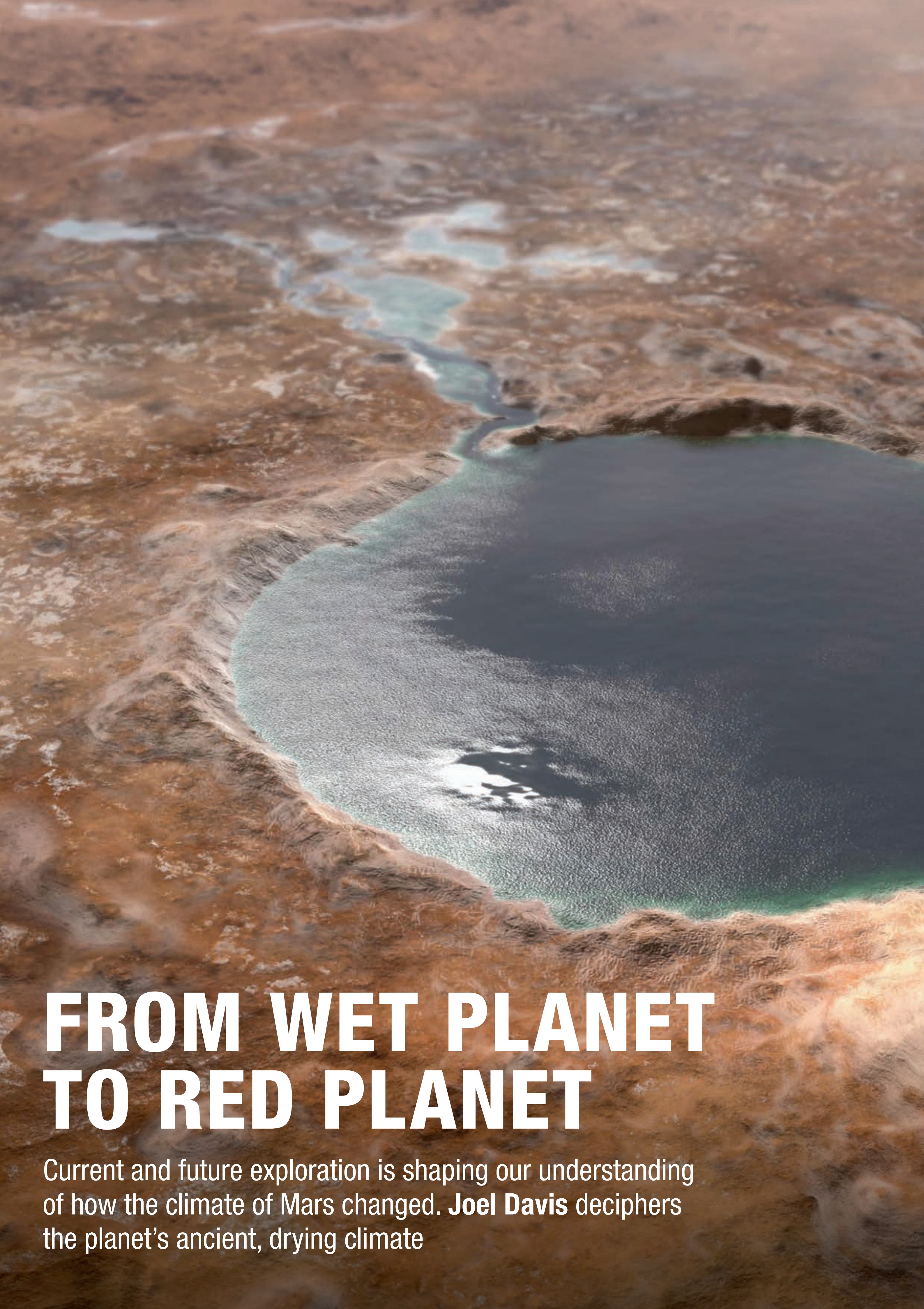
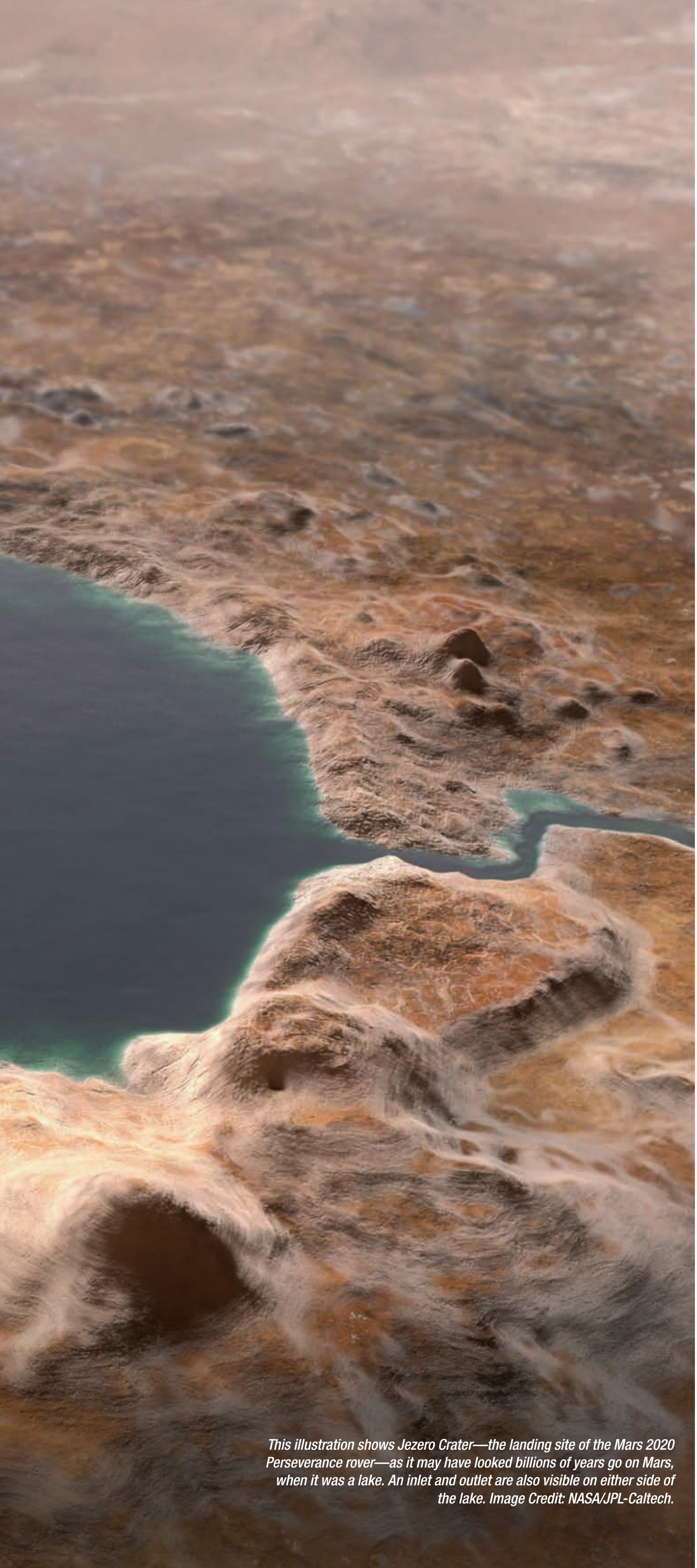


