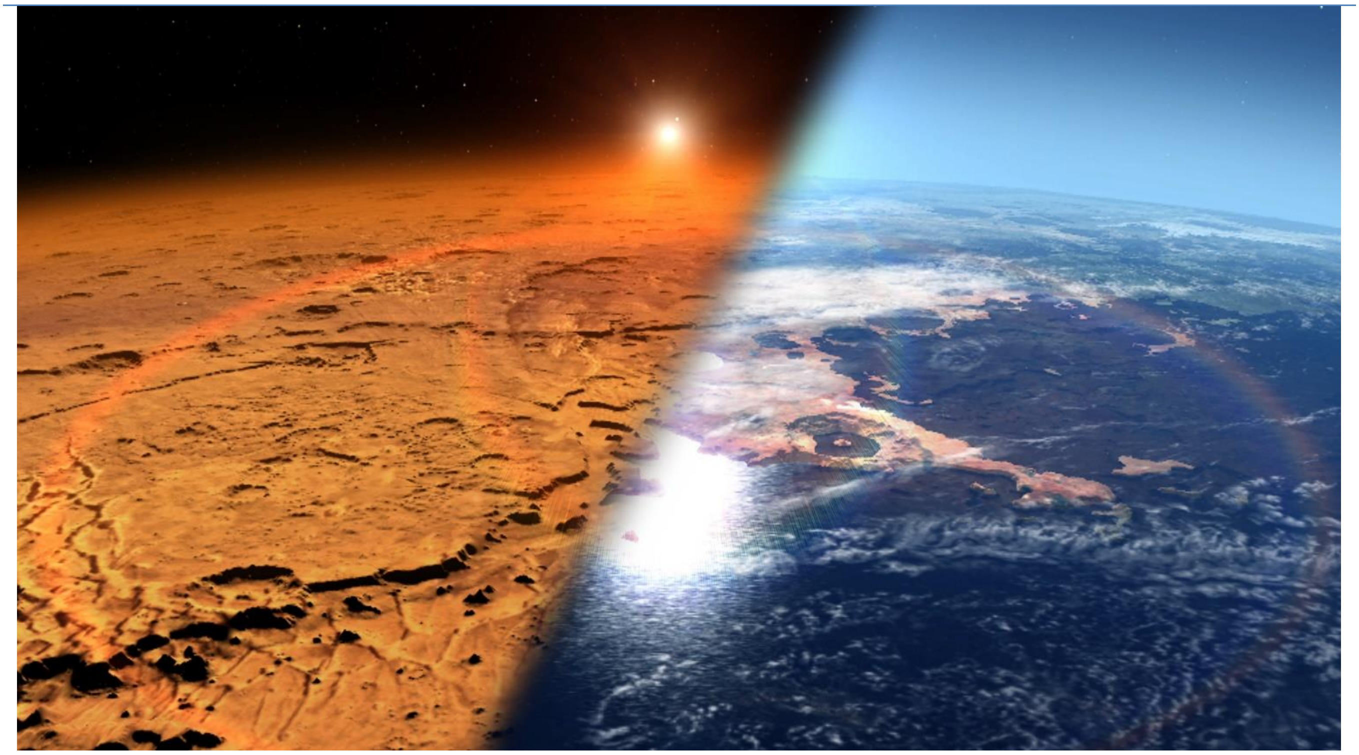
The CCoM Consortium

The Changing Climate of Mars



Artist's concept of a warm and wet early Mars (right) compared to the cold and dry environment of today (left). Image credit: NASA GSFC

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on behalf of the CCoM Consortium

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Version 1

Contents

Abbreviations and Acronyms

APXS	Alpha Particle X-Ray Spectrometer
CCoM	Changing Climate of Mars
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CV	Cosmic Vision
ESA	European Space Agency
HiRISE	High Resolution Imaging Science Experiment
IR	Infra-Red
JAXA	Japanese Aerospace Exploration Agency
MEP	Mars Exploration Program (NASA)
MGS	Mars Global Surveyor (NASA)
MEx	Mars Express (ESA)
MOLA	Mars Orbital Laser Altimeter
MRO	Mars Reconnaissance Orbiter (NASA)
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
OMEGA	Visible and Infrared Mineralogical Mapping Spectrometer (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité)
Roscosmos	Roscosmos State Corporation for Space Activities
SAM	Sample Analysis at Mars
UAE	United Arab Emirates
UV	Ultra-Violet
UV-Vis-TES	Ultra-Violet-Visible-Thermal Emission Spectrometer

Executive Summary

We present a concept, CCoM (Changing Climate of Mars), as a scientific theme for ESA's forthcoming Voyage 2050 strategy. The concept includes an indicative mission scenario of two rovers and an orbiter; based on current international priorities, it is expected that the mission would be a joint venture with other space agencies. The mission design could feed forward into future missions to Mars using the orbiter as a communications relay.

The Objective of CCoM is to locate and visit at least two sites on Mars where the geological record captures the climate transition associated with the Noachian-Hesperian boundary. The boundary marks a significant transition, as that is where there greatest change in environment occurred, assumed to be associated with atmospheric loss. We propose two rovers at separate landing sites: one rover will investigate volcanic and/or impact-related material, the second will assess the transition from fluvial/marine to aeolian sediments, looking for the final sequence of material deposited through the agency of water.

