



Recommendation for the Narrowing of ExoMars 2018 Landing Sites

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The ExoMars 2018 Landing Site Selection Working Group (LSSWG):

F. Westall (CNRS, Orléans, F), H. G. Edwards (Bradford Univ. UK), L. Whyte (McGill Univ. CAN), A. G. Fairén (Cornell Univ. USA), J.-P. Bibring (IAS, Orsay, F), J. Bridges (Univ. of Leicester, UK), E. Hauber (DLR, Berlin, D), G. G. Ori (IRSPS, Pescara, ITA), S. Werner (Univ. of Oslo, N), D. Loizeau (Univ. Lyon, F), R. Kuzmin (Vernadsky Inst. Moscow, RUS), R. M. E. Williams (PSI, Tucson, USA), J. Flahaut (VU Amsterdam, NL), F. Forget (LMD, Paris, F), J. L. Vago (ESA), D. Rodionov (IKI, Moscow, RUS), O. Korablev (IKI, Moscow, RUS), O. Witasse (ESA), G. Kminek (ESA), L. Lorenzoni (ESA), O. Bayle (ESA), L. Joudrier (ESA), V. Mikhailov (TsNIIMASH, Moscow, RUS), A. Zashirinsky (Lavochkin, Moscow, RUS), S. Alexashkin (Lavochkin, Moscow, RUS), F. Calantropio (TAS-I, Torino, ITA), and A. Merlo (TAS-I, Torino, ITA).

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1 EXECUTIVE SUMMARY

In agreement with the procedure established by ESA and Roscosmos for the evaluation of candidate landing sites for the ExoMars 2018 mission, and considering the ExoMars mission's search-for-life scientific objectives, the Landing Site Selection Working Group (LSSWG) recommends that further analysis concentrate on the four landing sites possessing higher scientific interest —Mawrth Vallis, Oxia Planum 1, Hypanis Vallis West, and Aram Dorsum.

Whereas the assessment performed has clearly identified four landing sites that are better suited to the mission's scientific goals, the verification of how well they meet the present engineering constraints is still on going — engineering constraints may be updated as the mission and spacecraft designs evolve. The landing and roving engineering constraints are satisfied to different degrees in each of these locations, although our preliminary evaluation indicates that Oxia Planum exhibits fewer problems than any of the other sites. However, we would expect that, upon closer inspection, all sites will have a certain amount of non-compliance, including Oxia Planum. It is therefore very important to proceed quickly to the next stage of analysis, which will allow performing Monte Carlo simulations to predict the probability of landing success based on the entry profile, atmospheric, and terrain properties at each of the candidate sites.

The LSSWG proposes to defer further evaluation of the relative science and engineering compliance merits among the four recommended sites to this next stage, once sufficient high-resolution images, spectral data, and landing performance simulations will have become available, allowing us make a more informed decision —perhaps narrowing down the recommendation to one main and one backup landing site.

The LSSWG wishes to acknowledge the excellent work performed by the proposing teams in preparing their proposals and subsequent presentations for the first LSS workshop. We also thank the Mars Reconnaissance Orbiter and Mars Express science teams for their assistance and support during this work.

2 DOCUMENT SCOPE AND INTRODUCTION

2.1 Scope

Chapter 1 presents a summary of the report's findings.

Chapter 2 explains the organisation and purpose of the document.

Chapter 3 describes the process that the two Agencies have defined to select a suitable landing site for the ExoMars 2018 mission.

Chapters 4, 5, and 6 present, respectively, the scientific, engineering, and planetary protection requirements that the LSSWG has used for reviewing ExoMars 2018 candidate sites.

Chapter 7 introduces the eight candidate locations proposed by the scientific community in response to the *Call for ExoMars 2018 Landing Site Proposals*. It discusses the various sites' merits and challenges.

Chapter 8 contains the LSSWG recommendation for the four sites to be retained for further analysis.

Finally, Chapter 9 lists alphabetically the acronyms used throughout the document.

2.2 Introduction

The European Space Agency (ESA) and the Space Research Institute of the Russian Academy of Sciences (IKI) [on behalf of the Russian Federal Space Agency (Roscosmos)] have tasked the ExoMars 2018 Landing Site Selection Working Group (LSSWG) with supporting ESA and Roscosmos in evaluating candidate landing site proposals' compliance with applicable scientific, engineering, and planetary protection requirements; consulting with the wider science community; and identifying up to four candidate site(s) for more detailed studies. The LSSWG will then formulate a recommendation to ESA and Roscosmos for the mission's landing site(s).

The ExoMars programme's scientific objectives are:

1. To search for signs of past and present life on Mars;
2. To investigate the water/geochemical environment as a function of depth in the shallow subsurface;
3. To study martian atmospheric trace gases and their sources;
4. To characterise the surface environment.

ExoMars 2018 will deliver a Rover and a Surface Platform (SP) to the surface of Mars. The rover will address the first two science objectives. It will carry a comprehensive suite of instruments dedicated to geology and exobiology research named after Louis Pasteur. The rover will be able to travel several kilometres searching for traces of past and present signs of life. It will do this by collecting and analysing samples from within outcrops, and from the subsurface—down to 2-m depth. The very powerful combination of mobility with the ability to access locations where organic molecules can be well preserved is unique to this mission. The rover will also perform numerous investigations on rocks and soils, also contributing to the fourth objective.

After the rover will have egressed, the ExoMars Surface Platform will begin its science mission. The SP will conduct environmental and geophysical measurements in support of the fourth objective. These results will also provide important context information for objective 1, benefiting also the Rover mission.

Besides the investigations carried out by each element, the programme also includes an excellent potential for cross-platform scientific studies. For example, coordinated measurements between the Trace Gas Orbiter (TGO) and the Rover, or the TGO and the SP may provide insights into the past and present habitability of Mars. Likewise, the SP and Rover will be able to image each other, and implement joint scientific measurements during the first part of their surface mission, while they are close together.

A necessary condition for realising all ExoMars 2018 objectives is to land safely at a scientifically interesting location. It is the mission industrial developers' responsibility to demonstrate that the Entry, Descent, and Landing (EDL) system will be able to land at the selected location(s) with the required probability of success. However, this work relies on much needed upstream analysis of candidate sites by LSSWG scientists and engineers.

As a first output of their ExoMars 2018 Landing Site Selection (LSS) support activities, the LSSWG has been asked to examine all candidate landing site proposals; requesting where applicable additional information from the proposing teams, the science community, and industrial teams; to prepare a well-informed recommendation for up-to-four sites to be the scope of the next, more detailed stage of evaluation. This recommendation is presented herein.

3 LANDING SITE SELECTION PROCESS

This section describes the LSS activities that have already taken place, as well as the remaining work to be performed.

3.1 Landing Site Selection Working Group

During October 2013, the European Space Agency (ESA) and the Space Research Institute of the Russian Academy of Sciences (IKI) [on behalf of the Russian Federal Space Agency (Roscosmos)] agreed to appoint a Landing Site Selection Working Group (LSSWG) to make recommendations to the agencies regarding landing sites for the ExoMars 2018 mission.

The LSSWG would include the necessary scientific and engineering expertise to evaluate the suitability of landing sites to meet science, engineering, and planetary protection constraints. Combining scientific and engineering competence in one body was considered paramount to the success of the landing site selection process. Having had two bodies, one scientific and another engineering, would have likely resulted in incompatible recommendations. In this manner, the successful combination of science interest and landing safety must be achieved within the LSSWG. The LSSWG composition is provided in Table 1.