# FROM WET PLANET TO RED PLANET

Current and future exploration is shaping our understanding of how the climate of Mars changed. **Joel Davis** deciphers the planet’s ancient, drying climate



This illustration shows Jezero Crater—the landing site of the Mars 2020 Perseverance rover—as it may have looked billions of years go on Mars, when it was a lake. An inlet and outlet are also visible on either side of the lake. Image Credit: NASA/JPL-Caltech.

It has been an exciting year for Mars exploration. 2020 saw three spacecraft launches to the Red Planet, each by different space agencies—NASA, the Chinese National Space Administration, and the United Arab Emirates (UAE) Space Agency. NASA's latest rover, *Perseverance*, is the first step in a decade-long campaign for the eventual return of samples from Mars, which has the potential to truly transform our understanding of the still scientifically elusive Red Planet. On this side of the Atlantic, UK, European and Russian scientists are also getting ready for the launch of the European Space Agency (ESA) and Roscosmos *Rosalind Franklin* rover mission in 2022.

The last 20 years have been a golden era for Mars exploration, with ever increasing amounts of data being returned from a variety of landed and orbital spacecraft. Such data help planetary geologists like me to unravel the complicated yet fascinating history of our celestial neighbour. As planetary geologists, we can apply our understanding of Earth to decipher the geological history of Mars, which is key to guiding future exploration. But why is planetary exploration so focused on Mars in particular? Until recently, the mantra of Mars exploration has been to follow the water, which has played an important role in shaping the surface of Mars. Liquid water is also thought to be key to the formation and evolution of life. However, it is not the present martian environment that shows the richest evidence for water—it is the ancient geological past.

Today, Mars is a cold, hyper-arid desert. Its surface is mostly covered by a thin layer of iron oxide dust, giving the Red Planet its characteristic red-orange hue, visible even with the most basic of telescopes from Earth. And we know that Mars is dry—the pressure from its thin $CO_2$ atmosphere is so low that liquid water at most latitudes would instantly boil to vapour. Towards the poles, water-ice is stable in the shallow sub-surface of the martian regolith and thick water-ice caps cover both the north and south poles. But liquid water, for the most part, is not thought to be stable anywhere ▶

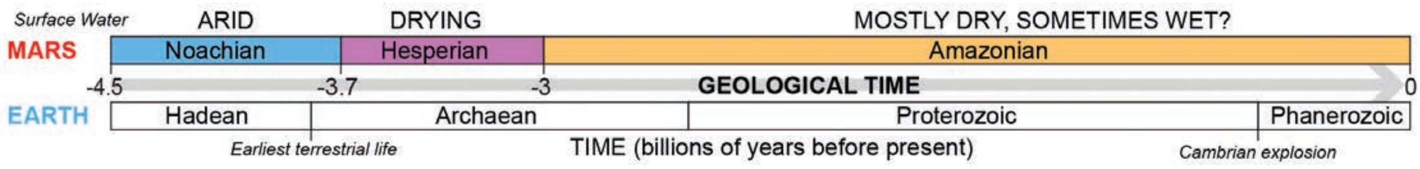



*Figure 1: Geological time scale of Mars (and its inferred climate) compared to Earth*