Specific science goals of CCoM are summarised as follows:

- To determine the absolute age, mineralogical composition and depositional environment of Mars' surface at the landing site(s);
- To correlate widely-observed orbital mineral assemblages with surface distributions of the same mineral assemblages at specific landing sites;
- To constrain the extent to which fluvial and other sedimentary systems have modified the Martian surface
- To measure the elemental and isotopic composition of Mars' atmosphere at the surface and from orbit
- To relate age and composition of the surface to the evolution of the planet and its atmospheric history

There is also a series of more generic goals that the theme will support, including:

- Development of new and existing international co-operations;
- Informing and inspiring the public, improving public perceptions of science and exploration;
- Training and establishment of a future European scientific and engineering workforce, utilising our expertise, increasing engineering skills in Europe and capitalising on prior investments.

If power, mass and budget allow, additional important science could be achieved by including a seismic package on each rover, to be deposited on the Martian surface at each landing site. This would complement the InSight seismic station and become the second phase of a Martian seismic network.

Rationale

We know, from images and spectroscopic data, that Mars experienced at least one major episode of climate change, which is taken to mark the Noachian-Hesperian boundary at about 3.5 Gy ago, but we, as yet, have insufficient information to conclude exactly when and how the environment changed. The main objective of this proposal on the Changing Climate of Mars (CCoM) is to investigate the period of climate change through detailed investigation of the bedrock and sediments that span the time period in question. We propose two rovers at separate landing sites: one rover will investigate strata spanning the Noachian-Hesperian boundary in association with a verifiable stratigraphic marker (i.e., a well-defined volcanic unit). The second rover will assess the transition from fluvio-lacustrine sediments to aeolian environments.

Currently, the international efforts to explore Mars are focussed on the goal of returning samples to Earth (Mars Sample Return, MSR) as a preliminary to a broader project to send humans to Mars. The returned samples will be subject to high precision analysis (particularly determination of their absolute ages) that should provide answers to many of the questions concerning Mars' evolutionary history and will certainly contribute to development of the mission profile envisaged here. However, the samples to be returned from Mars will have spent at least 10 years on Mars' surface (albeit inside a protective tube) and will experience diurnal and annual thermal cycling. This has the potential to alter the samples, which up to the point of collection would have been in chemical equilibrium with the surrounding strata. Mars 2020, the NASA rover that comprises the first phase of MSR, has its own series of science questions to answer, as does ESA's ExoMars 2020 mission. Although both missions are scheduled to land in ancient terrain (Jezero Crater and Oxia Planum, respectively), neither is designed to address the specific issue of global climate change, particularly the on-going debate about the disagreement between climate models and morphological evidence for environmental conditions on Mars in the Noachian (e.g., Wordsworth, 2016). Hence the need for dedicated missions developed to reach sites with specific stratigraphic importance.

Objectives

The Objective of this Changing Climate on Mars (CCoM) theme is to locate and visit at least two sites on Mars where deposits that transition across changing climate regimes can be found. The most significant and geographically widespread transition is that between the Noachian and the Hesperian, as that is where the greatest change in environment occurred, associated with atmospheric loss.

Specific insights to environmental change will be gained through determination of the mineralogy of the deposits with detailed analysis of mineral chemistry and sedimentary features. Measurement of the K-Ar age of the rocks will enable determination of the time of the final alteration episode experienced by the mineral assemblages. Light element isotopic analysis of the surface and of the atmosphere will relate the past environment to the present.

Specific science goals of CCoM are summarised as follows:

- To determine the absolute age and mineralogical composition of Mars' surface at the landing site(s)
    - what is the age and timing of the transition from wetter to drier environments?
    - is the transition traceable through alteration of volcanic rocks and/or sediment deposition?

    - what volumes of fluid (water? CO_2? SO_2?) were required to effect the alteration, and what were the sources of the fluid?
    - Is the transition coeval at the two sites? i.e., was the Noachian-Hesperian transition global in terms of its onset and duration?
- To correlate widely-observed orbital mineral assemblages with surface distributions of the same mineral assemblages at specific landing sites;
    - How do the two distributions differ?
    - Can this comparison be employed to calibrate the mineralogy and mineral chemistry of extended areas of Mars' surface?
- To constrain the extent to which fluvial and other sedimentary systems have modified the Martian surface
    - identify and characterise water-rock interactions at the surface and determine the water to rock ratio
- To measure the elemental and isotopic composition of Mars' atmosphere at the surface and from orbit
    - model how the atmosphere has changed since the planet's formation, setting boundaries on the volume of atmospheric species that have been lost over Mars' history
- To relate age and composition of the surface to the evolution of the planet and its atmospheric history
    - match models of climate change on Mars with the timing, temperature and fluid volumes inferred from surface and atmosphere observations

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International Context and fit to ESA strategy

In 2004, the Science Directorate of ESA called for White Papers to inform its new strategy, Cosmic Vision, which would define the Agency's science strategy for the decade 2015-2025. The document was published in 2005 and is the guide for space missions defined in the 2015-2025 timeframe but having launch dates and mission end times past 2035. This forward-looking plan laid out the priorities that the ESA community recognised as key to furthering our understanding of the universe, and our place within it; the document was arranged in four themes, the first of which was "What are the conditions for planet formation and the emergence of life?". One of the three sub-divisions within Theme 1 concerned life and habitability in the Solar System and had exploration of Mars by lander and rover as potential mission scenarios. Although Mars was regarded as a high priority, no mission to Mars have been selected within the Cosmic Vision programme. Exploration of Mars was part of the Aurora (now Exploration) Programme of the Human Spaceflight Directorate that is running in parallel with the Science Directorate's Cosmic Vision programme. Three missions to Mars were planned within Aurora: the Schiaparelli lander (a technology testing mission that crash-landed in 2016), the very successful ExoMars Trace Gas Orbiter (launched in 2017 and currently orbiting Mars) and the ExoMars Kazachok Lander and Rosalind Franklin rover, due for launch in July 2020. The Aurora/Exploration programme was and is focussed on preparations for the human exploration of Mars, and its sequence of missions was planned with this in mind.

