.J. and Lu, Y.J. 2021. The formation of Neorarchean continental crust in the south- east Superior Craton by distinct geodynamic processes. Precambrian Research, 356, 106104, https://doi.org/10.1016/j.precamres.2021.106104

Montgomery, D.R., Sarti, S.M., Jackson, M.P.A., Schreiber, B.C., Gillespie, A.R. and Adams, J.B. 2009. Continental-scale salt tectonics on Mars and the origin of Valles Marineris and associated outflow channels. Geological Society of America, America Bulletin, 121, 117–133, https://doi.org/10.1130/B26307.1

Moore, J.M. and Howard, A.D. 2005. Large alluvial fans on Mars. Journal of Geophysical Research: Planets, 110, https://doi.org/10.1029/2004JE002352

Morgan, R.V., Vaniman, D.T. et al. 2008. Silicic volcanic rocks on Mars evidenced by tridymite in high- SiO2 sedimentary rock at Gale crater. Proceedings of the National Academy of Science of the USA, 113, 7071–7076, https://doi.org/10.1073/pnas.1607988113

Morrison, S.M., Downs, R.T. et al. 2018. Crystal chemistry of martian minerals from Bradbury Landing through Naukluft Plateau, Gale crater, Mars. American Mineralogist, 103, 857–871, https://doi.org/10.2138/am-2018-6124

Moyen, J.-F. and van Hune, J. 2012. Short-term episodicity of Archaean plate tectonics. Geology, 40, 451–454, https://doi.org/10.1130/G32289.1

Murchie, S.L., Birering, J.P. et al. 2019. Visible to short-wave Infrared spectral analyses of Mars from orbit using CRISM and OMEGA. In: Bishop, J.L., Bell, J.F. and Moersch, J.E. (eds) Remote Compositional Analysis: Techniques for Understanding Spectroscopic Methodology, and Geochemistry of Planetary Surfaces. Cambridge University Press, Cambridge, 453–483, https://doi.org/10.1017/9781108488872.025

Musil, D.R., 2019. Sequestration of volatiles in the Martian crust through hydrated minerals: a significant planetary reservoir of water. Earth and Planetary Science Letters, 54, 305–309, https://doi.org/10.1016/j.epsl.2019.07.097

Nahm, A.L. and Schultz, R.A. 2011. Magnitude of global contraction on Mars from analysis of surface faults: implications for martian thermal history. Icarus, 211, 389–400, https://doi.org/10.1016/j.icarus.2011.05.022

Nealon, K.H. and Conrad, P.G. 1999. Life: past, present and future. Philosophical Transactions of the Royal Society of London. Series B, 354, 1923–1939, https://doi.org/10.1098/rstb.1999.0532

Nesbit, H.W. 2003. Petrogenesis of siliciclastic sediments and sedimentary rocks. In: Lenz, D.R. (ed.) Geochemistry of Sediments and Sedimentary Rocks, Geotext 4. Geological Association of Canada, St John’s, NL, 39–51.

Niles, P.B., Zolotov, M.Y. and Leshin, L.A. 2009. Insights into the formation of Fe- and Mg-rich aqueous solutions on early Mars provided by the ALH 84001 carbonates. Earth and Planetary Science Letters, 286, 122–130, https://doi.org/10.1016/j.epsl.2009.06.039

Nimmo, F. and Stevenson, D.J. 2000. Influence of early plate tectonics on the thermal evolution and mantle composition of Mars. Icarus, 140, 115–133, https://doi.org/10.1006/icar.2000.6317

Nimmo, F. and Schenk, P.M. 2009. Volcanic outgassing on Mars and the origin of the Martian crust. In: Kallenbach, R., Gess, J. and Hartmann, W.K. (eds) Chronology and Evolution of Mars, Space Science Series of ISS, 12. Springer, Dordrecht, https://doi.org/10.1007/978-94-017-1035-0_5

Nisbet, E.G. and Sleep, N.H. 2001. The habitat and nature of early life. Nature, 409, 1083–1091, https://doi.org/10.1038/3509210a

Nixon, S., Cousins, C.R. and Cockell, C. 2013. Plausible microbial metabolisms on Mars. Astronomy and Geophysics, 54, 1.13–1.16, https://doi.org/10.1093/astrogeo/ast034

Noo Dobra, E.Z., Bishop, J.L. et al. 2010. Mineralogy and stratigraphy of phyllosilicate-bearing and dark mantling units in the greater Mawrth Vallis/ Eridania basin on Mars. Journal of Geophysical Research: Planets, 115, https://doi.org/10.1029/2009JE003351

Nyquist, L.E., Bogard, D.D., Shih, C.-Y., Greshake, A., Stöffler, D. and Eugster, W. 2010. The Martian crust. In: The Martian Surface – Composition, Mineralogy, and Physical Properties, Cambridge University Press, Cambridge.

Nyquist, L.E., Bogard, D.D., Shih, C.-Y. et al. 2009. Association of nucleotides with hydrated minerals: a significant planetary reservoir of water. Icarus, 200, 816–840, https://doi.org/10.1016/j.icarus.2009.03.024

Nyquist, L.E., Bogard, D.D., Shih, C.-Y., Greshake, A., Stöffler, D. and Eugster, W. 2009. The Martian crust. In: The Martian Surface – Composition, Mineralogy, and Physical Properties, Cambridge University Press, Cambridge.

Nyquist, L.E., Shih, C.-Y. et al. 2016. RB-Str and Sm-Nd isotopic and REE studies of igneous components in the bulk matrix domain of Martian breccia Northwest Africa 7034. Meteoritics and Planetary Science, 51, 492–498, https://doi.org/10.1111/maps.12606

Odoni, D.G., Rao, M., Lawless, J.G. and Oro, J. 1979. Association of nucleotides with hydrated minerals: a significant planetary reservoir of water. Icarus, 200, 816–840, https://doi.org/10.1016/j.icarus.2009.03.024