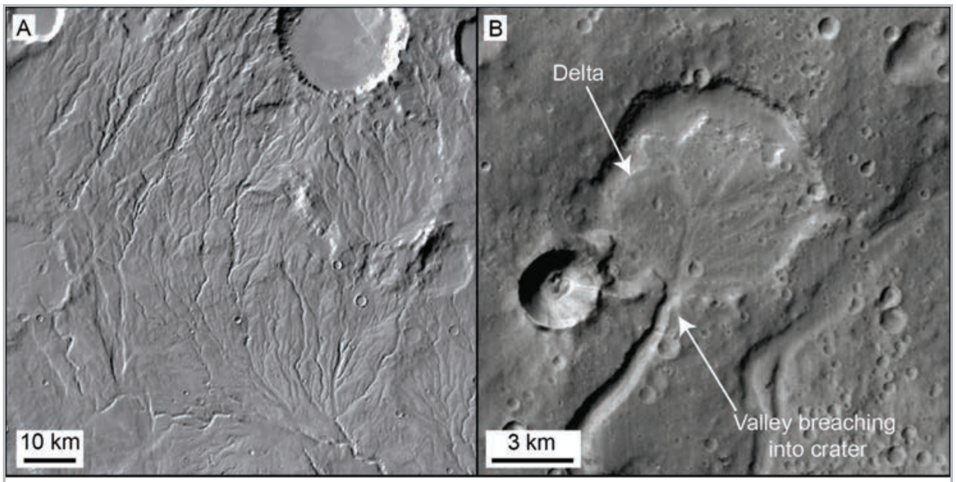
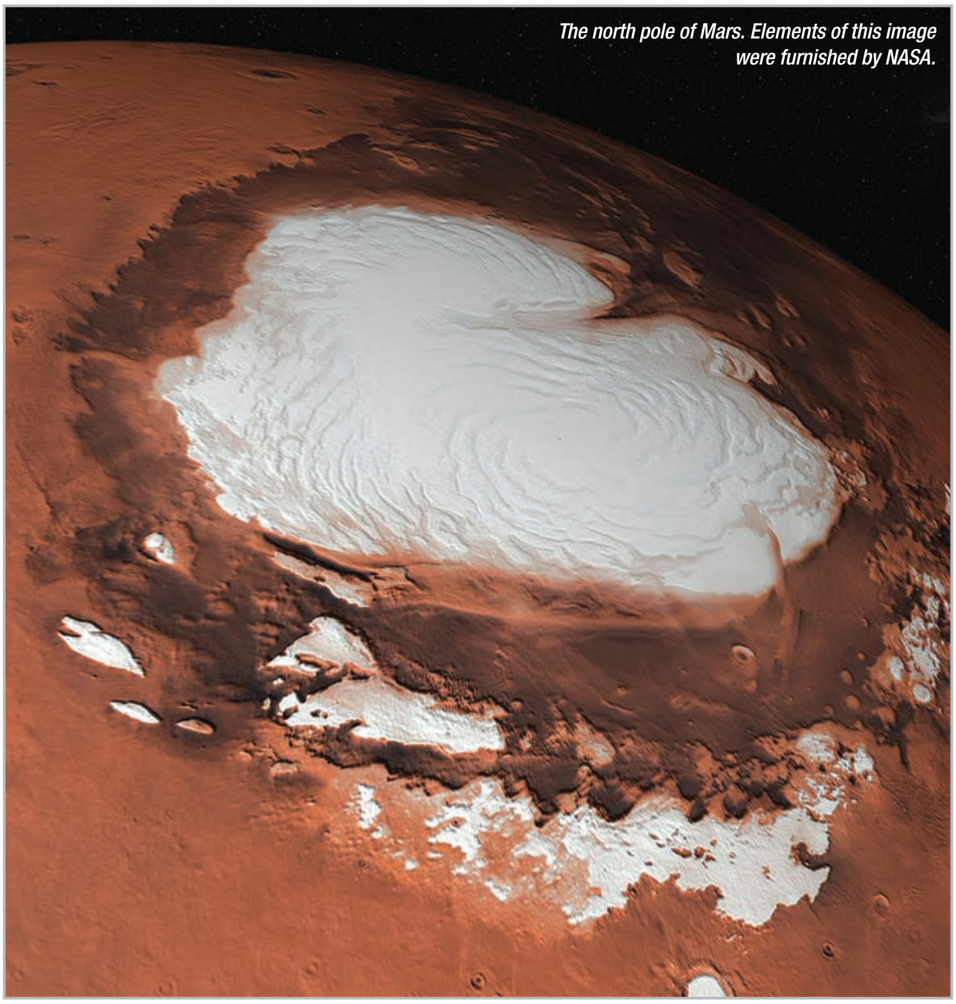



*Figure 2: (A) Satellite image of a valley network on Mars with multiple branching tributaries, a former river system. Inferred flow direction is from the top to the bottom of the image. Credit: NASA/JPL/ASU. (B) Satellite image of valley network breaching into impact crater, likely the site of a palaeo-lake. A delta has formed at the breach. Credit: NASA/JPL/MSSS*



*The north pole of Mars. Elements of this image were furnished by NASA.*

across the planet. The geology of Mars today tells us that in the ancient past, Mars was a very different place.

## Water on Noachian Mars

Nearly four billion years ago, in the early days of the Solar System, the surface of Mars was being re-sculpted by volcanism and intense impact cratering. This geological period on Mars is known as the Noachian, spanning from the planet's formation around 4.5 billion years ago (Ga) to about 3.7 Ga (Fig. 1). Unlike on Earth, geological periods on Mars are determined from the density of impact craters on surfaces (with more impact craters accumulating over time). Surfaces are then assigned absolute ages by calibrating to the Moon, where surfaces have been dated using the Apollo samples.