#	Name		Expertise	Country
1	Frances Westall	CNRS-Orléans	BIOSIGNATURES/ESWT/PPWG: Preservation, ancient geology	FR
2	Howell Edwards	Bradford U.	BIOSIGNATURES: Preservation, mineralogy, Raman	UK
3	Lyle Whyte	McGill U.	BIOSIGNATURES: Polar microbiology, cold drilling, biomarkers	CAN
4	Alberto Fairén	Cornell U.	BIOSIGNATURES: Mars hydrogeology and biosignatures	USA
5	Jean-Pierre Bibring	IAS	GEOLOGY/ESWT: Hydrated minerals, Mars history	FR
6	John Bridges	U. of Leicester	GEOLOGY: LS mapping, topography	UK
7	Ernst Hauber	DLR	GEOLOGY: Topography, layered deposits, alluvial fans	DE
8	Gian Gabriele Ori	IRSPS	GEOLOGY: Sedimentary geology, mapping	ITA
9	Stephanie Werner	U. Oslo	GEOLOGY: Dating, mineralogy, resurfacing processes	NO
10	Damien Loizeau	U. Lyon	GEOLOGY: Dating, geomorphology, mineralogy	FR
11	Ruslan Kuzmin	IKI	GEOLOGY: Ice/water processes	RUS
12	Rebecca Williams	PSI	GEOLOGY: Fluvial geomorphology and sedimentary processes	USA
13	Jessica Flahaut	VUAmsterdam	GEOLOGY: Mineralogy, layered deposits, mapping	NL
14	François Forget	LMD	ATMOSPHERICS: Atmospheric Modelling	FR
15	Jorge L. Vago	ESA	SCIENCE: ExoMars Project Scientist	ESA
16	Daniel Rodionov	IKI	SCIENCE: ExoMars Project Scientist	RUS
17	Oleg Korablev	IKI	SCIENCE/ESWT: IR mineralogy and atmospheric aerosols	RUS
18	Olivier Witasse	ESA	SCIENCE: TGO Project Scientist	ESA
19	Gerhard Kminek	ESA	SCIENCE/PPWG: Planetary Protection, organics degradation	ESA
20	Leila Lorenzoni	ESA	PROJECT: ExoMars EDL and landing site engineer	ESA
21	Olivier Bayle	ESA	PROJECT: ExoMars EDM systems engineer	ESA
22	Luc Joudrier	ESA	PROJECT: ExoMars Rover GNC and operations engineer	ESA
23	Viktor Mikhaylov	TsNIIMASH	PROJECT: ExoMars EDL & ground testing manager	RUS
24	Alexander Zashirinsky	Lavochkin	INDUSTRY: ExoMars EDL engineer	RUS
25	Sergey Alexashkin	Lavochkin	INDUSTRY: ExoMars DM Chief Designer	RUS
26	Fabio Calantropio	TAS-I	INDUSTRY: ExoMars EDL engineer	ITA
27	Andrea Merlo	TAS-I	INDUSTRY: ExoMars Rover GNC engineer	ITA

Table 1: Landing Site Selection Working Group (LSSWG) team composition. Science members have a yellow and orange colour background, with orange denoting also ExoMars Science Working Team (ESWT) and/or Planetary Protection Working Group (PPWG) representation. Project and Industry members are indicated in blue.

The engineering members of the LSSWG include representatives of the project teams from the agencies and from major mission development companies in the industrial consortium.

The LSSWG science members were selected through an open, competitive process.

A *Call for Letters of Application for Membership in the ExoMars 2018 Landing Site Selection Working Group* was issued on 1 November 2013. Forty-one Letters of Application (LoA) were received on 25 November 2013. A review commission consisting of ESA and IKI experts and two external scientists examined the LoAs. Fourteen scientists, covering many disciplines were appointed on 6 December 2013.

3.2 Call for ExoMars 2018 Landing Site Proposals

The LSSWG set out to work immediately on the preparation of a *Call for ExoMars 2018 Landing Site Proposals*. This was done through weekly teleconferences and exchange of e-mails. The Call was released on 17 December 2013, with a deadline on 28 February 2014. The members of the LSSWG could not propose landing sites or be part of landing site proposals. Ten proposals were received. Of these, two were rejected. One was outside the allowable latitude band, and the other was judged to contain insufficient information to evaluate the site. The proposers were informed accordingly.

3.3 First ExoMars 2018 Landing Site Selection Workshop

The LSSWG assisted ESA and IKI/Roscosmos in the organisation of a first, open workshop to discuss each of the landing site proposals considered viable.

The LSSWG performed the following tasks prior to the workshop:

- Reviewed all proposals in detail;
- Provided general comments to proposing teams to help them prepare presentations about their site.
- Transmitted proposal-specific comments and concerns to each team;
- Produced templates for the landing site presentations, including detailed Table of Contents and placeholders for the various subjects that had to be treated.

The first ExoMars 2018 Landing Site Selection Workshop was held at ESAC on 26–28 March 2014. Approximately sixty participants attended the workshop. During the first morning, the Agencies described the ExoMars 2018 mission and the Landing Site Selection (LSS) process. This was followed by presentations about the scientific, planetary protection, and engineering requirements that candidate landing sites must satisfy. A talk dedicated to the ExoMars 2018 Descent Module (DM) design provided important technical context for better understanding the Entry, Descent, and Landing (EDL) strategy. Thereafter, a presentation introduced the eight candidate landing sites, summarising the initial comments regarding science and engineering concerns that the LSSWG had provided as feedback to the proposing teams to help them prepare their workshop material. The morning session concluded with a talk addressing the wind regime at each of the proposed sites.

In the afternoon of the first day and the morning of the second day the proposing teams described their sites in detailed, one-hour presentations. Following a general discussion of all sites, the LSSWG requested workshop participants to express their scientific preference by identifying, in order of priority, the four sites they believed would provide the best opportunity for achieving the search-for-life objective. The participants judged four locations ahead of the rest in terms of their suitability for accomplishing the mission's goals.

The third day of the workshop was used for more presentations and discussions, and for planning the request of additional orbital information (high-resolution image and spectral data to better characterise the sites).

3.4 LSS Schedule and Next Steps

Fig. 1 presents the schedule for LSS activities in relation to that of the project. The goal is to try to match landing site selection milestone decisions with the project needs for major Agency reviews.