As of mid-2019, both the Cosmic Vision and Aurora/Exploration programmes have almost finished their forward planning for future missions – all that remains to be completed is final selection (in 2021) of an M-class mission and development of the European component of a joint ESA-NASA mission to return samples from Mars (currently scheduled for launch in 2026). It seems appropriate, therefore, to consider a new programme of Martian exploration, conceived as a theme within the Vision 2050 strategy, but also addressing some of the planning considerations following the potential continuation of the Exploration programme.

The international context of future mission planning is also highly-favourable for a Mars-focussed theme within Vision 2050. NASA has an enormously successful Mars Exploration Program (MEP), which currently has both the Curiosity rover and Insight lander active on the surface of Mars, plus 3 spacecraft in orbit around the planet. The next phase of NASA's MEP is the Mars 2020 rover, which will explore deltaic sediments at Jezero Crater. An important component of the mission (to be launched in July 2020) is its ability to collect and cache samples for subsequent return to Earth. NASA's final planned mission to Mars in its current strategic cycle is the joint ESA-NASA mission of 2026 that will retrieve and return the collected samples. In early 2020, NASA will solicit input to the National Academy of Science Decadal Survey – the US equivalent of ESA's Cosmic Vision and Vision 2050. Given the success of its MEP, it is likely that exploration of Mars will again feature prominently in the Decadal Survey. It is the successes of the ESA and NASA Mars missions that have laid the groundwork for the plans outlined in this White Paper.

As far as other space agencies are concerned, there are plans for missions of exploration, and potentially sample return, but no mission with the specific aim of investigating the past record of Mars' climate. Currently, RosCosmos, the Russian Space Agency, is working with ESA on the ExoMars Lander, whilst JAXA, the Japanese Space Agency is focussing on a mission to explore Phobos, one of the moons of Mars. The UAE will launch its orbiter, Hope, in 2020 and China and India also have plans for launches in the same timeframe; the goals of these missions are focussed towards either atmospheric studies or the search for biomarkers. Thus, we believe that missions designed to address the changing climate of Mars will attract wide support from other space agencies, although the concept outlined here can be achieved as an L-class mission by ESA alone.

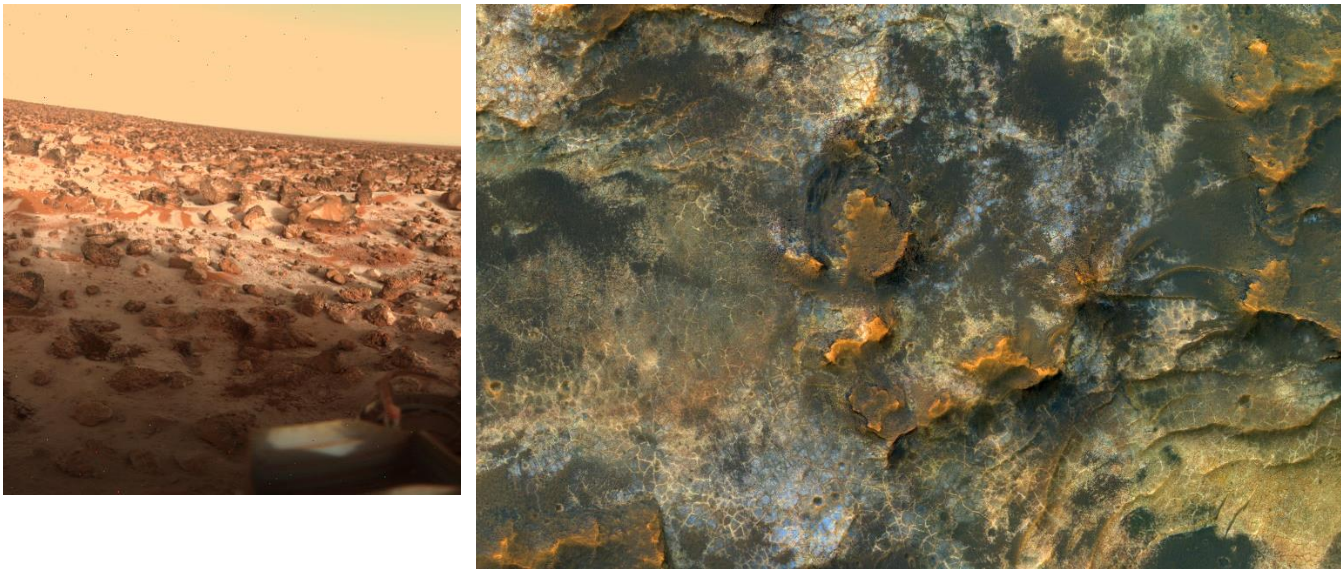
The Changing Climate of Mars: Science Case

Mars is a small rocky planet, with a diameter about half that of Earth. It currently has a thin atmosphere (~6 mb), mostly of carbon dioxide (~ 96 %). Because it is readily visible (by telescope) in the night sky, Mars has been an object of fascination and scientific study for almost 400 years. In the modern era of space exploration, the first images taken of Mars were obtained by the Mariner 4 fly-by mission in 1965 at a distance of about 10,000 km and showed a barren and cratered planet not unlike the surface of the Moon. Images from Mariners 6 and 7 in 1969 gave a little more detail. They flew past Mars at a distance of about 3400 km, and were the first to fly over the South Pole, capturing images of the polar cap. They determined that Mars had a thin atmosphere of mainly carbon dioxide. The next successful probe, Mariner 9, orbited Mars for a year between November

1971 and October 1972. Detailed pictures of the surface were captured showing a landscape marked with impact craters, volcanoes and the scars of fluvial activity. The images that this mission recorded changed our views of Mars - and brought discussion of the potential for life on Mars back on to the agenda.