Around half of the martian surface is Noachian aged and across most of these surfaces we see strong evidence for liquid water. Cutting across many Noachian surfaces are what we as Mars geologists colloquially refer to as the "valley networks". When viewed from orbit, these valley networks are linear to branching erosional troughs that follow topography. They resemble river valleys on Earth and are thought to have formed in a similar manner, through precipitation and water erosion (Fig. 2). The largest valley networks form systems up to 5,000 km long, equivalent to many continental-scale drainage basins on Earth.

We have known about these valley networks since the Viking era of Mars exploration in the 1970s. Although there was initially some discussion about whether these features could have formed via other mechanisms (such as lava), it is now generally accepted that they formed via water erosion. However, it is unclear how long these features took to form. The valley networks have not fully eroded the Noachian landscape (many ancient impact craters are still preserved), which suggests that they were only active for geologically brief periods of time, perhaps as little as a

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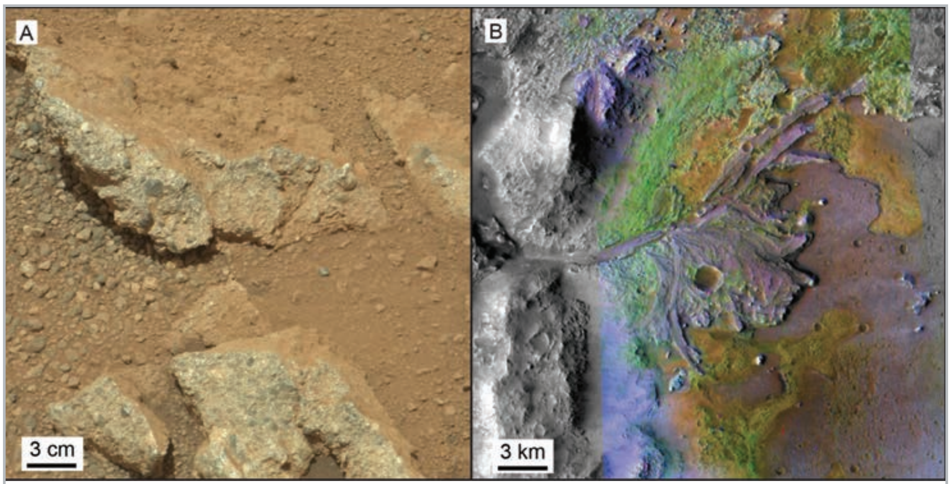


*Figure 3: (A) Image from the Curiosity rover of a conglomerate in Gale crater, likely deposited by an ancient river. Credit: NASA/JPL/MSSS. (B) False colour satellite image of the delta in Jezero crater, the future landing site of NASA's Perseverance rover. The false colours indicate variations in composition. Credit: NASA/JPL/ASU*

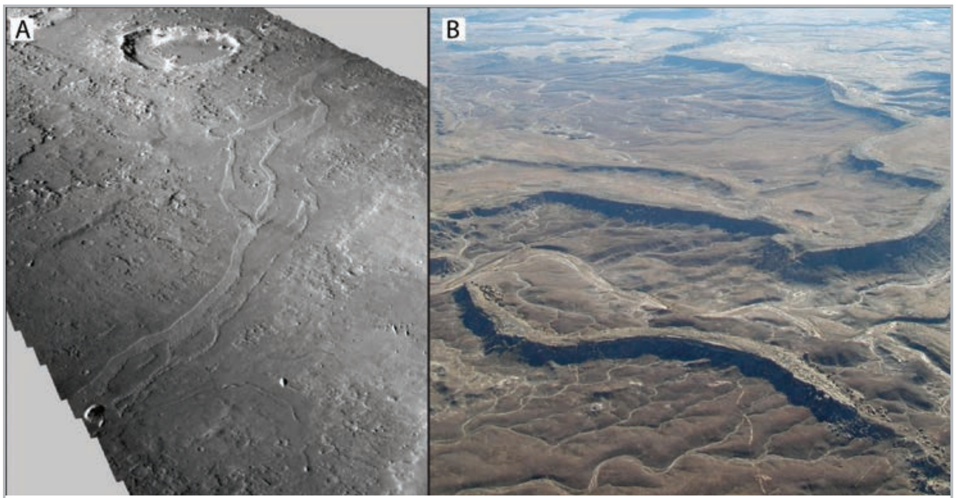


*Figure 4: (A) 3D perspective view of a 100-km-long ridge system on Mars, interpreted as exhumed river channel sediment (an "inverted channel deposit"). Credit: NASA/JPL/MSS/Matt Balme. (B) Aerial view of Jurassic river channel deposits in Utah, USA, preserved as a ridge. Credit: Rebecca M.E. Williams*

few thousand years or maybe as long as ten million years—either way, a small fraction of the total time in the Noachian.

Excitingly, valley networks have been observed to intersect impact craters, suggesting that in the Noachian water may have pooled in the craters to form a lake (Fig. 2). Gale crater, the exploration site for the *Curiosity* rover since 2012, is one of these palaeo-lakes (Fig. 3; although it is unclear if Gale represents a Noachian lake or is younger in age). At least 200 large palaeo-lakes have been identified on the surface of Mars so far. In many, we find fan-shaped sedimentary deposits, interpreted as ancient river deltas that formed within crater lakes. These deltas are defined by the branching remains of channels and meanders, and are considered a prime target for the detection of ancient life on Mars due to the ability of deltas to concentrate potential organic matter. However, in Earth's rock record it is rare for such deltaic deposits to be preserved in planform (that is, where their shape from above is still recognisable), so we have a limited understanding of how much geological time these features represent. NASA's *Perseverance* rover will begin to explore one of these ancient deltas at Jezero crater in 2021 (Fig. 3).

