Lecture 8: Prospects for Life on Mars

Aims of Lecture

(1) To summarise the reasons why Mars is considered to be, or to have been, a possible habitat for life;

(2) To describe past, and anticipated future, efforts to detect evidence for life on Mars; and

(3) Briefly to discuss the scientific implications of such a discovery.

Contents of Lecture

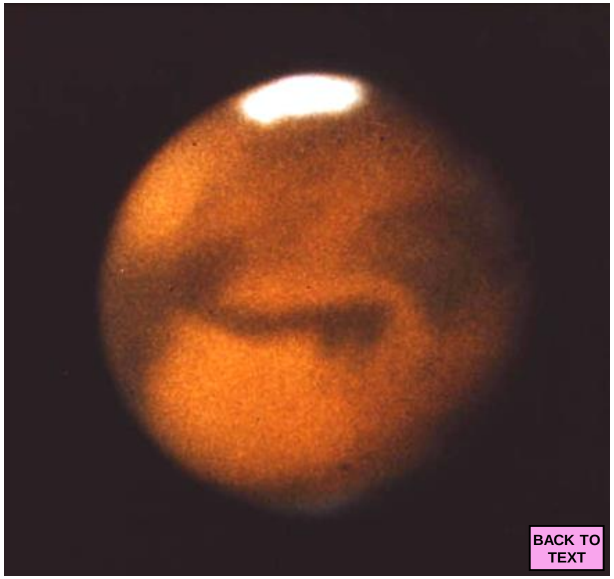

Fig. 1. Mars viewed through a telescope from Earth (Robert Leighton/NASA).

1. Introduction

Mars has long featured prominently in speculations concerning life elsewhere in the Solar System. Historically, this is mainly because early telescopic views revealed polar caps, suggesting the presence of water, and dark surface features which exhibit seasonal variations and which were attributed to surface vegetation (Fig. 1). Interest reached fever pitch in the late 19th century when the American astronomer Percival Lowell thought that he could detect canals built on the planet by a Martian civilisation.

The early space missions provided both good and bad news for proponents of life on Mars. On the one hand, they conclusively demonstrated that Lowell's canals did not exist, and that the present surface environment of Mars is extremely hostile to life as we know it. On the other hand, these missions did reveal extensive evidence for liquid water having been present in the past, and with it the implication that Mars may once have been much more hospitable to life.

2. Water on Mars

The evidence for past water on Mars consists of:

2.1 Outflow channels

These features provide evidence for the catastrophic release of large quantities of liquid water. Some of these (e.g. Fig. 2) originate from the giant Valles Marineris canyon system, which may have ponded water in the past, while others arise from seemingly collapsed regions where subsurface water, perhaps from an aquifer or melted permafrost layer, appears to have been released catastrophically (Fig, 3). Most have estimated ages between 3.7 and 3.0 billion years, but some smaller examples may be only a few tens of millions of years old. Insofar as the outflow channels indicate the presence of sub-surface aquifers, they suggest that potentially habitable underground environments existed at least until the time of their formation (see Section 5, below).

Fig. 2. Part of Ares Vallis, a large outflow channel flowing into Chryse Planitia. The large crater is about 60 km across (Viking image, NASA).

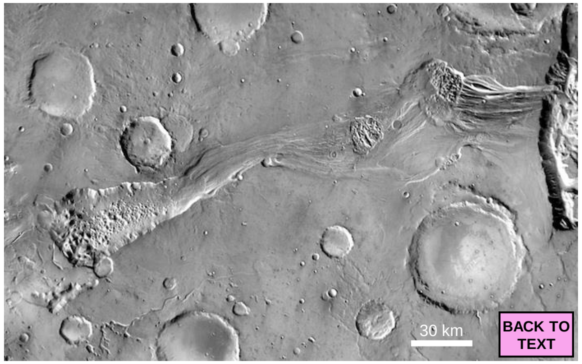

Fig. 3. Ravi Vallis, an outflow channel beginning in a region of chaotic terrain, caused by the sudden release of ground water (Mars Odyssey/NASA).

2.2 Sinuous channels

These are superficially similar to terrestrial river valleys (Fig. 4), but their short, stubby tributaries suggest they were formed by ground water sapping (essentially by springs), rather than by precipitation. Most have estimated ages in the range ~4 to 3.5 Gyr. Their morphologies imply a more sedate release of water than for the outflow channels, which provides stronger evidence for higher temperatures and atmospheric pressures at the time of formation.