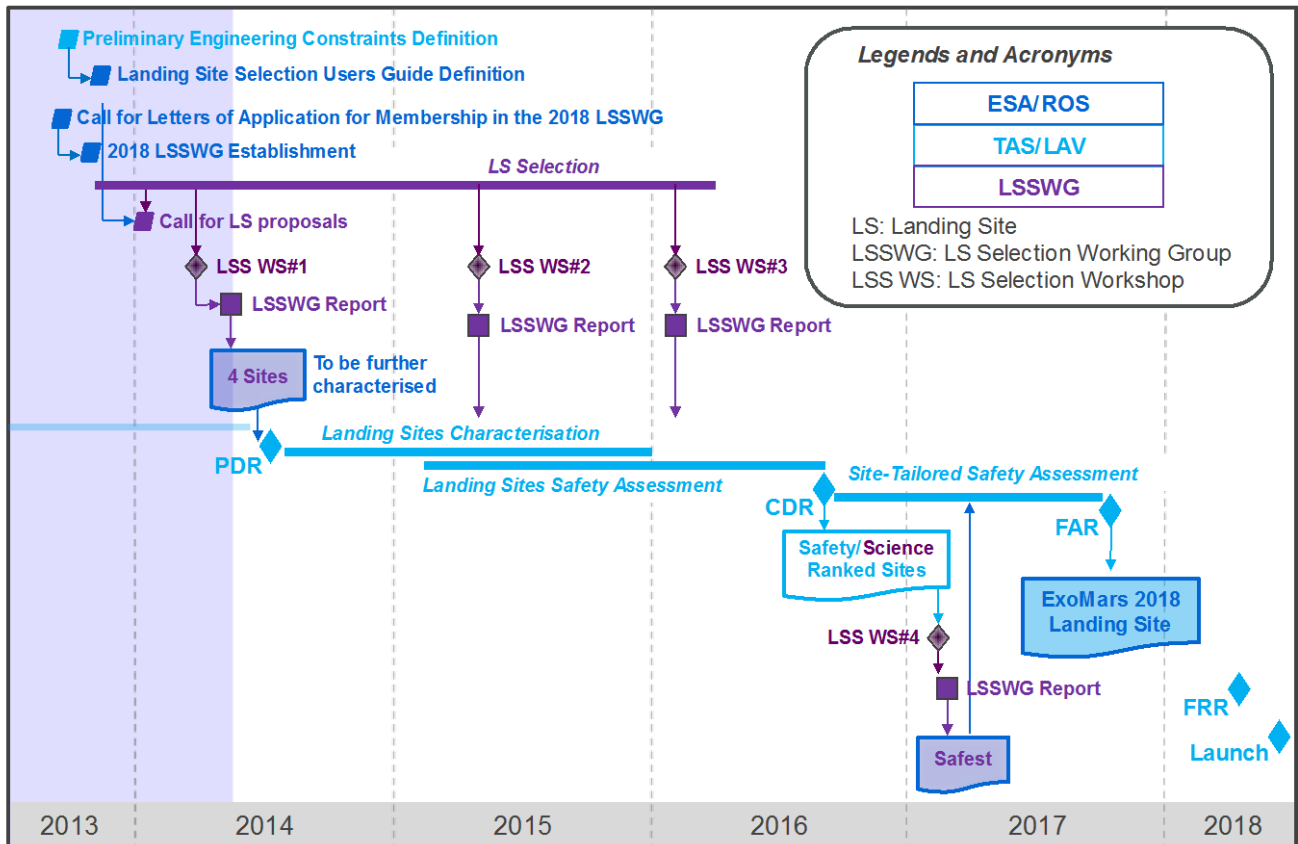


Fig. 1: Landing site selection process in relation to project schedule.

The instructions issued by the Agencies to the LSSWG for preparing this report read: “The LSSWG will take into account the information presented at the first landing site selection workshop, plus the outcome of discussions for the various proposed sites, and the interest of participants as expressed during the workshop to produce a ranked list of candidate landing sites. No more than four sites will be shortlisted for further detailed evaluation. All of the shortlisted sites must be scientifically compelling and safe for landing and surface operations (based on the available information).”

The requested LSSWG recommendation for the down-selection of ExoMars 2018 candidate landing sites can be found in Chapter 8.

The Agencies will communicate the identified landing sites to their industry mission development teams. The industry teams will perform an assessment of the sites’ landing safety. Likewise, the proposers and the LSSWG will continue to study the sites’ science interest. However, to successfully conduct the next, more detailed examination of the proposed sites will require access to new, high-resolution information from MRO and MEX. An important part of the work will be to ensure that these data are requested, received, and analysed by the LSSWG and industry mission development teams.

Please note that the LSSWG, ESA, and IKI/Roscosmos will keep open the possibility to replace an already shortlisted site until 30 January 2015—in case one site were to prove unfeasible or if compelling new information were to make a new site particularly interesting. However, the preferred course of action would be not to have to exercise this possibility.

Other landing site workshops will follow when sufficient progress has been achieved, typically once a year. The goal is to complete the certification of a suitable (science, engineering, and planetary protection) landing site by the mission’s Critical Design Review (CDR), presently planned for September 2016.

The final landing site(s) recommendation for the 2018 mission will be produced by the LSSWG prior to the mission's Flight Acceptance Review (FAR), currently planned on October 2017. This recommendation will be delivered to ESA's Director of Science and Robotic Exploration and the appropriate Russian authorities. Roscosmos and ESA will then follow the applicable approval procedure with their Governing Bodies.

Table 2 presents a tentative schedule for the entire LSS process.

Date	Activity
17 Dec 2013	Release of Call for Landing Site Proposals.
28 Feb 2014	LS Proposals due.
Feb/Mar 2014	Screening of candidate LS proposals by LSSWG.
26–28 Mar 2014	First ExoMars 2018 LSS science workshop at ESAC.
Apr/May 2014	LSSWG prioritisation of candidate LSs (based on science, engineering, and Planetary Protection requirements).
Sep 2014	Up to four top landing locations identified by LSSWG for further, more detailed study. Aim to complete prior to PDR.
2 nd half 2016	Characterisation work continues. Other science conferences help to further refine findings. Aim to have at least a site certified by CDR (planned for Sep 2016).
Oct 2017	Final LSSWG recommendation to D/SRE and appropriate Russian authorities prior to mission's FAR.

Table 2: Tentative schedule for ExoMars 2018 Landing Site Selection process.

4 SCIENTIFIC CONSTRAINTS

4.1 Rover Surface Mission

The ExoMars rover will have a nominal lifetime of 218 sols (approximately 7 months). During this period, it will be able to travel several kilometres, relying on solar array electrical power.

The rover's Pasteur payload will produce self-consistent sets of measurements capable to provide reliable evidence, for or against, the existence of a range of biosignatures at each search location. Pasteur contains: panoramic instruments (wide-angle and high-resolution cameras, an infrared spectrometer, a ground-penetrating radar, and a neutron detector); a subsurface drill capable of reaching a depth of 2 m to collect specimens; contact instruments for studying rocks and collected samples (a close-up imager and an infrared spectrometer in the drill head); a Sample Preparation and Distribution System (SPDS); and the analytical laboratory, the latter including a visual and infrared imaging spectrometer, a Raman spectrometer, and a Laser-Desorption, Thermal-Volatilisation, Derivatisation, Gas Chromatograph Mass Spectrometer (LD + Der-TV GCMS).

If any organic compounds are detected on Mars, it will be important to show that they were not brought from Earth. Great care is being devoted during the assembly, testing, and integration of instruments and rover components. Strict organic cleanliness requirements apply to all parts that come into contact with the sample and to the rover assembly process. Once assembled, the analytical laboratory drawer will be sealed and kept at positive pressure, throughout transport, final integration, launch, cruise, and landing on Mars. The ExoMars rover will also carry a number of blank calibration samples to demonstrate that it is free from contaminants. Upon landing, one of the first science actions will be for the drill to pass a blank sample to the analytical laboratory. The instruments will be trained on the blank material; their results will be used to establish the mission's analytical background.

4.2 Surface Platform Surface Mission

After landing the rover will be sitting on top of the Surface Platform (SP). The rover and the SP will unfold their solar panels and camera masts. The SP will deploy ramps that the rover can use to move onto the martian surface. Most likely, a few days will be required to image the surroundings and decide which is the safest exit direction for the rover to leave the lander. Once the rover will have egressed, the SP will begin its science mission—to conduct environment and geophysics experiments for about a martian year. The SP payload has not been selected yet.

4.3 Landing Site Scientific Constraints

From a science point of view, a landing site satisfying the Rover mission's search-for-life requirements is also expected to be extremely interesting for the Surface Platform's science.

For the ExoMars Rover to achieve results regarding the possible existence of signs of life, the mission has to land in a scientifically appropriate setting: The ExoMars 2018 mission must target a geologically diverse, ancient site interpreted to have strong potential for past habitability, and for preserving the physical and chemical signs of life and organic matter (including abiotic/prebiotic organics).

The rover will 1) analyse the local geology—surface and subsurface—at km- to sub-mm scales; 2) search for and evaluate the nature of past habitable environments at the landing site; 3) investigate favourable geological materials for preserving biosignatures; and 4) analyse them to search for physical and chemical signs of life—as well as seek evidence of abiotic, or prebiotic carbon chemistry—in the 0–2-m depth range.

4.3.1 Depositional Age of Terrain

The site must be ancient (older than 3.6 Ga)—from Mars' early, habitable period: Pre- to late-Noachian (Phyllosian), possibly extending into the Hesperian.

4.3.2 Preservation of Organics

Regarding the search for molecular biosignatures, sites must provide easy access to locations with reduced radiation accumulation in the subsurface. The presence of fine-grained sediments (on Earth, organic molecules are better preserved in fine-grained sediments—which are more resistant to the penetration of biologically-damaging agents, such as oxidants—than in coarse materials) in units of recent exposure age would be very desirable.

Young craters can provide the means to access deeper sediments, and studies on Earth suggest that fossil biomarkers can survive moderate impact heating. Additionally, impact related hydrothermal fractures may have contributed to creating habitats for microbial life in the past. However, for landing safety reasons it is better not to have many craters in the ellipse, so sites exposed by high erosion rates would be preferable.