Another unusual landform found on Noachian surfaces are "inverted channel deposits". These features are amalgamations of river channel sediment that became resistant to erosion and are now preserved as ridges in the landscape instead of depressions (Fig. 4). River channel deposits preserved as ridges seems unusual, but similar features exist in deserts on Earth: in Oman, Egypt, and the American southwest. Much of my own research is devoted to the investigation of these fascinating features, which cross the boundary between geology and geomorphology. Whilst the valley networks represent upland, erosional rivers, we think that the inverted channel deposits were the lowland, depositional rivers set within alluvial floodplains. Like many features on Mars, we are only beginning to understand the formation of the inverted channel deposits, but they could potentially represent millions of years of geological time, perhaps even more than the valley networks. Many of these inverted channel deposits are found adjacent to phyllosilicate-bearing rocks, which formed in the presence of water. Phyllosilicates and other aqueous minerals are particularly common on Noachian surfaces; significant amounts of water would have been required to alter Mars's basaltic crust and generate these minerals.

Taking a step back, when viewing Mars as a whole, we can see that chains of valley networks and palaeo-lake basins flow northwards, possibly representing the remains of a planet-wide hydrological cycle. These systems converge on the edge of Mars's northern lowlands—a huge basin that makes up one third of the martian surface (Fig. 5). There is ample discussion about whether this hemisphere-spanning basin once contained an ocean-sized body of water; ▶

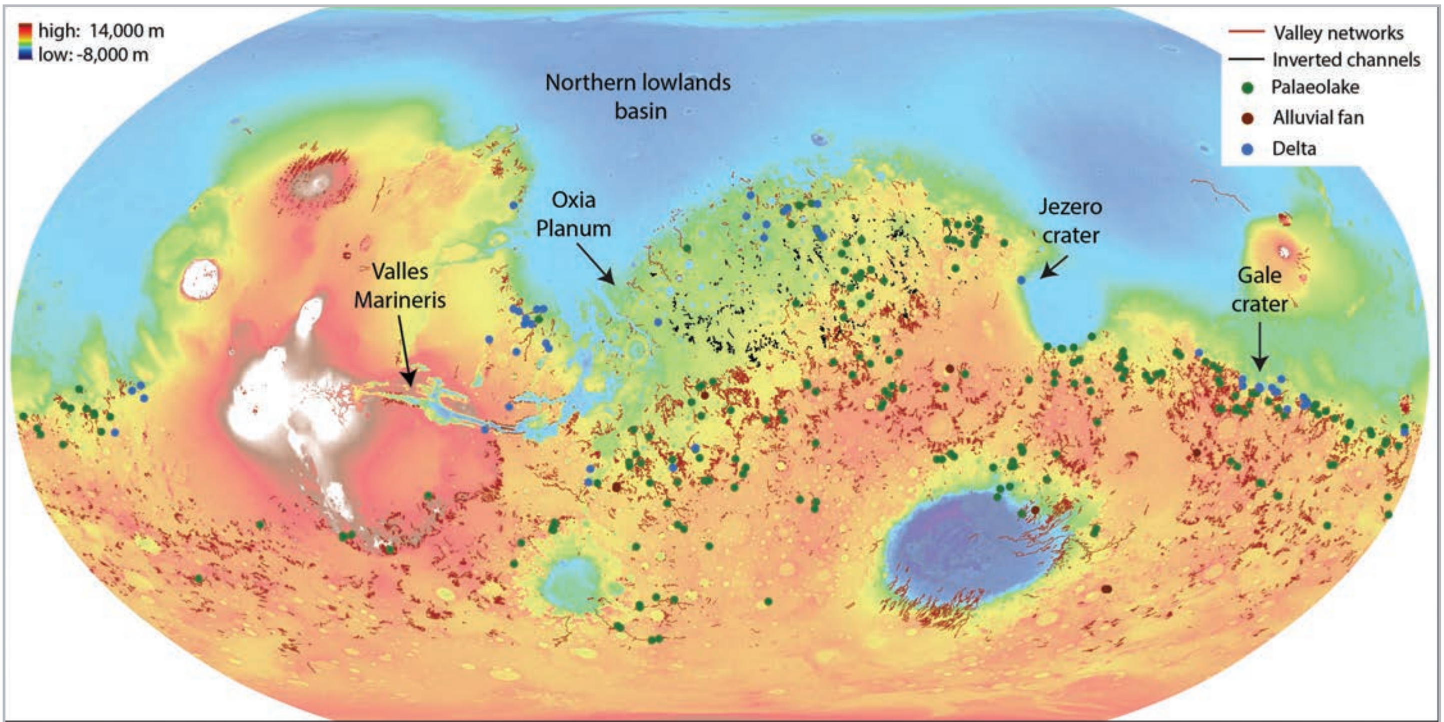


*Figure 5: Topographic map of the surface of Mars. Most of the features formed by water are concentrated on the oldest, Noachian terrains, and converge on Mars's northern lowland basin. Credit: NASA/JPL/GFSC*