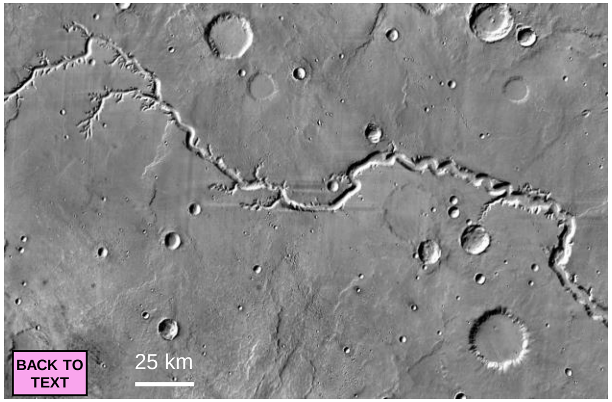

Fig. 4. A section of Nirgal Vallis, a ~400 km long sinuous Martian valley. Note the meanders and short, stubby, tributaries (Mars Odyssey THEMIS mosaic/Google Mars/NASA).

2.3 Dendritic networks

Of all Martian channels, these are the most like terrestrial drainage networks (Fig. 5), although whether they were actually formed by rainfall, or by ground water sapping, is still debated. The dendritic networks are the oldest Martian channels, mostly being older than 3.7 billion years and confined to the ancient southern highlands. Note that the extent to which it has rained on Mars is heavily constrained by the preservation of ancient craters which would have been eroded away in an Earth-like climate.

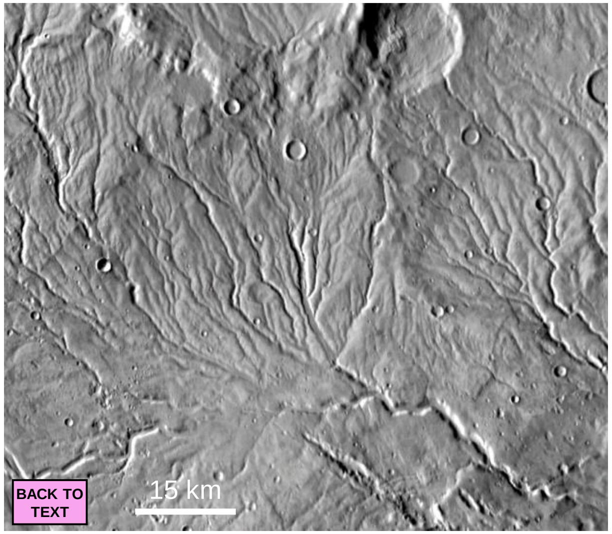

Fig. 5. Warrego Vallis, a dendritic valley network in the southern highlands ((Mars Odyssey THEMIS mosaic/Google Mars/NASA).

2.4 Oceans, lakes and deltas

The large Martian outflow channels, and many other fluvial features, flow northwards into the lowlands that occupy much of Mars' northern hemisphere (Fig. 6). This raises the possibility that between ~ 4 and 3 Gyr ago the northern lowlands were occupied by one or more oceans.

Although the evidence for oceans on Mars is controversial (for a recent review see Zach Dickeson and Joel Davis, *Astronomy & Geophysics*, 61, 3.11-3.17, 2020), the geological evidence for large crater lakes appears unequivocable (Fig. 7). Some of the craters that are inferred to have once held lakes exhibit deltas at the mouths of channels flowing into them, together with clear mineralogical evidence that water was involved in their formation (Fig. 8). Thus, there is little doubt that between ~4 and 3 Gyr ago Mars had abundant water on its surface and, as far as we can judge, would have been a habitable environment for suitably adapted micro-organisms.

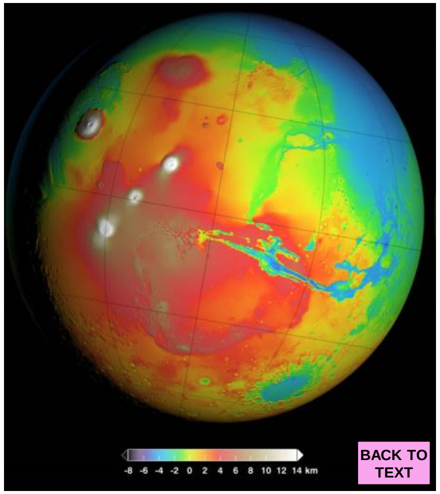

Fig. 6. Martian topography (NASA).

Fig. 7. Layered sedimentary rocks (siltstones and sandstones) in the Kimberley Formation of Gale Crater. These rocks are consistent with deposition in a fluvio-deltaic environment ~3.5 Gyr ago and indicate that Gale Crater (diameter ~150 km) contained one or more lakes at that time. As for Jezero Crater (Fig. 8), and other Martian crater lakes, this would appear to have been a habitable environment. The colour has been modified for Earth-like illumination, making the sky artificially blue (Curiosity rover/NASA).