In 1976-77, the two Viking spacecraft orbited the planet, and returned a series of images of channels, gullies, impact craters and volcanoes across Mars' surface, confirming the active thermal and hydrological history that Mars had experienced. Complementing these images were those from the Viking landers that recorded a desolate landscape of frost-coated angular boulders. Frost-action, and ablation by wind-blown dust, show that erosional processes were still active on Mars' surface. Additional close-up pictures of the surface came in 1976-1977 from the Viking landers (Figure 1a). They showed a flat to gently undulating and dusty surface, peppered with angular rocky boulders of varying size. Over the four decades since Viking, five more spacecraft have landed successfully on Mars' surface, and the quality and resolution of the images obtained has improved immensely. We have a much greater understanding of the processes that have shaped Mars' surface, and the variety of landscapes that result from those processes. Better imagery from orbit has also allowed a detailed chronology for Mars to be constructed (Tanaka 1986, Tanaka et al. 2014), but this is a relative chronology, rather than an absolute timeline: to date, the ages of three samples from localities at Gale Crater have been directly measured (Martin et al., 2017).

Figure 1: The landscapes of Mars



A thin layer of water ice frost on the Martian surface at Utopia Planitia captured by Viking 2 Lander camera 2. The view is looking towards the south southeast, the long boulder to the right is roughly one meter across. (Viking 2 Lander, P-21873); (b) The image shows polygonal units that match clay-rich areas. This location, in Eridania Basin, was the site of an ancient lake, so these clay-rich sediments may have been habitable. NASA/JPL-Caltech/University of Arizona; PIA23105.jpg**;** (c) NASA/JPL-Caltech/MSSS Instrument: Mastcam image Ful JPEG: PIA21256.jpg**.**

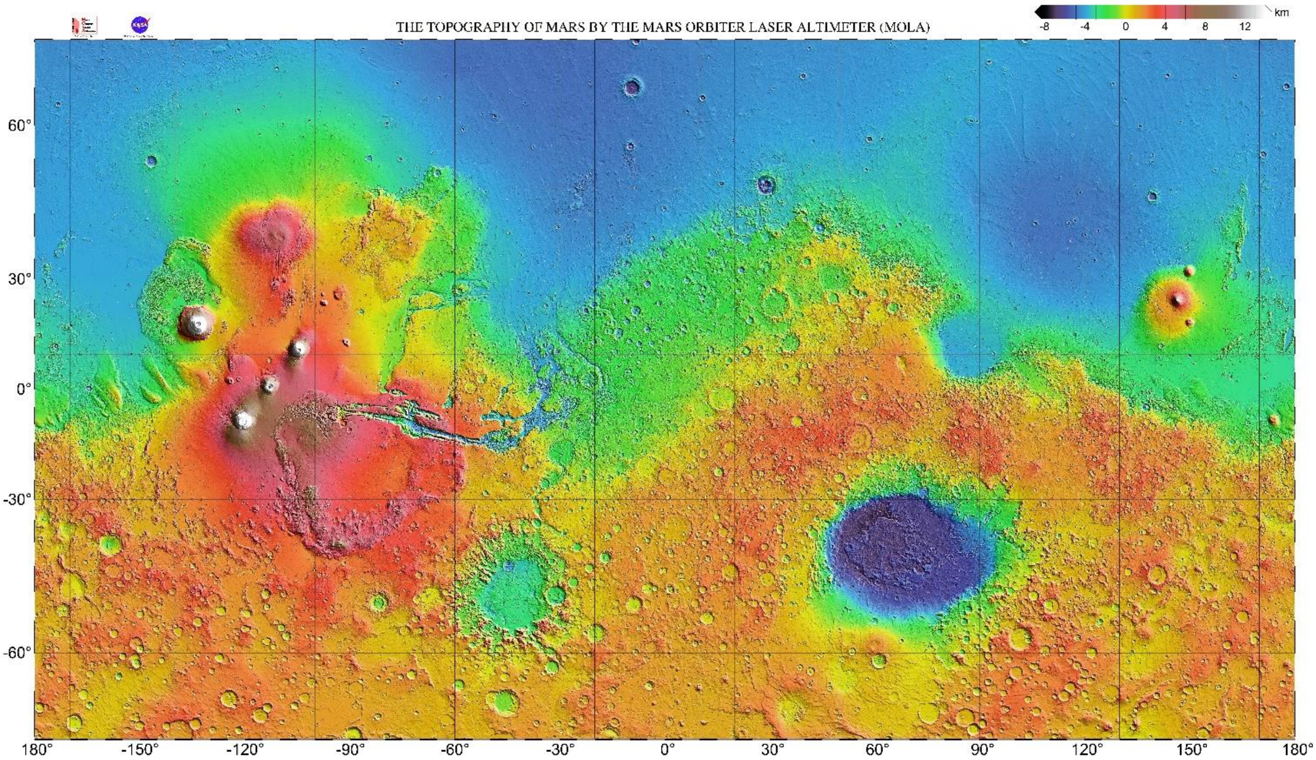
Water is not stable on Mars' surface today, because the atmospheric pressure is now too low. However, the existence of features apparently produced by flowing water indicate that at times in its past, Mars has had an active fluvial history. This, in turn, implies that Mars must have had a much thicker atmosphere, one that stabilised liquid water. The surface temperature when water was present must also have been higher than it is now. Although recognition of a fluvial history for Mars has been accepted for several decades, it is only with the advent of high-resolution imaging and spectroscopy from orbit that secondary products from the action of water have been mapped (Fig X). Clay minerals and sulphates and, to a lesser extent, carbonates have been found across the surface, allowing a stratigraphy for the minerals to be established. The alteration history of Mars can be related to Mars' chronology, as defined by cratering statistics (Fig. 3).