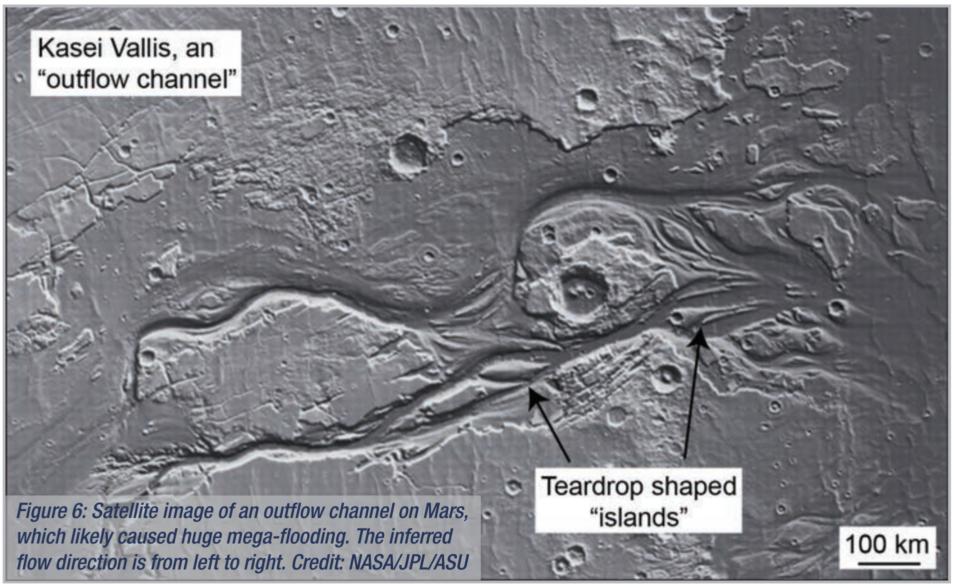


*Figure 6: Satellite image of an outflow channel on Mars, which likely caused huge mega-flooding. The inferred flow direction is from left to right. Credit: NASA/JPL/ASU*

▶ indeed, it is almost completely unknown whether there was enough water on the surface of Mars to fill such a vast basin. However, detailed analysis of Mars's geology can provide a framework to begin to address this fascinating question. My colleagues and I recently investigated an ancient delta deposit located at the end of a large valley network system called Hypanis Vallis, at the edge of the northern lowlands basin. The geology of the Hypanis delta suggests that it formed into a large body of water and grew in response to a falling water level—a receding northern ocean perhaps? Luckily for us, in 2023 the *Rosalind Franklin* rover will land at location called Oxia Planum, on the margins of the northern plains, so answering this question about the existence of an ancient Noachian ocean may not be too far off.

## The Mars climate problem

There is abundant geological evidence from both orbiting spacecraft and rovers for water in the Noachian. But how was liquid water able to exist on ancient Mars when today it cannot?

A commonly held assumption is that Mars had a thicker atmosphere in the Noachian than it does at present, and that some sort of $CO_2$-$H_2O$ greenhouse effect raised the surface temperatures above freezing. Hence, Noachian Mars is often referred to as being "warm and wet". Measurements by NASA's MAVEN spacecraft indicate that the Noachian atmosphere was about 1 bar pressure, similar to Earth today (Mars is 0.006 bars currently), and composed of $CO_2$, most of which has since been lost to space. This loss of $CO_2$ to space also explains why we do not see extensive deposits of carbonate on Mars, the sedimentary sink for $CO_2$ on Earth. Mars's early atmosphere could have been shielded from removal by an ancient magnetic field, or perhaps $CO_2$ was continuously resupplied by volcanic gases. However, our problems in understanding the Noachian palaeo-climate are just beginning.

Although we can see extensive evidence for liquid water in Mars's Noachian rock record, we still do not fully understand the environment and climate that allowed it to exist. When climate modellers try to reconstruct the ancient Noachian palaeo-climate, the models often fail to show mean annual surface temperatures above freezing.

This issue largely comes from the "faint young Sun paradox", which is the idea that the Sun was much less luminous in its early history and so Mars received even less heat than it does today, and which the proposed greenhouse effect was unable to compensate for. So where does that leave liquid water in the Noachian? Well, an alternative scenario is that water on Noachian Mars was mostly frozen, locked up in thick ice caps in the high-elevation regions around the equator. Melting would only occur due to localised and brief episodes of heating, such as from volcanism or impact cratering. However, it is unclear whether these brief melting episodes in this "icy highlands" scenario are sufficient to explain Mars's Noachian geological record. Both the "warm and wet" and "icy highlands" scenarios are end members; the Noachian may have actually been somewhere in between these models—perhaps "occasionally warm and wet" is a better descriptor.

## After the Noachian

Another major question that planetary geologists like myself are interested in is what happened to Mars after the Noachian? The fact that so much of this ancient geology is preserved for us to study today suggests that erosion after the Noachian was very slow. Correspondingly, we see a lot less evidence for long-lived liquid water in the geologically younger surfaces, which are divided into the Hesperian (~ 3.7-3.0 Ga) and Amazonian (~ 3.0-0 Ga) periods. The Hesperian and Amazonian geological records suggest that Mars became increasingly dry. This is the case at Gale crater, where we see temporal transition in the rock record from phyllosilicates (formed in the presence of water) to iron oxide (formed anhydrously). One idea to explain this is that following the Noachian, the removal of Mars's early thick atmosphere reached a point where it was no longer able to sustain liquid water for long periods of time. However, that is not to say that water was absent completely after the Noachian.