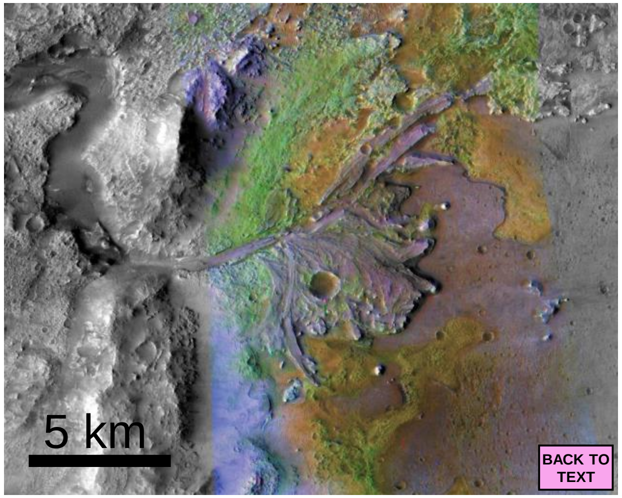

Fig. 8. False colour IR spectrometer data of a delta in the 45 km diameter Jezero Crater. Blue: pyroxene-bearing rocks in crater wall; Green: clay minerals (e.g. smectite); Orange: olivine-rich sands blown into crater; Purple: no distinct spectral signature. (NASA/Ehlmann et al., *Nature Geoscience*, 1, 355-358, 2008).

2.5 Recent water on Mars?

Although most of the evidence for liquid water on the surface of Mars dates from billions of years ago, there is intriguing evidence for more recent (and perhaps even contemporary) outpourings of water on the surface, albeit at a much smaller scale. For example, there are small-scale outflow channels, such as Athabasca Vallis (Fig. 9), for which crater counting indicates ages of only tens of millions of years. The likely sources of water are sub-surface aquifers that have been breached by volcanic or tectonic activity, which implies that sub-surface habitable environments may have existed until recently (and may still exist).

Evidence for even more recent liquid water on the Martian surface may be provided by gullies (Fig. 10(a)) and the seasonally recurring dark streaks (Recurring Slope Lineae, RSL; Fig. 10 (b)) observed on steep, generally sun-facing, slopes. However the involvement of liquid water (most plausibly in the form of brines) in the creation of these features is still debated.

Fig. 9. Part of Athabasca Vallis, a small outflow channel thought to be only ~20 Myrs old; image is ~2.5 km across (MGS/MSSS/NASA).

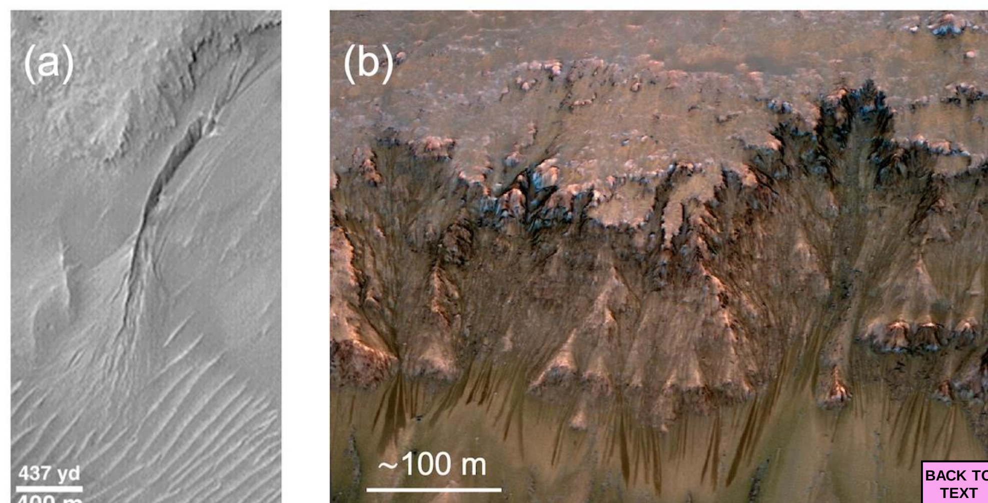

Fig. 10 (a). A gulley formed in the wall of Nirgal Vallis; evidence for youth is provided by the fact that gulley deposits overlie aeolian dunes (MGS/MSSS/NASA). **(b)** Recurring Slope Lineae (RSL) in the wall of Newton Crater; individual RSL are ~1-5 m wide (MRO/HIRISE/NASA). Water (or brine) released from sub-surface aquifers may be involved in the formation of both types of feature, but this is still uncertain.

3. Possibilities for life on Mars

The evidence for past liquid water on Mars implies that the planet was once much more hospitable than it is today. In particular, the sinuous channels, crater lakes and delta deposits imply the *prolonged* presence of liquid water at the surface, which would only have been possible if both the temperature and pressure were higher, probably owing to a stronger CO_2 greenhouse effect.