Part of the continued thrust towards exploration of Mars is the potential that the planet has to host life. Earth and Mars formed at the same time from the same materials, and have experienced similar differentiation and core formation processes. Given that Mars had a thicker atmosphere in the past, plus flowing water on the surface, this opens up the possibility that living organisms arose on Mars in the same way that they originated on Earth. Although Mars is believed currently to be lacking in any type of biological activity at the surface (sterile because of UV irradiation), it requires only a few cm of rocky overburden to attenuate the UV flux to a non-destructive level, such that microorganisms might be able to survive below the surface.

The past few years have seen a dramatic increase in the number, resolution and quality of images and compositional data from Mars' surface returned by both orbiting satellites and rovers. This has given us a much better understanding of the evolutionary history of Mars – and how and why it is so similar to Earth in many respects, but so very different in many others.

It has been apparent, ever since the images returned by Mariner 9, that the surface of Mars is not homogeneous – there is a noticeable difference between the northern and southern hemispheres (Figure 2). The former is mainly low-lying smooth terrain with a sparse distribution of craters, whilst the latter is heavily-cratered and is superposed by a variety of features including the long-active Tharsis volcanic complex, the Valles Marineris rift system and a series of deep impact basins.

Figure 2: Topographic Map of Mars based on MOLA data



Global mapping of Mars' surface has allowed a chronology to be established based on crater size-frequency distributions. Mars' history is divided into 3 epochs: the Noachian, the Hesperian and the Amazonian (Tanaka 1986, Tanaka et al. 2014). The Noachian is the oldest and deposits of this age occur mainly in the southern highlands, whilst the northern lowlands are dominated by Amazonian deposits. Age ranges for the different epochs are defined through comparison with the lunar cratering record, which is anchored by the absolute ages of Apollo and Luna samples. While the relative sequence of events based on the crater frequencies is well established, the absolute age assignment to the epoch boundaries very much depends on the cratering models used (Neukum et al. 2001, Ivanov 2001, Hartmann 2003, Werner et al 2014, Werner 2019). The different cratering chronology models may shift the same geologically defined boundary in time by up to 500 million years. Therefore linking critical events in Martian climate history to, e.g., solar evolution, is still hampered by the ambiguously-defined absolute timeframe.

The OMEGA instrument on Mars Express (MEx) and the CRISM instrument on Mars Reconnaissance Orbiter (MRO) have provided detailed coverage from orbit of the distribution of specific mineral groups and the results have been used to produce a mineralogical map of Mars. This has enabled construction of an evolutionary timeline based on the occurrence of different mineral assemblages; the timeline is complementary to the cratering chronology Figure 3 shows how the cratering and mineralogy chronologies are aligned. Also shown on the figure are the crystallisation ages of several Martian meteorites plus the K-Ar age of sediments at Gale Crater, as measured by SAM and APXS on the Curiosity rover. Detailed analyses of Martian meteorites show that nakhlites experienced hydrous alteration, although their crystallisation age of 1300 million years locates their origin as during the cold and dry climate phase of Mars. Additionally, despite attempts to define source regions for Martian meteorites, their places of origin on Mars are unknown, and thus they lack the geological context necessary to interpret many of the details that can be inferred from rocks analysed either *in situ* or from known locations.

The different mineralogies result from changes in environmental conditions (Milliken et al. 2010). For many years, as described above, the paradigm has been that during the Noachian epoch, as a result of a thicker atmosphere, surface temperatures were warmer than in later epochs, allowing liquid water intermittently to be stable at the surface. Towards the end of the Noachian, atmospheric pressure dropped dramatically, leading to change to a cold and dry environment with a different weathering regime and concomitant production of different mineral assemblages.

Although this model used to be widely accepted, more recent interpretations of topographic features have questioned the idea of a 'warm and wet' early Mars. Comparison of the dendritic valley networks that characterise the Noachian landscape with analogous aqueous features on Earth have suggested that the networks result from surface run-off from snow- or rainfall, rather than from melting of ice-sheets or up-welling of groundwater. Any such fluvial activity is likely to be relatively short-lived, lasting up to about 1 - 10 My or so (Hoke et al., 2011). Further suggestion that the Noachian was more arid than previously understood comes from study of the drainage patterns of crater lakes within the valley networks. Most valley networks exposed at the surface are from the Noachian-Hesperian boundary (e.g., Hynek et al. 2010; Irwin et al., 2005; Fassett and Head, 2008). Older, mid-Noachian surfaces generally do not show similar geomorphic expressions, which could be because of poor exposure, etc. Further fluvial deposits are probably buried in the rock record. Impact bombardment is an important influence on the landscape in the Noachian – not just as an agent of destruction, but because lakes can form in the impact crater basins that are left behind. Sediments from the lakes are frequently enclosed within craters, i.e., water has not eroded the crater rims by episodes of flooding, implying a low water flow rate. There are Noachian basins that have been breached (Fassett and Head 2008), and there are several with lake deposits, as well as craters that show an open basin system where water flowed into and out of the crater (e.g., Jezero crater). These different landforms at least tell us that water volume and flow rate was not constant during early Mars.