4.3.3 Aqueous History

The site must show abundant morphological and mineralogical evidence for long-duration, or frequently reoccurring, low-energy transport, aqueous activity. We seek a geological setting with a water-rich/hydrothermal history consistent with life favourable conditions (e.g. evidence of slow-circulating or ponded water).

4.3.4 Availability and Distribution of Outcrops

The site must include numerous sedimentary rock outcrops. The outcrops must be distributed over the landing ellipse to ensure that the rover can get to some of them (the expected rover traverse range is a few km—during the mission's 218-sol nominal duration).

As an indication, assuming the mission lands in a scientifically interesting area, the Reference Surface Mission (RSM) scenario for the rover's 218-nominal mission duration results in roughly three quarters of the time spent performing science, and one quarter traversing to new science locations—assumed to be at increasing distances from each other, starting from 100 m and up to 500 m apart. The rover would be able to increase its traveling range, e.g. if deemed useful to reach a particularly interesting location, but this would be at the expense of science time.

4.3.5 Paucity of Dust Coverage

It is essential to avoid loose dust deposits distributed by aeolian transport. The site must have little dust coverage. Scientifically there are two reasons for this: 1) Dust is not an interesting target for the rover. While driven by the wind, this material has been processed by UV radiation, ionising radiation, and potential oxidants in the atmosphere and on the surface of Mars. Any organic biomarkers would be highly degraded, or even completely destroyed, in these samples. 2) The usefulness of the drill will be nullified if the landing site has a dust layer thicker than the drill's maximum penetration depth. Additionally, dunes constitute a serious risk for the rover's locomotion system.

5 ENGINEERING CONSTRAINTS

Engineering constraints are criteria that, in case they are not satisfied, can result in a candidate landing site being judged unfeasible for the mission and therefore rejected.

This Chapter presents landing site engineering constraints as they were analysed by the LSSWG. However, the ExoMars 2018 Descent Module (DM) is in its design phase. Therefore the values reported herein will be subject to frequent updates as the project work evolves.

This section addresses landing site characteristics relevant for:

- Safe entry descent and landing;
- Safe surface operations;
- Maximization of rover performance.

5.1 EDL Engineering Constraints and Performance Drivers

5.1.1 Landing Elevation

The landing site's elevation must allow an adequate atmospheric column capable of providing the drag and time needed for the successful completion of all Entry, Descent, and Landing (EDL) events.

The maximum altitude achievable by the landing system is -2 km with respect to the MOLA geoid. Therefore, the terrain elevation within the landing ellipse pattern must be ≤ -2 km MOLA.

5.1.2 Local Time and Season

For a nominal launch in the 2018 launch opportunity, the ExoMars mission will land in $L_s = 324^\circ$ at a Local Solar True Time between 10:00 and 11:05 (morning).

For a backup launch in the 2020 launch opportunity, the ExoMars mission will land in $L_s = 34^\circ$ at a Local Solar True Time between 10:55 and 12:40 (late morning).

5.1.3 Landing Ellipse Size and Orientation

Including margin to account for off-track radar operations (i.e. while oscillating under the parachute), the landing ellipse under evaluation for site selection has been assumed to be 104 km x 19 km.

A detailed navigational analysis reveals, however, the existence of a more-or-less linear relationship between Entry Flight Path Angle (EFPA) dispersion and landing site latitude. From 5°S to 25°N the EFPA dispersion varies between 0.154° and 0.289° . This dependency translates into an increase of the landing ellipse's 3-sigma, major axis with latitude. The 104 km major axis size utilised for the analysis can be considered conservative for low latitude locations, just about right for $15\text{--}18^\circ\text{N}$, but too small thereafter. This is further discussed for individual candidate sites.

The orientation of the landing ellipse will change depending on when the launch takes place within a given launch window. As shown in Fig. 2, for the 2018 launch opportunity (in yellow), the orientation of the landing ellipse can vary between 90° and 102° azimuth (computed clockwise from the North direction). For a 2020 launch (in light-blue), the landing ellipse azimuth can span the $88^\circ\text{--}127^\circ$ range. This effectively defines a landing ellipse pattern, achieved by rotating the 104 km x 19 km (3 sigma) landing ellipse between 88° and 127° .

Since it is required that landing sites be compliant with both launch opportunities, the adequacy of candidate landing sites against the applicable scientific, engineering, and planetary protection constraints will be verified over the entire landing ellipse pattern.

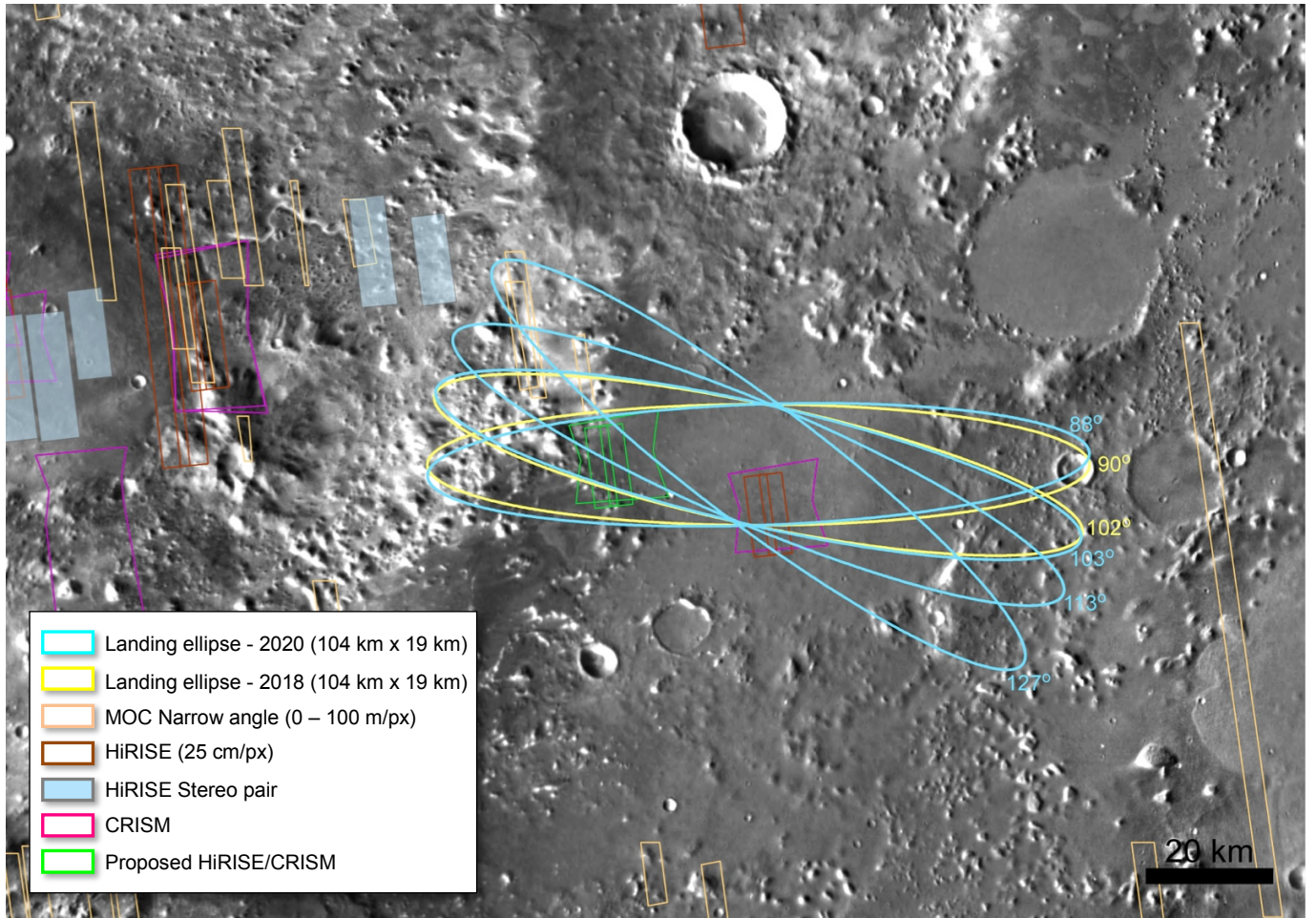


Fig. 2: Example of an ExoMars (104 km x 19 km) landing ellipse pattern. For a 2018 launch (in yellow), the orientation of the landing ellipse can vary between 90° and 102° azimuth (computed clockwise from the North direction). For a 2020 launch (in light-blue), the landing ellipse azimuth can span the 88°–127° range, depending on the launch date within the 2020 launch window opportunity. The ellipse pattern is centred at 18.36° N, 77.59° E, at an elevation of –2.66 km with respect to the MOLA geoid in planetocentric coordinates. The footprints of existing HiRISE, CRISM (in purple), and MOC (orange) images are shown. In green are depicted new, requests for a HiRISE image (rectangle) and a CRISM image (hourglass shape) centred at 18.365° N, 77.719° E.