At this time (3.5 to 4.0 Gyr ago) conditions on Earth and Mars were probably much more similar than they are today. We know that life was present on the Earth at about the same time, and under what were probably similar conditions (i.e. CO_2 atmosphere, liquid water, temperatures above freezing), and this is the main reason for taking the possibility of life on Mars seriously. Some biologists have gone as far as to predict that life would almost necessarily have formed under these conditions. For example, the Nobel Prize-winning biochemist Christian de Duve writes in his book *Vital Dust: Life as a Cosmic Imperative* (1995):

> *"Life is almost bound to arise … wherever physical conditions are similar to those that prevailed on our planet some 4 billion years ago …."*

By searching for life on Mars we can *test* this prediction. However, even if life did evolve on Mars in the past, it is possible that it retreated deep below the surface, or became extinct altogether, as conditions on the planet worsened. Thus, there are broadly three possibilities for life on Mars which we need to examine:

- Extant near-surface life;
- Extant life beneath the surface; and
- Extinct life.

4. Extant surface life

4.1 The Viking biology experiments

The most detailed scientific search for extant life on Mars was performed by the two Viking landers in 1976. These were equipped with a robotic arm (Fig. 11) which scooped up the top few cm of soil near the landing site and dropped it into an onboard biological laboratory. The Viking study actually consisted of three separate biology experiments (shown schematically in Fig. 12), and a search for organic compounds in the soil using a mass spectrometer.

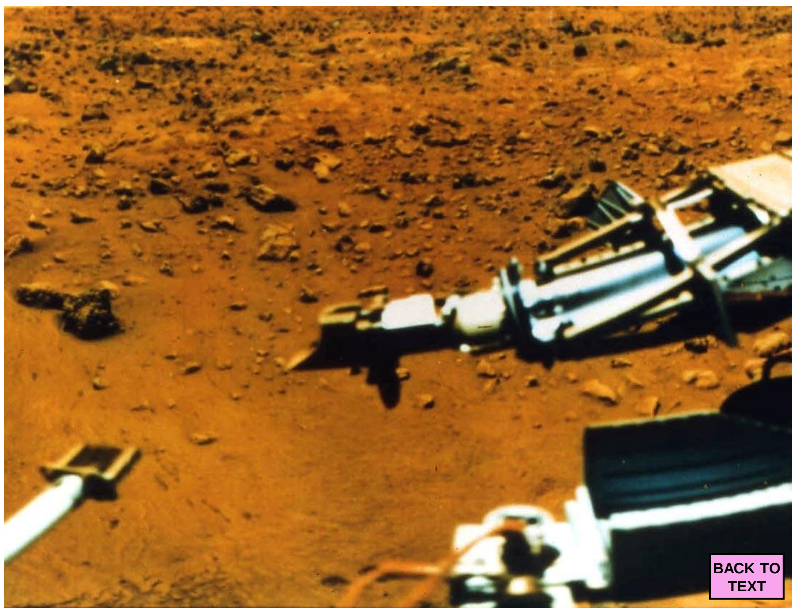

Fig. 11. Viking 1 on the surface of Mars in 1976. Note the arm with the scoop for collecting soil samples for the biology experiments (NASA).

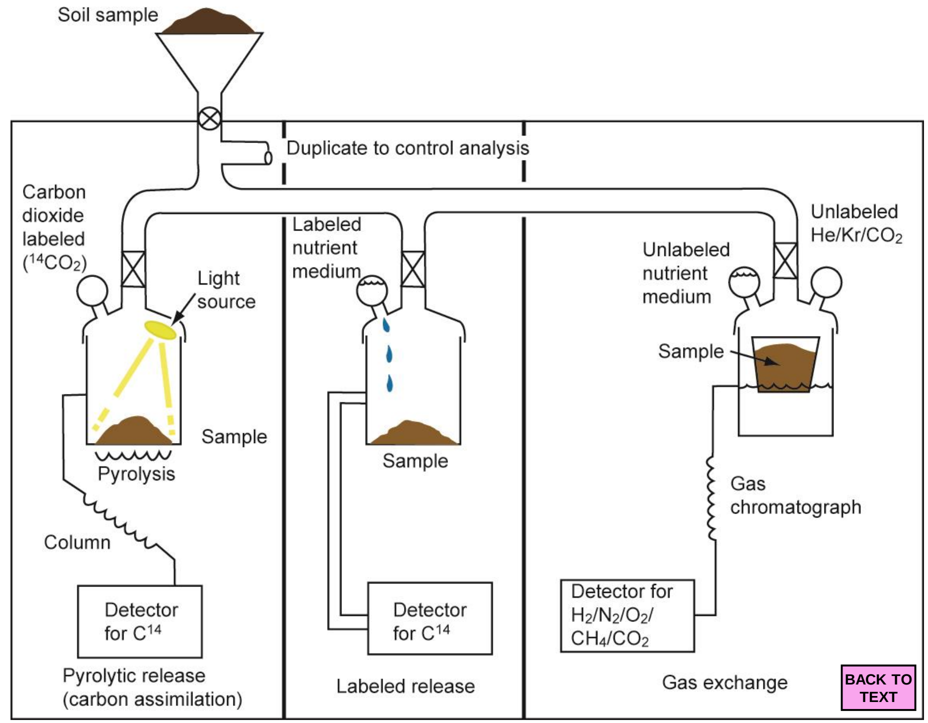

Fig. 12. Schematic illustration of the three Viking biology experiments. See text for details.