If we look at Hesperian surfaces, we see that many of them are cut by huge channel systems (Fig. 6). These features, known as outflow channels, strongly contrast with the valley networks in that they are hundreds of kilometres wide and thousands of kilometres long—individually! The outflow channels typically branch around teardrop shaped former islands, indicating that they had immense erosive power and probably required huge volumes of water to form. We can often trace the origin of the outflow channels to a single source region, which has led many to suggest that they formed by the rapid release of sub-surface water or the melting of large volumes of ice in mega-flooding events, an order of magnitude larger than the biggest floods we know of on Earth. However, these mega-floods were probably brief events, perhaps lasting as little as a few days, and do not necessarily require a warm climate to sustain them. Instead, the mega-floods may have been triggered by large volcanic eruptions or impact events.

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Within Mars's equatorial canyon system, Valles Marineris, we can see numerous, conical alluvial fans along the canyon walls (Fig. 7). On Earth (for example, in Death Valley, USA), alluvial fans form sub-aerially ▶

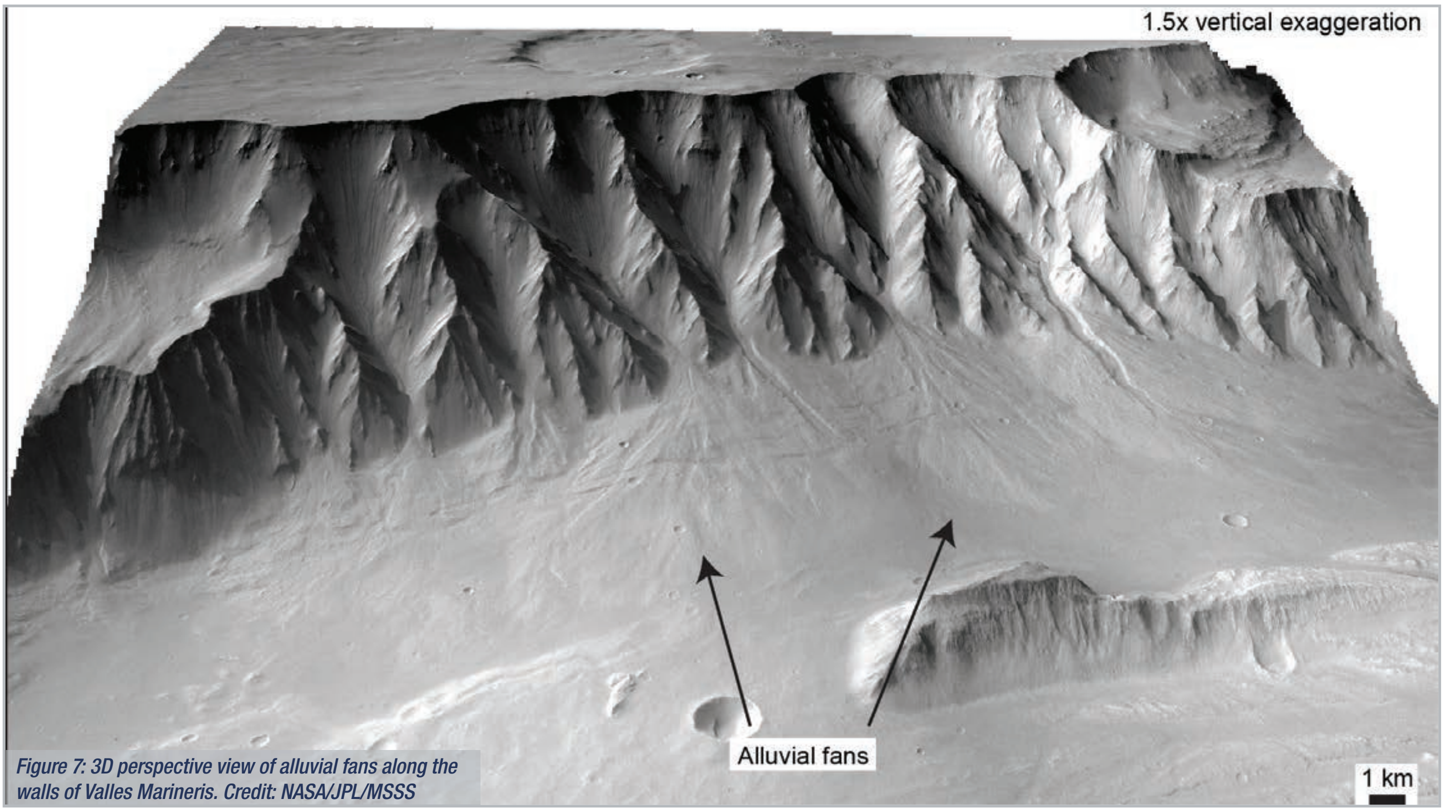


*Figure 7: 3D perspective view of alluvial fans along the walls of Valles Marineris. Credit: NASA/JPL/MSSS*

▶ in mountainous regions, driven by the episodic flow of water and sediment down a slope and into a dry basin, where it forms a fan. Interestingly, these alluvial fans are believed to have formed after the mega-flooding events and it is not entirely clear how the martian climate was able to sustain them. One idea is that local micro-climates may have existed in Valles Marineris and could sustain liquid water, leading to intermittent, geologically brief "wet episodes", in an otherwise dry climate. There are many other features recorded in the Hesperian and Amazonian surfaces that suggest that these intermittent "wet episodes" affected other regions of Mars as well. Although we do not see the global networks of former rivers that we do on Noachian surfaces, both Hesperian and Amazonian terrain show some evidence for the influence of liquid water, albeit a declining one. However, as we approach the geologically recent past, we see more and more evidence that Mars became entirely frozen, paving the way for today's hyper-arid surface environment.