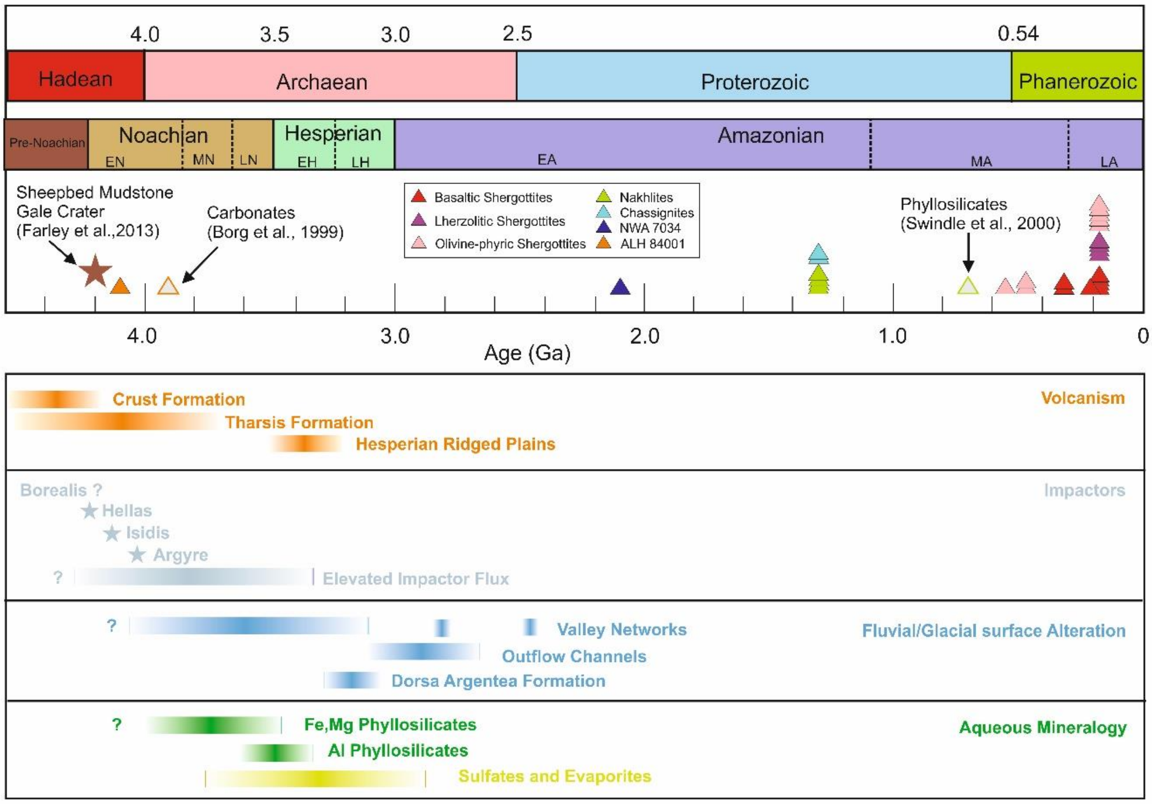
There is, however, a serious discrepancy between results obtained from climate modelling and those inferred from topographic interpretation. Climate modelling suggests that the valley networks formed as a result of the episodic melting of highland ice sheets ((Wordsworth et al., 2015). The geology has however consistently suggested that rainfall or snowfall was involved (e.g. Craddock and Howard, 2002, JGR). The distributed source of water necessary to create the widespread dendritic channels cannot be explained by regional ice sheet melt. Recent climate models that integrate changing solar flux (the 'Faint Young Sun' argument), obliquity variations and the presence of high-altitude clouds have found that early Noachian temperatures were cooler than previously proposed, and that significant quantities of greenhouse gases are required to warm the surface sufficiently to produce the required flows of water (Wordsworth et al., 2015). Local or regional "wet" climate may have persisted late in Mars' history (see: Kite *et al*., *Sci. Adv.* 2019). It is, therefore, still not clear whether the change in climate was a gradual or a sudden transition, or what Mars' surface looked like in the Early Hesperian.

If plate tectonics-like processes were ever active on early Mars, it must have been of extremely short duration and effectively ceased by the beginning of the Tharsis formation at least 4 Gy ago, the upshot of which is a well-preserved ancient crust from before 4.1 Gy ago, corresponding to the scarce and highly-altered Hadean-Archaean material present on Earth. One of the attractions of studying early Martian deposits is the insight we will be given to processes occurring simultaneously on Earth and the Moon, in terms of cratering record, evidence for a crater bombardment in the period before 4.1 Ga and the solar flux. This is important because the earliest fossil evidence for terrestrial life comes from trace fossils in meta-sediments with ages around that of the Noachian-Hesperian boundary (here assumed to occur at about 3.5 Ga, but with a range of 3.0-4.2 Ga).

Indeed, better understanding of the global to regional habitable conditions on Mars through time will help us to constrain more precisely the possibilities for microbial-scale habitability, which may be quite different to the regional-global scales normally considered (Westall et al., 2013, 2015). If microbial-scale habitable conditions occurred over a broader timescale, or if they were more limited and without contiguity, this would have important implications for the potential for biosignatures at the surface of the planet, as well as with respect to possibilities for evolution.

Experiments have shown that reactions between anhydrous minerals and water (especially as brine) occur very rapidly, on a timescale of days, even at low temperature (Philips-Lander et al., 2019). Hence reactions between mineral assemblages in the MSR collection tubes with water of crystallisation or inter-layer water released from clay minerals could change the chemical balance of the system and not be a true reflection of the hydration state of the original material collected. There could even be movement of cations during the reactions – for example, removal of aluminium from plagioclase would alter fluid composition and change the products of serpentinization of olivine (Pens et al., 2016). Since the conversion of Fe- and Mg-bearing phyllosilicates to Al-bearing silicates is a key marker for changing environmental conditions on Mars (Bishop et al., 2018), it is essential that in situ analysis of clay-bearing sediments is performed, rather than relying on analysis of returned samples.