(a) Pyrolytic release experiment

This experiment, also known as the 'carbon assimilation experiment', was designed to test if Martian organisms took CO_2 from the atmosphere and converted it into organic material. To this end, the soil sample was exposed to CO_2 made from the radioactive isotope of carbon (^{14}C) which had been brought from Earth (left hand panel of Fig. 12). Some experiments were run in the presence of water, and others not, and in the presence and absence of light. After allowing 5 days for metabolism to occur, the soil was heated to 635°C break apart ("pyrolize") and release any organic molecules which may have been generated by organisms in the soil. These would be detectable through assimilated radioactive ^{14}C.

The experiment did demonstrate that CO_2 was taken up by the soil in a manner that initially appeared consistent with biological activity. However, the presence or absence of water had no effect (perhaps unlikely for a biological reaction), and some, albeit reduced, activity occurred with the light switched off (seemingly eliminating photosynthesis as a cause). Moreover, heating the soil samples to 90°C for two hours prior to exposing them to CO_2, which should have killed any microorganisms which may have been present, did not eliminate the effect (although more severe heating, to 175°C for three hours did significantly reduce the take up of CO_2).

Although today we might choose to heat the sample to greater than 90°C in order to be sure of sterilizing it, it does seem very unlikely that microorganisms adapted to the sub-zero temperatures of the Martian surface could have survived this treatment. For this reason, the seemingly positive result of this experiment was therefore ascribed to a geochemical reaction between the CO_2 and oxidants in the soil (e.g. H_2O_2), perhaps involving the formation of organic polymers, and not to biological activity.

(b) Labelled release experiment

In this experiment organic nutrients, again labelled with radioactive isotopes, were placed in contact with the soil (central panel of Fig. 12). The idea was that if these nutrients were utilised by organisms in the soil then radioactive waste gasses, such as CO_2, would be given off and detected. Again, the initial results appeared positive. Moreover, in this case heating the samples to 50°C for three hours prior to addition of the nutrients greatly reduced the effect, and heating to 160°C for three hours stopped it entirely. This is the kind of result that might be expected if the participating microbes had been killed by the heat.

Of the three Viking biology experiments, the labelled release experiment was the most consistent with the presence of life in the Martian soil. Unfortunately, on its own this result does not prove the presence of life, because oxidising chemicals in the soil might also react with the nutrients to produce a similar response.

(c) Gas exchange experiment

In this experiment (right hand panel of Fig. 12), the soil samples were again exposed to a mixture of nutrients (this time not labelled with radioactive ^{14}C) and the sample monitored for gasses released by living organisms. This experiment searched for a wider range of gasses than the labelled release experiment and CO_2, N_2 and O_2 were detected. However, a biological origin was considered unlikely because sterilising the sample at 145°C for 3.5 hours did not prevent the reaction. Moreover, O_2 was released in the dark (excluding photosynthesis) and when H_2O alone was added to the sample, rather than the full set of nutrients. For these reasons, the release of both O_2 and CO_2 was once again attributed to chemical reactions with oxidants in the soil and not to biological activity.

(d) Mass spectrometer results

The mass spectrometer was designed to detect organic molecules in the soil at the ppb level. No convincing evidence of organic molecules was detected (traces of benzene, toluene and chloromethane were detected were attributed to terrestrial contaminants). This result was extremely negative for proponents of Martian life. Combined with the confusing and inconclusive results of the three biology experiments, this led to the general conclusion that life was not present in the soil samples analysed at the two Viking landing sites.

This conclusion is now less clear cut. In 2008 the Phoenix lander discovered perchlorates in the Martian soil (e.g. $Mg(ClO_4)_2$ and $Ca(ClO_4)_2$), which could react with and destroy organic molecules as the samples were heated prior to analysis with the mass spectrometer. Therefore it is possible that the organic content of Martian soils is higher than indicated by the Viking results (see review paper by I. ten Kate, *Astrobiology*, 10, 589, 2010). That said, the top few cm of the surface are probably the last place on Mars where life might be expected, so the Viking results are in any case of limited value in assessing the wider prospects for life on Mars (e.g. in the deep sub-surface).

4.2 More recent surface searches for life

To-date the Viking experiments are the only attempt to detect active microbial metabolism on Mars. All subsequent landers have restricted themselves to geological investigations of past habitability, sometimes supplemented with searches for extant organic molecules.

Currently, the most active such mission is NASA's Curiosity rover landed that landed in Gale crater on 6 August 2012 (Fig. 13). As noted above, Curiosity It has found evidence that Gale crater once contained a lake, and so probably was once a habitable environment (Fig. 7).