5.1.4 Terrain Relief and Slopes

Terrain relief features and slopes constitute EDL performance drivers, as they may impact radar measurements and affect the stability of the landing platform.

The radar Doppler altimeter velocimeter uses multiple beams to measure the vertical and horizontal components of the descent velocity vector. The initial measurements are acquired after jettisoning the DM's front shield, while the vehicle is still hanging under its parachute. Continuous measurements are performed throughout the descent phase, until 10 m above the local ground level; thereafter the radar is switched off.

Over the whole descent trajectory, slopes at various length scales can alter the knowledge of “distance to ground at landing”, with potential serious consequences on fuel consumption, control authority, and landing conditions.

At present, the slope constraint set points are defined to be:

Base-length	Slope Requirement	Rationale
2000 m	$\leq 3^\circ$	To ensure slant and incidence compatible with radar.
330 m	$\leq 8.6^\circ$	To ensure proper fuel consumption during powered descent.
7 m	$\leq 12.5^\circ$	To ensure an adequate altitude error at touchdown.
2 m	$\leq 15^\circ$ (TBC)	To ensure stability at landing.

The analysis of landing sites will be performed according to the following assumptions:

- Length scales of 2 to 10 km: Slope $\leq 3^\circ$ on base-length of 2000 m.
Rationale: This requirement is driven by the specification of maximum slant range to be measured. The radar may be activated in the altitude range 3.0–6.5 km, but not operated in closed-loop until an altitude of 2500 m has been reached. Unambiguous altitude measurement is necessary for altitudes below 2500 m. The radar does not operate in closed-loop on base lengths ≥ 2 km. The radar is active on base lengths ≤ 5 km.
- Length scales of 0.33 to 2 km: Exponential self-affine model $C \cdot \Delta X(H-1)$, leading from 3° at 2000 m to 8.6° at 330 m.
- Length scales of 7 to 330 m: Exponential self-affine model $C \cdot \Delta X(H-1)$, leading from 8.6° at 330 m to 12.5° at 7 m.
Rationale: Ensure proper control authority and fuel consumption during powered descent.
- Length scales up to 7 m: Maximum relief 1.55 m up to a maximum slope of 18° . Corresponds to 12.5° on a 7-m base length, and 17.2° over a 5-m base length.
Rationale: To minimise the altitude error at landing.

5.1.5 Rock Distribution

The landing platform is designed with a clearance between nozzles and terrain of 0.35 m as the legs touch down, and 0.18 m following deformation of the legs' shock absorbers. Currently, the required clearance for the landing platform is 0.18 m (TBC).

Until this parameter has been confirmed, the applicable EDL rock distribution constraint is that the site must have a rock abundance $\leq 7\%$ — derived from the rover constraint for rock abundance.

5.1.6 Radar Reflectivity

The ExoMars 2018 EDL design requires that the surface materials present at the landing site be radar reflective, providing sufficient backscatter signal to enable measuring the altitude and velocity with respect to ground during the descent. The relevant constraints have been determined on the basis of a realistic assessment of terrain reflectivity.

The following ranges for backscattering constraints are driven by the current radar requirements.

- Terrain Backscattering at nadir: -15 dB to 27.5 dB
- Terrain Backscattering at 10° off-nadir: -17 dB to -10 dB
- Terrain Backscattering at 20° off-nadir: -18 dB to -13 dB
- Maximum Backscattering decay from 0° to 5° off-nadir: -30.4 dB
- Maximum Backscattering decay from 0° to 10° off-nadir: -37.3 dB
- Maximum Backscattering decay from 0° to 15° off-nadir: -40.6 dB

5.1.7 Atmospheric Parameters

The ExoMars 2018 DM is being designed to land safely and accurately under a range of atmospheric conditions. In order to ensure the expected performance can be achieved, “not to exceed” thresholds have been defined for atmospheric density, horizontal, and vertical winds.

The applicability of these thresholds is altitude dependent since they are associated with sensitive events in the EDL sequence, such as peak deceleration, deployment of parachutes, terminal descent velocity, initiation of powered descent, etc.

From entry through the descent phase (parachutes), altitude references for atmospheric parameters are given with respect to the local MOLA geoid. However, following front shield ejection—when the radar will start operating—altitude references are given with respect to ground. The set of atmospheric thresholds used for the DM design is provided in Table 6.

5.2 Rover Engineering Constraints and Design Capability

This chapter describes the rover design capabilities to allow assessing the feasibility of reaching scientific points of interest within the landing ellipse pattern.

As the rover system is still under development, the characteristics reported herein are indicative and remain to be confirmed and tested to the necessary extent.

The rover's effective capabilities depend on the type of the terrain, on the power/energy availability, and on the environment. The season, the latitude, the nature and inclination of the terrain, the near surface wind, the atmospheric dust opacity, the dust deposition rate are all factors that can affect rover performance. For the sake of clarity, this will not be recalled systematically in the following sections.

The rover will be commanded from Earth by means of Activity Plans. These Activity Plans will be prepared and checked to ensure their compatibility with available rover resources at the time of their planned execution. The rover will include on-board intelligence, allowing it to autonomously:

- Stop the execution of an Activity Plan in case of trouble or lack of resources (e.g. the environmental conditions may have changed with respect to the ground prediction) and reach a safe state;
- Replan the Sol's activities based on alternatives previously defined by Ground Control;
- Travel safely to a target designated by Ground Control, avoiding hazards such as rocks, steep slopes, and crevasses.

5.2.1 Mobility System Description

The ExoMars rover has six driving wheels capable of steering. Deployment actuators are available to raise the rover on the Surface Platform, before egress. The rover size is approximately 1.7 m in length by 1.5 m in width (excluding the solar arrays).

The wheels are mounted on three bogies (one on each side, and one on the rear) that can rotate relative to the body to provide passive adaptation to the terrain shape and keep the wheels on the ground. The wheels are flexible to increase their contact surface. The wheels' diameter is 285 mm and their width is 120 mm, resulting in an approximate indicative surface load under each wheel of 14.6 kN/m². The landing site terrain must be able to bear such load; therefore, very thick layers of loose soil must be avoided.

The rover is designed to drive over 25 cm step obstacles and over crevasses of 15 cm width. The rover's nominal ground clearance is about 30 cm.

The rover can be controlled from Earth with various levels of commanding to:

- Execute low-level manoeuvre commands, such as Ackerman curves, point turns, or crabbing—thanks to its six-steering-wheels capabilities;

- Execute a trajectory using vision-based position control;
- Perform on-board path planning (based on autonomous hazard detection using stereo cameras at about 2 m above the ground mounted on a pan-tilt assembly) and execute a trajectory using vision-based position control.

Energy considerations, terrain slopes, rock distribution, and soil characteristics can affect rover trafficability. For design and test purposes, a number of reference terrains have been defined (not reported herein).

5.2.2 Latitude

The ExoMars rover is designed to operate in the latitude range between 5°S to 25°N.

5.2.3 Surface Thermophysical Properties

The ExoMars rover is designed for:

- Surfaces having thermal inertia $\geq 150 \text{ J m}^{-2} \text{ s}^{-0.5} \text{ K}^{-1}$.
- Surfaces having $0.1 \leq \text{albedo} \leq 0.26$.