Figure X: Timeline of Major Events in Mars' History



Timeline of major events in Mars' history, with the geologic aeons of Earth. Question marks indicate cases where processes could also have occurred earlier but the geologic record is obscured by subsequent events. Figure and caption adapted from Wordsworth (2016). Based on data from Werner and Tanaka (2011), Fassett and Head (2011), Ehlmann et al. (2011) and Head and Pratt (2001). Martian meteorite data from Borg et al. (1999), Nyquist et al. (2001), Swindle et al. (2000), Agee et al. (2013). Gale Crater data from Farley et al. (2013). Note that depending on the crater chronology model used, absolute age assignments may differ.

Landing Site Constraints

There are several sets of parameters that must be reconciled in the selection of suitable landing sites. These can be categorised as:

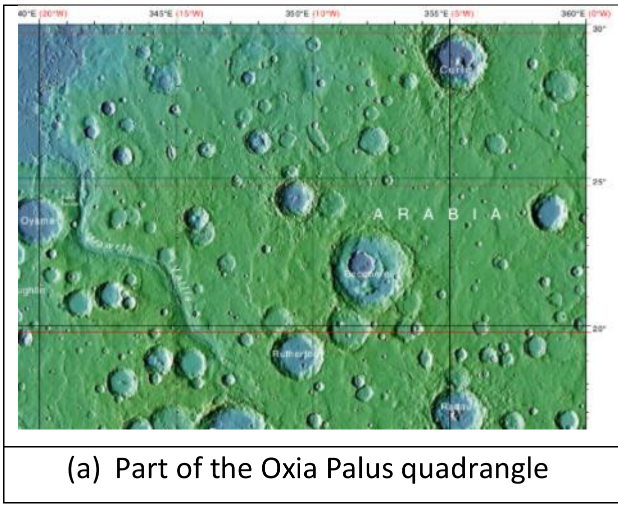
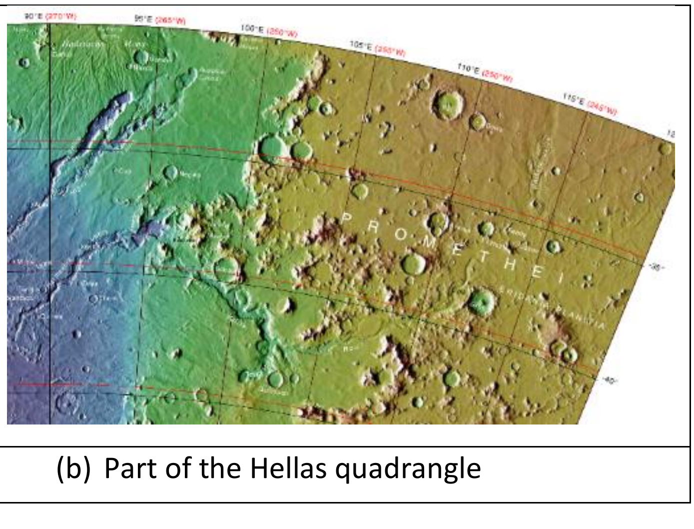
i) Science – will the selected sites fulfil the scientific goals of the mission?
ii) Technology – what are the technology requirements that might lead to modification of the science goals of the mission?
iii) Engineering – what are the engineering requirements of the mission, in terms of landing ellipse, and how might they modify the science goals of the mission?

The landing sites finally selected will be a result of trade-offs amongst the three parameter sets. Because we wish to explore the Noachian-Hesperian transition in both volcanic and sedimentary landscapes, it is likely that the two sites will be sufficiently far apart that a single rover could not explore both sites. Neither of the two rovers will need precision landing, although a reasonably flat landing site at low latitude and low altitude will be required to enable successful operation. Preliminary engineering requirements are likely to be a range of 0 ± 40° latitude and an altitude of less than 2000 m below the MOLA datum, although these figures are dependent on the delivery mechanism for the landing craft. The rovers should be capable of traversing up to a few kilometres per day, and also able to climb reasonable gradients.

In order to achieve the maximum number of CCoM theme objectives, the selected landing sites must cover a range of rock lithologies of specific ages. Thus a region where late Noachian-age rocks are overlain by early Hesperian deposits would be an ideal location in which to observe variations in mineralogy and mineral chemistry. This would be the first mission to explore the Noachian highlands of Mars. Two such possible sites are described below; they are intended to be indicative of the types of localities suitable for investigation. Much more detailed study would determine the optimum separation of landing sites: should they be at the same or similar latitudes (i.e., both either on the N or in the S) but different E-W hemispheres so they are experiencing the same season but different day/night cycles? Or should they be at different latitudes (one to the north and one to the south of the equator) but the same E-W hemisphere so that they experience different seasonal variations but have the same diurnal cycle? Additional considerations on landing site locations would emerge if each rover were to carry a seismic package, to establish a network with InSight.

Location A: (Figure 4a; volcanic or impact-related rocks): Based on analysis of the geologic map of Mars (Tanaka et al., 2014) and the MOLA topographic data map (Figure 2), potential landing sites to examine Late Noachian epoch volcanic terrain might include one of the craters (for example, Becquerel crater; 22.1°N, 352.0°E) in Arabia Terra. Such a locality would be sited between Oxia Planum (designated landing site for ExoMars 2020 and Meridiani Planum (landing site of the Opportunity Rover) and would draw on information obtained from both those missions. The potential landing site for the Curiosity Rover and ExoMars 2020, Mawrth Valles is also in the same locality, and information from its characterisation would also be useful. It is a region where the Early Hesperian highland unit superposes the Late Noachian highland unit (Tanaka et al., 2014), and comprises sequences of undifferentiated volcanic and impact rocks as well as fluvial and aeolian deposits.