Among Curiosity's many instruments (for details see https://mars.nasa.gov/msl/), the most important from an astrobiology point of view is the Sample Analysis at Mars (SAM) package which contains a mass spectrometer for analysing organic materials. So far only a modest range of organic molecules have been detected by pyrolysis of sedimentary rocks at Gale Crater, including a range of small aliphatic and aromatic hydrocarbons (e.g. C_6H_6, C_2H_3, C_3H_5, etc), sulphur-bearing hydrocarbons (e.g. C_4H_4S, C_5H_6S, etc) and chlorine-bearing hydrocarbons (e.g. C_6H_5Cl). The total organic carbon concentrations are of the order of 20 ppm, and may by fragments of more complex, kerogen-like, organic materials in the host rocks (see Jennifer Eigenbrode et al., *Science*, 360, 1096, 2018).

Variable atmospheric CH_4 has been detected by Curiosity (Fig. 14). Possible sources include: rover outgassing, volcanic outgassing, chemical weathering (serpentinization), breakdown of organics delivered by meteorites, release of geologically trapped methane, or biological methanogenesis. In June 2019 an even larger spike in CH_4 (21 ppbv). However, these methane spikes have not been detected by ESA's Trace Gas Orbiter, which arrived at Mars in 2016 to search for methane and other trace gasses in the atmosphere, possibly implying a very local source.

Fig. 13. A Curiosity selfie taken in October 2019. Note the two small drill holes to the left of the rover for SAM analyses (NASA).

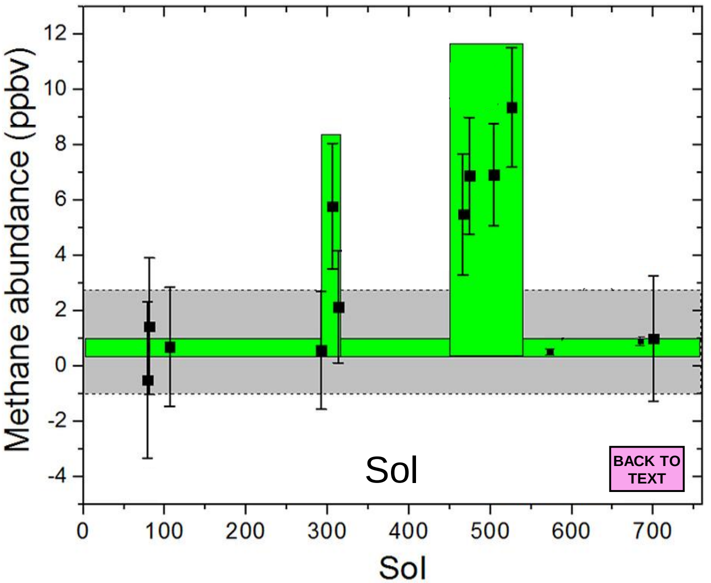

Fig. 14. Atmospheric CH_4 variations detected by Curiosity in Gale crater (NASA).

In 2020 NASA launched its Perseverance rover to investigate Jezero crater and its delta (see Fig. 8). The rover itself is similar to Curiosity, but with a different set of instruments. It will also cache samples for possible future sample return (for details see the mission website.

In 2022 ESA will launch its ExoMars rover, Rosalind Franklin (Fig. 15). The most relevant astrobiology instrument is the Mars Organic Molecule Analyser (MOMA) which, like SAM on Curiosity, will search for organic molecules in rock and soil samples. ExoMars has an advantage over earlier missions in being able to drill to depths of ~2 m, and therefore analyse samples obtained from below the oxidising and radiation-bathed surface.

4.3 Sample return

Ultimately, a comprehensive search for past or present life in the near-surface of Mars will require the return of samples to Earth. Currently a Mars Sample Return mission is tentatively planned for the late 2020s, possibly to collect samples cached by NASA's Perseverance rover. These would be transported to an ascent vehicle (Fig. 16) which would rendezvous with an orbiting spacecraft that would return them to Earth. Current plans would return ≳10 separate samples, having a total mass of ~0.5 kg, collected within several km of the cache site. Such a mission would greatly add to our knowledge of the sample site (i.e. Jezero crater if the Perseverance cache is used) and Martian geology more generally, and would make possible very sensitive analyses for organic material in laboratories on Earth.