5.2.4 Traverse Range and Rover velocity

The ExoMars Rover is designed to traverse 4 km along track, consistent with the requested capability of being able to drive 500 m between each of six experiment sites within its 218-sol nominal mission duration.

The rover's nominal commanded speed is about 40 m/h. However, wheel slippage can increase depending on the terrain (soil type, slope, rocks); the effective speed would then be smaller. For activities requiring very accurate positioning, the rover's speed can be reduced to about 10 m/h. On very easy terrains, the maximum 70 m/h speed could be achieved—mainly on a straight line on flat ground.

By using its on-board path planning capability every few meters, the rover can compute autonomously a path toward any Earth-specified goal coordinates. This functionality, however, reduces the rover's average speed to about 15 m/h, allowing to drive approximately 70 m/sol—along the path on a terrain with overall rock abundance of 6.9% [M. Golombek and D. Rapp (1997) "Size-frequency distributions of rocks on Mars and Earth analogue sites: Implications for future landed missions" *Journal of Geophysical Research* 102, 4117-4129].

Assuming the following additional terrain characteristics for soil and slope distributions, representative point-to-point travel distances per sol can be estimated. Table 3 presents simulation results for a "crusty/cloddy/silty sand" type of soil.

Ls/Lat.	5°S	0°N	15°N	25°N
324°	72	68	63	41
340°	69	72	65	47
0°	64	71	69	55
30°	55	66	72	62
60°	44	61	72	66
71°	41	59	73	67

Table 3: ExoMars rover Autonomous Navigation representative travel distances (point-to-point, in metres) per sol as a function of Ls and latitude for soil of type "crusty/cloddy/silty sand" with bulk density of 1800 kg/m³. The adirectional slope distribution on a 5-m scale follows a Chi-Square distribution with parameter 7 and a maximum slope of 21.5°. The on-board path planning standard settings would avoid slopes $\geq 20^\circ$ and hemispheric rocks of 20 cm height.

For much easier terrains, trajectories can be planned on Earth, uploaded, and executed by the rover. The achievable point-to-point distance per sol would obviously depend on the terrain, but also on the ability of Ground Control to accurately assess the terrain difficulties up to the desired target. With good conditions, 150 m/sol point-to-point could be reasonably executed, although it must be noted that this remains to be tested.

Finally, for terrains presenting intermediate difficulties, Ground Control could specify the initial part of the traverse, based on available images/data, and the rest of the trajectory could be executed using on-board path planning. Simulation results for one such example are presented in Table 4.

Ls/Lat.	5°S	0°N	15°N	25°N
324°	98	95	89	68
340°	95	99	92	74
0°	91	97	95	82
30°	82	93	98	89
60°	71	87	99	93
71°	68	85	99	94

Table 4: ExoMars rover combined Trajectory Execution plus Autonomous Navigation indicative travel distances (point-to-point, in metres) per sol as a function of Ls and latitude on terrain as above. In this case the first 40 m are assumed planned by Ground Control (i.e. not autonomous navigation).

5.2.5 Static Stability and Slope Access

The rover has been designed to be statically stable on slopes $\leq 40^\circ$ with respect to the horizontal plane. Some margin will be included during operations to ensure safety at all times. Additionally, on-board monitoring of the rover tilt will prevent any dangerous situations.

The rover's drill and analytical laboratory are designed to work with a rover body inclination $\leq 10^\circ$ with respect to the horizontal plane.

The rover mobility system will allow driving on terrains with slopes. The rover will experience slippage that will limit the maximum slope inclination depending on the soil type. Allowable slopes are given below for various types of terrain.

- Slope $\leq 26^\circ$ for gravel and medium to coarse sand;
- Slope $\leq 21^\circ$ for very fine sand;
- Slope $\leq 10^\circ$ for fine dust.

The rover will be able to extricate itself from a situation where two front wheels are approximately 50% buried. These known dangerous situations will be avoided as much as possible by continuous slippage monitoring.

5.2.6 Surface Winds

Horizontal Wind: ≤ 30 m/s at 1 m above ground level (during rover surface operations).

Vertical Wind: ≤ 12 m/s at 1 m above ground level (during rover surface operations).

5.3 Preliminary Summary Tables for Engineering Constraints

Since the ExoMars 2018 mission is under development, these constraints are preliminary. The final constraints will be confirmed in the course of the project's life cycle.

Engineering Parameter	Requirement	Notes
Landing Latitude	5° S to 25° N	Driven by Surface Platform and Rover design. Latitudes beyond this range would cause either degraded electrical power, or challenging thermal conditions. Latitudes within the 0°–15° N band maximise the rover's travelling capabilities.
Landing Elevation	≤ −2 km MOLA	For sufficient atmospheric braking during EDL.
Landing Ellipse Dimensions	Major axis: 104 km Minor Axis: 19 km	Landing ellipse dimensions where all listed constraints must be verified.
Landing ellipse Orientation	88° to 127°	Azimuth angles measured clockwise from north. Ellipse Orientation will vary slightly depending on the landing site's latitude.
Slopes at 2- to 10-km length scale	≤ 3.0°	To ensure slant and incidence compatible with radar.
Slopes at 330-m length scale	≤ 8.6°	To ensure proper fuel consumption during powered descent.
Slopes at 7-m length scale	≤12.5°	To ensure proper altitude error in the touchdown phase.
Slopes at 2-m length scale	≤15.0°	To ensure stability at landing
Rock abundance	K < 7 %	Drives the rover traverse performance and also drives the probability of encountering a rock during landing
Thermal Inertia	≥ 150 J m ⁻² s ^{-0.5} K ⁻¹	□iven by rover thermal design constraints and by the need to have a load-bearing surface.
Albedo	0.1 ≤ albedo ≤ 0.26	□iven by rover thermal design constraints
Radar Reflectivity	Ka band radar backscatter cross-section at nadir: > −15 dB and < 27.5 dB	The terrain backscatter characteristics are key for the proper functioning of the radar. These values are relevant to nadir backscatter. Other conditions are described in the dedicated section.

Table 5: Summary of preliminary surface/terrain engineering constraints.

Altitude	Density	Horizontal Winds	Vertical Winds	Sound Speed	Event Driver
40 km MOLA	$\leq 15\%$ (TBC) uncertainty				Deceleration
6–10 km MOLA	$\leq 8\%$ (TBC) uncertainty	Max ≤ 25 m/s (TBC)	Max ≤ 12 m/s (TBC)	$\leq 5\%$ (TBC) uncertainty	Drogue parachute deployment
4–6 km MOLA		Max ≤ 25 m/s (TBC)	Max ≤ 12 m/s (TBC)	$\leq 5\%$ (TBC) uncertainty	Main parachute deployment
1–4 km MOLA		Max ≤ 25 m/s (TBC)	Max ≤ 12 m/s (TBC)	–	Main parachute descent
10–600 m above ground		Max ≤ 25 m/s (TBC)	Max ≤ 12 m/s (TBC)	–	Parachute terminal velocity and powered descent
0–10 m above ground	$> 13 \text{ g/m}^3$	Max ≤ 25 m/s	Max ≤ 12 m/s (TBC)	–	Final descent and touchdown
1 m above ground		Max ≤ 30 m/s	Max ≤ 12 m/s	–	Rover surface operations

Table 6: Summary of preliminary atmospheric engineering thresholds. The thresholds for altitudes above 6 km must not be exceeded anywhere along the portion of the descent trajectory that lies within 100 km of the proposed landing site. All thresholds for uncertainty are specified as 3-sigma (99.87 % probability) values. The thresholds for maximum horizontal and vertical wind speed apply to all landing sites, regardless of their elevation.

6 PLANETARY PROTECTION CONSTRAINTS

6.1 Mars Special Regions

The ExoMars 2018 mission is not compatible with landing in a Mars Special Region.