Figure 4: Examples of possible landing sites for CCoM mission

	
(a) Part of the Oxia Palus quadrangle	(b) Part of the Hellas quadrangle

Location B: (Figure 4b; fluvially-deposited sediments): using the same resources, potential landing sites to examine Late Noachian-Early Hesperian epoch fluvially-deposited sediments might include the region to the north east of Hellas Planitia. It is low-lying, and comprises basin fill of Early

Hesperian aeolian and lacustrian sediments (plus some volcanics), dissected by fluvial channels (Tanaka et al., 2014).

CCoM Mission Concept

Indicative timeline:

	2035			2036				2037				2038			
	Q2	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
1	Launch														
2				Arrival											
3					Prime Mission										
4													Mission Extension		

Model Payload

The model payload proposed here comprises an orbiter plus rover. The two rovers will have identical payloads but be deployed to different landing sites.

Orbiter:

- Wide angle camera
  - Determine high resolution images of the surface
- UV-Vis-TES Spectrometer
  - Determine the composition and mineral distribution of the surface
- Mass and Isotope Analyser
  - Measure the elemental and light element (H, C, N and O) stable isotope composition of the atmosphere at altitude

Rover:

- 3D imager with multispectral capability
  - Provide sets of images in colour of the surrounding landscape. Multispectral capability will enable additional compositional information to be acquired.
- Close up camera
  - Provide a detailed view of sampling area to provide images of the surface at a spatial resolution of ~100 μm. This will give an impression of the texture, permeability, grain size and grain size variation of the surface.
- Sampling capability
  - To collect material from the surface and sub-surface for delivery to combined GC system
- APXS or LIBS
  - To determine the chemistry of the strata and soil
  - Provide calibrated K abundances for K-Ar age-dating
- Raman or IR Spectrometer
  - Acquire compositional data of the rocks and soil for comparison with compositional data acquired by instruments on other landers
- X-Ray diffractometer

    - Determine the compositional mix and structure of the mineral assemblages in the rocks and soil
- Combined GC-MS and GC-IRMS system
    - Measure the elemental and light element stable isotope (H, C, N and O; noble gases) composition of rocks and atmosphere at the surface.
    - Determine the presence and identity of organic molecules in the rocks and soil
    - Provide calibrated Ar abundance and isotopic composition for K-Ar age-dating
- Seismic package
    - seismometer and heat-flow instruments to interface with Insight to provide a network of seismic stations, refining the 3D structure of Mars and determining the rate of heat flow from the core.

References

Craddock RA, Howard AD. 2002. The case for rainfall on a warm, wet early Mars. *J. Geophys. Res.* 107:5111

Farley K. A. et al. (2014). In situ radiometric and exposure age dating of the Martian surface. Science https://doi.org/10.1126/science.1247166

Fassett and Head 2008. Valley network-fed, open-basin lakes on Mars: Distribution and implications for Noachian surface and subsurface hydrologyIcarus (doi:10.1016/j.icarus.2008.06.016) and

Goudge TA et al. 2012. An analysis of open-basin lake deposits on Mars: Evidence for the nature of associated lacustrine deposits and post-lacustrine modification processes. Icarus (doi:10.1016/j.icarus.2012.02.027)

Hartmann WK and Neukum G. 2001. Cratering chronology and the evolution of Mars. *Space. Sci. Rev.* 96:165–94

Ivanov B. A. 2001. Mars/Moon cratering rate ratio estimates. Space Science Reviews 96:87–104.

Hoke MRT et al. 2011. Formation timescales of large Martian valley networks. *Earth Planet. Sci. Lett.* 312:1–12. doi:10.1016/j.epsl.2011.09.053)

Hynek BM et al. 2010. Updated global map of Martian valley networks and implications for climate and hydrologic processes. *J. Geophys. Res.* 115:E09008

Irwin RP III et al. 2005. An intense terminal epoch of widespread fluvial activity on early Mars. 2. Increased runoff and paleolake development. *J. Geophys. Res.* 110:E12S15

Milliken R. et al. 2010. Paleoclimate of Mars as captured by the stratigraphic record in Gale Crater. GRL, doi:10.1029/2009GL041870)

Neukum, G. et al. 2001. Cratering records in the inner solar system in relation to the lunar reference system. Space Sci. Rev. 96, 55–86.

Pens M et al., 2016. Contrasted effect of aluminum on the serpentinization rate of olivine and orthopyroxene under hydrothermal conditions. Chem. Geol. 441, 256-264

Phillips-Lander CM et al., 2019. Aqueous alteration of pyroxene in sulfate, chloride, and perchlorate brines: Implications for post-Noachian aqueous alteration on Mars. GCA 257, 336-353.

Werner SC 2014. Moon, Mars, Mercury: Basin formation ages and implications for the maximum surface age and the migration of gaseous planets. Earth and Planetary Science Letters 400:54–65.

Werner SC 2019. In situ calibration of the Martian cratering chronology. Meteoritics & Planetary Science 54, Nr 5, 1182–1193. doi: 10.1111/maps.13263

Westall F. et al. 2015, Biosignatures on Mars: what, where and how? Implications for the search for Martian life. Astrobiology, vol 15, pp 998-1029.

Westall F. et al. 2013. Habitability on Mars from a microbial point of view. Astrobiology, 13, 887-897.

Wordsworth R. 2016. The climate of early Mars. Ann. Rev. Earth Planet. Sci. 44:381–408

Wordsworth R. et al. 2015. Comparison of ''warm and wet'' and ''cold and icy'' scenarios for early Mars in a 3D climate model. *J. Geophys. Res. Planets* 120:1201–19

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