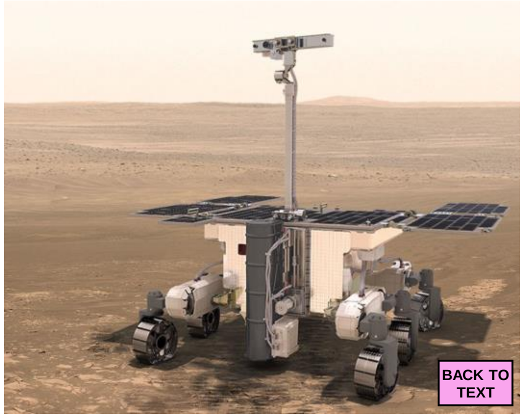

Fig. 15. Artist's drawing of ESA's Rosalind Franklin rover on Mars (ESA). Details of the rover's instruments can be found at: https://exploration.esa.int/web/mars/-/45103-rover-instruments

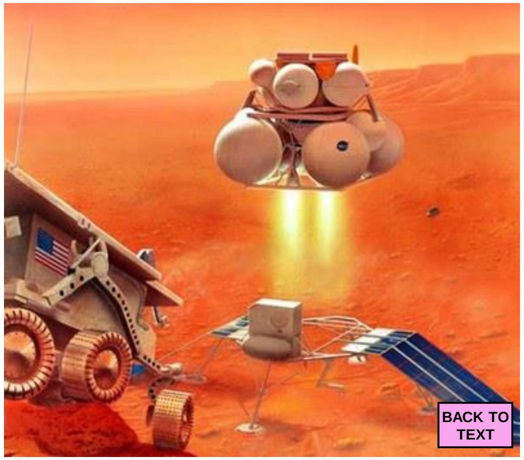

Fig. 16. Artist's impression of a robotic Mars Sample Return mission (NASA).

5. Extant sub-surface life

It is possible to imagine much more hospitable regions, at least for microorganisms, than the near surface of Mars. For example, in 2018, the ground penetrating radar on ESA's Mars Express spacecraft found evidence for a body of liquid water (aquifer or lake) ~20 km in size (but unknown thickness) about 1.5 km below the surface of Mars' South Polar Cap (R. Orosei et al., *Science*, 361, 490, 2018), which could potentially be habitable for micro-organisms. This interpretation has been questioned, but in any case sub-surface bodies of water (or brines) are quite likely on Mars.

Evidence for recent discharges of water at the Martian surface (Section 2.5, above) raises the possibility that sub-surface oases for life may exist even today. Such regions would be warmer than the surface, liquid water might exist, and they would be shielded from the solar ultraviolet radiation. There is also evidence (based on crater morphology and other observations) for a deep global cryosphere/aquifer system occupying the top few km of much of the Martian crust (Fig. 17). This is the likely repository for some of the water that we know Mars had in the past, and may be the source of water that appears to have been released in geologically recent, if relatively small-scale, outflows such as that shown in Fig. 9.

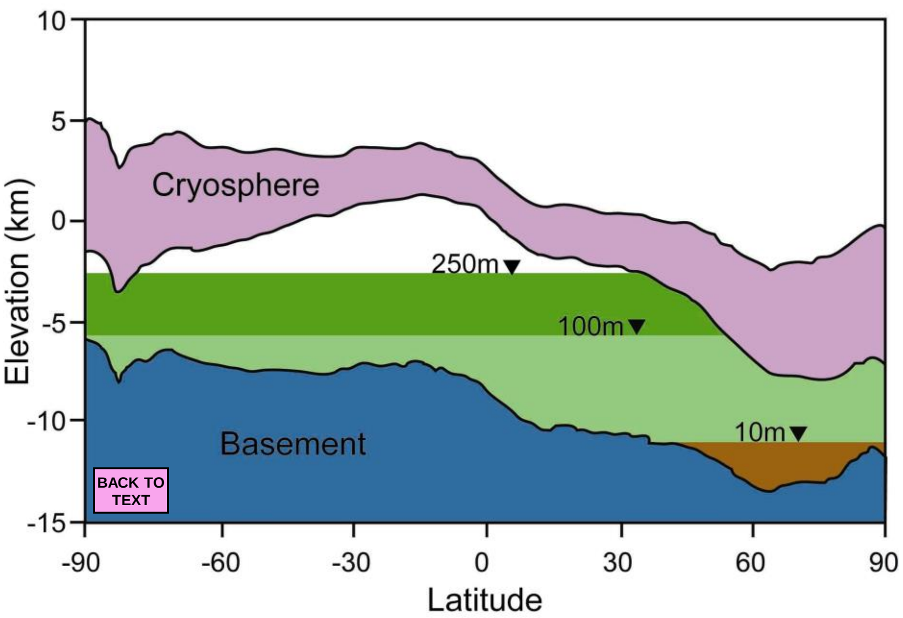

Fig. 17. Schematic illustration of Mars' cryosphere, showing storage capacity for liquid water as depths averaged over the planet. Actual depth to basement is not known (after M. Carr, *Water on Mars*).

The base of such a cryosphere, where geothermal heat may melt the ice, may provide a benign environment for the kinds of sub-surface lithoautotrophic ecosystems (SLiMEs) recently discovered on Earth (Lecture 7). However, proving the existence of Martian SLiMEs will require drilling to depths of several km, and may be beyond the capabilities of small-scale robotic probes (this may be an argument for future human exploration).