A Mars Special Region is defined as any environment providing temperature ($\geq -25^{\circ}\text{C}$) and water activity (≥ 0.5) levels that would permit the replication of terrestrial organisms (Kminek et al., 2010; COSPAR). Observable surface features currently classified as Mars Special Region are gullies, bright streaks associated with gullies, and pasted-on terrain. A candidate landing site must not include any of these features.

Any evidence of dark streaks or candidate Recurrent Slope Lineae (RSL) (definition as per McEwen et al., 2014) in a proposed landing site or close to a proposed landing site (i.e. in the same geological unit or in a unit with a similar formation history) must be identified. Such features will be treated as Mars Special Region until demonstrated otherwise through the analysis of more high-resolution imaging.

6.2 References

COSPAR Planetary Protection Policy, as amended, 24 March 2011.

McEwen, A. S. et al (2014), Recurring slope lineae in equatorial regions of Mars. *Nature Geoscience*, **7**, 53–58.

Kminek, G. et al. (2010), Report of the COSPAR Mars Special Region colloquium. *Advances in Space Research*, **46**, 811–829.

7 PROPOSED LANDING SITES

7.1 Introduction to the Candidate Landing Sites

The eight proposed sites are presented in Table 7 (ordered by latitude, from north to south).

LS Name	Ellipse pattern's centre coordinates	MOLA altitude: max (avg) km
Mawrth Vallis 2	22.25°N, 342.00°E	−2.0 (−2.2)
Mawrth Vallis 1	22.16°N, 342.05°E	−1.8 (−2.2)
Oxia Planum 1	18.20°N, 335.45°E	−2.8 (−3.1)
Oxia Planum 2	16.63°N, 333.19°E	−2.5 (−2.7)
Coogoon Valles	16.50°N, 336.50°E	−2.6 (−2.7)
Hypanis Vallis	11.80°N, 314.96°E	−2.3 (−2.7)
Simud Vallis	8.49°N, 325.24°E	−4.9 (−5.0)
Aram Dorsum	7.87°N, 348.80°E	−1.9 (−2.1)
Southern Isidis	4.35°N, 86.20°E	−3.4 (−3.8)

Table 7: Eight landing site proposals were accepted for review. The Oxia Planum proposal included two ellipses. The Mawrth Vallis 1 & 2 proposals addressed the same area and can be considered as one landing site.

Fig. 3 shows the position of the eight ellipses. The four sites that received a higher science endorsement at the First LSS Workshop —Mawrth Vallis, Oxia Planum 1, Hypanis Vallis, and Aram Dorsum— are indicated in red.

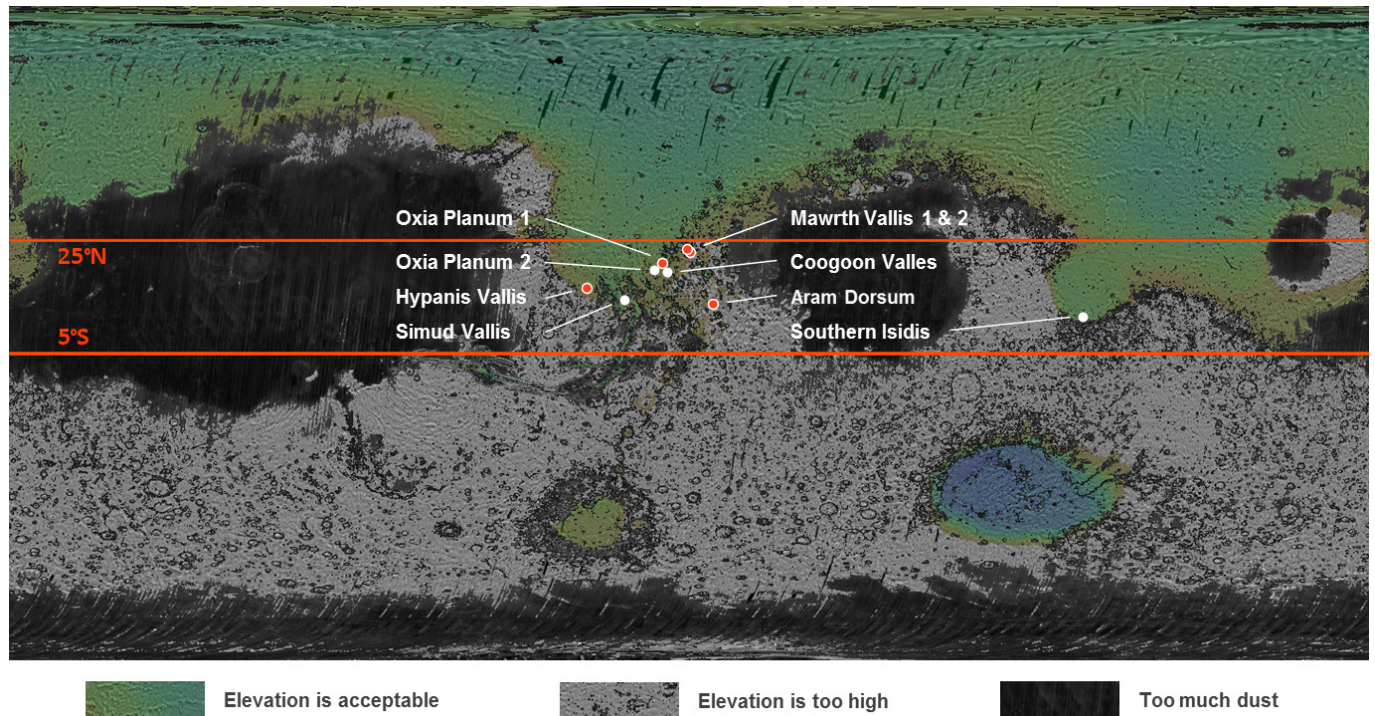


Fig. 3: Map showing the eight landing sites proposed for the ExoMars 2018 mission. The four locations that received a higher science endorsement—Mawrth Vallis, Oxia Planum 1, Hypanis Vallis, and Aram Dorsum—are indicated with red dots. The two red lines delimit the allowed latitude range for landing sites, 5°S to 25°N. The coloured surfaces correspond to areas below the maximum landing site elevation of −2 km MOLA; grey sections have elevations above this limit. Finally, black shading is utilised for areas of unacceptably low thermal inertia, indicative of high dust coverage, and for local slopes too steep for landing.

Hereafter we provide a brief description of the candidate sites:

Mawrth Vallis (Two very similar ellipses: EL1: 22.16°N, 342.05°E; EL2: 22.25°N, 342.00°E):

The proposed ellipse lies in middle to late-Noachian terrains southwest of the Mawrth Vallis channel; it was initially suggested as a landing site by two independent teams. The region surrounding Mawrth Vallis contains one of the largest exposures of phyllosilicates detected on Mars. These phyllosilicates occur in light-toned, finely layered deposits of unknown origin, but the extent of the deposits is suggestive of a large, stable aqueous system. Outcrops in Mawrth Vallis are compositionally diverse, with a generally observed sequence of Al-phyllosilicates on top of Fe-smectites over large surfaces, and local outcrops of sulphates, indicating multiple, varied wet environments. These rocks show the highest degree of alteration identified so far on Mars. The deposition and alteration are ancient (mostly > 3.8 Ga). The material of interest has lain buried under a dark cap unit that has only recently been eroded away. Hence it is expected that the main target outcrops would be well preserved.

Oxia Planum (Two ellipses: EL1: 18.20°N, 335.45°E; EL2: 16.63°N, 333.19°E):

Two ellipses were proposed in the Oxia Planum area, at the outlet of the Coogoon Valles system. These ellipses were chosen to include extensive exposures rich in Fe/Mg-phyllosilicates, as seen on both OMEGA and CRISM multispectral data. These detections are associated with layered rocks and likely represent the southwestern expansion of the Mawrth Vallis clay-rich deposits, pointing to an extended alteration process. The crust is ancient (> 4 Ga) and underwent intense erosion until 3.6 Ga ago, although the phyllosilicate bearing rocks have been exposed only recently. Both ellipses have fluvial-related morphologies, such as valleys and a fan or delta.