## Future exploration

Deciphering the ancient martian palaeo-climate and its evolution through time is one of the reasons why extensive, in situ rover investigations of the planet's Noachian geology are necessary. Indeed, both *Perseverance* and *Rosalind Franklin* will explore Noachian-age sites at Jezero and Oxia Planum, respectively. Despite their age, the rocks at Jezero and Oxia Planum may also record evidence that can explain how the climate of Mars changed after the Noachian, and whether liquid water continued to be available intermittently.

*Perseverance* could reveal whether the Noachian-age lake at Jezero crater was covered by ice, a possibility under the "icy highlands" scenario. *Perseverance* will also be the first spacecraft to investigate examples of inverted channel deposits and these deltaic landforms in situ. Excitingly, found at Jezero (and rarely for Mars) are deposits of carbonate-bearing rocks. Investigating how these carbonates formed and whether they were sequestered from an early, $CO_2$-rich atmosphere will provide key insight into the nature of the Noachian climate and its decline. One of the end goals of *Perseverance* is to cache various samples for eventual return to Earth. Having Noachian samples of known geological context finally in our hands will significantly advance our understanding because we will be able to establish absolute ages for events on Mars (as was the case with the Lunar Apollo samples).

The geological environment at Oxia Planum is less clear: it is set within a topographic basin that may have once hosted a lake or been on the margins of an ocean-sized body of water. Oxia Planum is also rich in phyllosilicate-bearing rocks, which for their formation required significant amounts of water to alter Mars's basaltic crust. But, like many things about Mars, exactly how these phyllosilicates formed is far from clear. The UK is leading the development of *Rosalind Franklin's* Panoramic Camera, which will be able to determine the composition and geological context of these aqueous minerals. Detailed mapping using orbital images, such as from the Colour and Stereo Science Imaging System (CaSSIS; Fig. 8), of both sites is currently underway to provide important geological context and to establish the locations of target outcrops for investigation, prior to landing.

Mars exploration is now moving towards the direct detection of ancient life, and this is the main objective of both *Perseverance* and *Rosalind Franklin*. However, establishing geological context for the local, regional, and global environment is imperative to enable us to confidently support any potential "life" claim. Mars, originally believed to have been a barren, volcanic landscape, is now proving to have a complex stratigraphy, rich in water-formed sedimentary rocks. For me as geologist, the exciting thing about both these upcoming rover missions is that they will be roving across and sampling the Noachian. They will be able to finally provide ground truth to our orbital observations and unravel the four-billion-year-old mystery of the Noachian climate and how it changed.


*Figure 8: False colour CaSSIS image of Oxia Planum, the landing site for the Rosalind Franklin rover in 2023. The dark material to the left is thought to be mafic, volcanic material, whereas the orange and blue materials are hydrated phyllosilicate minerals, formed in the presence of water. Credit: ESA/University of Bern/UoA-Jason Perry*

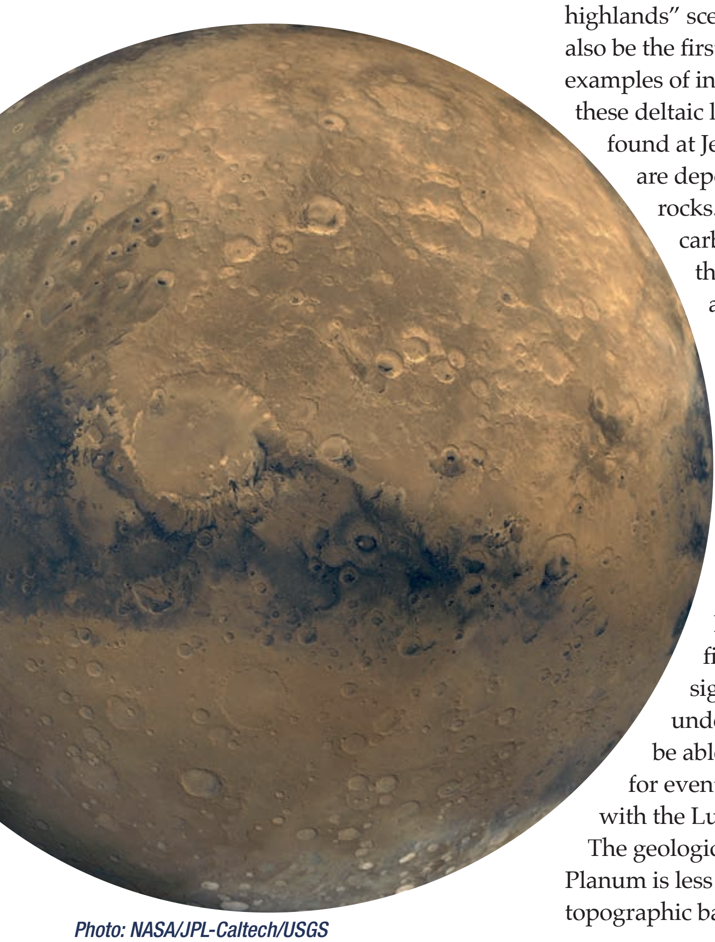

*Photo: NASA/JPL-Caltech/USGS*

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