6. Extinct life: The case for Martian palaeontology

Even if there is no extant life on Mars today, there remains the possibility that life arose on the planet in the distant past but is now extinct. If so, it is possible that ancient Martian sedimentary deposits, such as those shown in Fig. 7, will contain fossils (presumably microfossils) of early Martian life forms. However, finding it may require a much more ambitious programme of surface exploration than any currently planned, possibly involving astronauts operating on the surface (Fig. 18).

There are two further points to make:

- While most Martian sedimentary rocks will probably be very old (i.e. 3-4 Gyrs), the lower rate of geological activity means that they are likely to be much less disturbed than terrestrial sediments of comparable age. If fossil material exists it may therefore be very well preserved!

- Martian sediments may preserve evidence for pre-biological chemical evolution on Mars (see Lecture 5), regardless of whether life itself actually evolved. Such a record would be scientifically extremely valuable, as it is unlikely to be preserved anywhere else in the solar system.

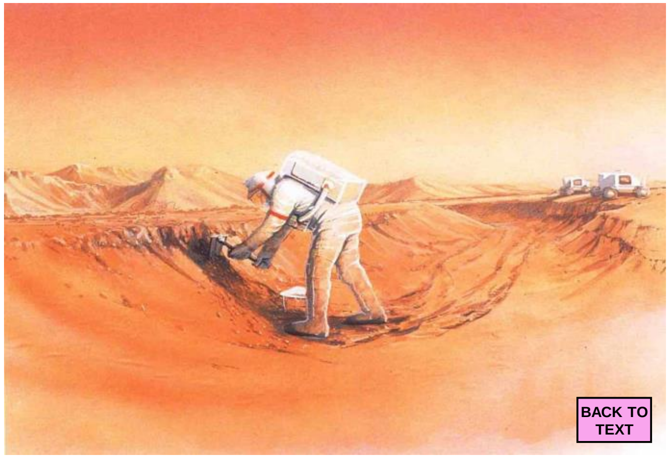

Fig. 18. A painting by Robert Murray showing an astronaut digging for fossils on Mars (courtesy of the artist).

7. The Martian meteorite ALH 84001

In 1996 it was claimed that evidence for past life on Mars had been found within the Martian meteorite ALH 84001 (Fig 19). The evidence consisted of four main strands:

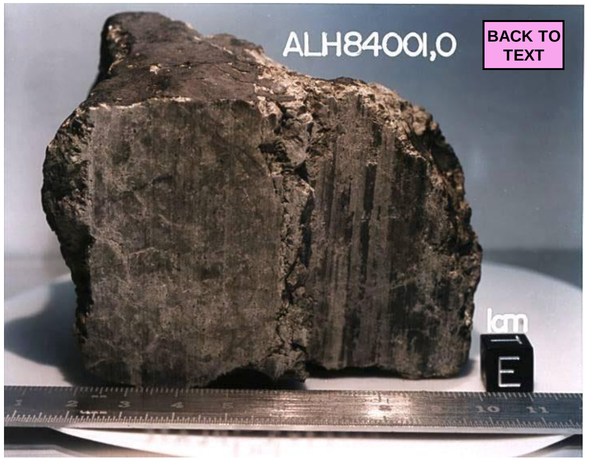

Fig. 19. The Martian meteorite ALH 84001 (NASA).

(a) The presence of small (50 micron) carbonate globules filling cracks within the rock (Fig. 20). These indicate that water once flowed through the rock, something which is also true of other Martian meteorites. The presence of small grains of magnetite associated with the carbonates, was claimed to be similar to magnetite grains produced by some kinds of terrestrial bacteria.

(b) The detection of organic molecules within the meteorite. However, the organic molecules detected (so-called polycyclic aromatic hydrocarbons) are not unique to living organisms, and have also been detected in other, non-Martian, meteorites.

(c) Very small (about 0.1 micron long and 0.01—0.02 micron wide) micro-fossil-like shapes which superficially resemble terrestrial micro-fossils but which are ten to a hundred times smaller and are unlikely to be biological in origin.

Fig. 20. Microscope view of carbonate globules within ALH 84001 (NASA).

The general consensus is that ALH 84001 does *not* contain plausible evidence for life on early Mars. However, this conclusion from a single rock by no means implies that life never existed on Mars. As discussed above, a much more detailed exploration of the planet will be required before any firm conclusions can be reached.

8. Wider implications of life on Mars

If evidence for life, whether extinct or extant, is found on Mars the scientific implications will be profound. It will first be necessary to try to establish whether the life is indigenous to Mars, or has been transported from Earth to Mars (or vice versa) by meteorites. If life did arise independently on Mars, then the fact that it did so twice on neighbouring planets in the same solar system would imply that it likely to be common on planets of other stars (as Christian de Duve has already predicted).

On the other hand, should we determine that life never evolved on Mars, despite the fact that 3 to 4 billion years ago the environment was probably similar to that under which life arose on Earth, we may have to admit that life is difficult to establish and hence likely to be rare in the Universe.