Coogoon Valles (16.50°N, 336.50°W):

The proposed ellipse lies at the end of the Coogoon Valles system, between Mawrth Vallis and Ares Vallis. Coogoon Valles has received little attention so far, although it includes clear indications of past water activity, including flow channels, scablands, layered sedimentary deposits, craters with fluidized ejecta and high albedo materials of special interest because of their inferred association with aqueous solutions. In the proposed ellipse, layered deposits show the presence of phyllosilicates, with a similar mineralogical sequence similar to that in Mawrth Vallis.

Hypanis Vallis (11.80°N, 314.96°E):

The proposed ellipse lies on one of the many exhumed fluvial fan/deltaic systems at the termination of Hypanis Vallis. This site contains fan-like deposits interpreted to be the remnants of a prograding delta. These deposits are characterised by the presence of distinct layering at their margins, providing access to sedimentary sections. Although very few CRISM observations are available within the ellipse, the lower strata of this delta might be enriched in Fe/Mg-rich phyllosilicates, as suggested by detections in other fans in the vicinity of the ellipse. The site offers access to [exhumed] sedimentary rocks of Early Hesperian age (3.45 Ga) with a very well defined sedimentary context across a significant proportion of the landing ellipse. The base of the lobes would provide windows into prodelta sediments where the finest grains accumulate.

Simud Vallis (8.49°N, 325.24°E):

The proposed ellipse lies at a junction between Simud Valles and Tiu Valles, two outflow channel systems connected to the north with the Chryse Basin, just west of the Mojave crater. The crater counts suggest an age of 3.5 Ga, belonging to the early-late Hesperian epoch. The area is characterized by a complex geomorphological evolution, as evidenced by many structures, including ridges and potential fluvial channels, which have been recognised and mapped inside and in the proximity of the landing ellipse. Alluvial sediments, mainly gravel, sand and boulders, likely resulted from local catastrophic events, such as the sudden water release following the collapse and breach of the Masursky crater wall. A part of the ellipse lies on the Mojave crater ejecta, which has been interpreted as the source crater for Shergottite meteorites. The main targets of interest are morphologic features that the proposing team interprets as ancient ponds.

Aram Dorsum (7.9°N, 348.8°E):

The proposed ellipse lies ~100 km north of Crommelin crater, in the Oxia Palus region. The site comprises layered sedimentary rocks with distinct development of a prominent inverted channel ridge (> 80-km long). The superposing materials that are present in the rest of the site appear to be a mixture of sedimentary deposits and suggest that the inverted channel system has been exhumed only relatively recently. Impact crater size-frequency statistics and regional stratigraphy indicate an ancient, Noachian age for the alluvial system. Some parts of the terrain have been exposed for as little as 100 Ma.

Southern Isidis (4.35°N, 86.2°E):

The proposed ellipse lies on the early Hesperian plains of southern Isidis Planitia, just north of the boundary with the Noachian highlands of Libya Montes. The terminal plains represent a complex mixture of materials eroded from the highlands and deposited due to filling of the Isidis basin. Potential science targets include: 1) exhumed Noachian fluvial deposits, valleys, and ridges (potential inverted valleys or eskers); 2) Noachian highland remnants and deposits rich in Fe/Mg and Al- rich phyllosilicates; and 3) the Deuteronilus and Arabia contacts, which have been interpreted as putative paleoshorelines.

7.2 A Note Concerning Site Description and Age Determination

The surfaces of a planet often preserve an imprint of their geological evolution. When dated, they can help us to estimate the timing and rates of the geological processes involved. Dating of planetary surfaces requires combining information from geological mapping and crater count statistics. The determination of absolute model ages is based on the use of a crater-production function (Fig. 4) and a cratering chronology model. The crater-production function describes the expected crater Size-Frequency Distribution (SFD) observed for a geological unit at a specific time. The cratering chronology model specifies the integrated cratering rate through time. Both the crater-production function and chronology model require scaling from the Moon (the only body for which isotope age information and crater frequencies can be correlated) to, for example, Mars. This scaling relies on our understanding of crater-to-projectile scale relationships for the target body we want to study. A number of uncertainties remain and therefore diverse crater-production functions can be used to calibrate crater density measurements. This has resulted in a variety of different lunar chronology models. This diversity propagates to other planets, such as Mars, and adds ambiguity to the related temporal interpretations (e.g. Werner and Tanaka 2011).

In this document we have estimated ages with the cratering chronology model and crater SFD by Ivanov (2001). The ages differ slightly when Hartmann's SFD (Hartmann 1999) or other chronologies are used. For comparison, the Werner et al. (2014) model ages are given between brackets. This latter model results in significantly older ages. For example, the plateau unit around Simud Vallis is about 4.1 Ga (4.32 Ga) old and experienced a resurfacing event 3.91 Ga (4.09 Ga) ago.

For statistical evaluation and age determination purposes, crater size and occurrence are recorded and plotted in histograms such as the crater SFD curves. The graphs used here (Fig. 4) plot cumulative crater frequencies (number of craters greater than a certain size per square kilometre, N_{cum}) against the crater diameter D on log-log plots. The crater distribution characteristics are defined by polynomial functions or multiple-segment power laws where, for example, the cumulative frequency N_{cum} is proportional to D^{-b} , where the exponent b varies between 4 and 1.5 (e.g., Hartmann 1999; Neukum et al. 2001).

The method to date surfaces from their crater SFD is based on the assumption that right at the end of its formation a given surface unit had no superposed craters; and that from then on it began to accumulate craters. However, the surface unit's geological history during the crater accumulation period can often complicate this ideal scenario. Depositional or erosional processes can obliterate small-diameter craters and thus skew the population. Nevertheless, the formation age can usually still be determined from the unaffected larger crater population and it is often also possible to date resurfacing episodes.

For the general description of landing site units we have utilised the new geological map produced by Tanaka et al. 2014. Ages have been estimated in the context of the geologically mapped units therein. For regional evaluation purposes, crater counts were performed on 100-m/pixel THEMIS IR image data (sufficient for examining craters

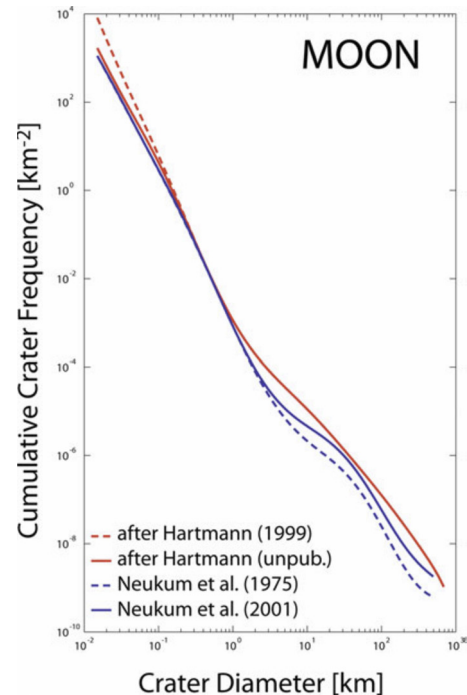


Fig. 4: Examples of four different, but commonly used, cumulative crater Size-Frequency Distributions (SFDs) determined for the Moon (log-log plot).

with diameters ≥ 1 km). For more detailed studies of the age and geological evolution of areas within the candidate landing ellipses we utilised 6-m/pixel CTX image data and for one case a nearby MOC image. For the next stage of characterisation, it is recommended to use HiRISE imagery for estimating exposure ages and for a more accurate determination of the depositional and erosional history of the candidate landing sites.

In the evaluation of the individual landing site candidates, we performed crater counts to determine the overall age of the site. Tanaka et al. (2014) give a first global interpretation in their geological map. However, we computed crater counts to check that the first evaluation criterion was satisfied —that the site must be ancient (older than 3.6 Ga). The absolute age is a function of the cratering chronology model, but the sites fulfil this requirement with all currently available models. The other evaluation criteria are related to the preservation of organics and aqueous history. These cannot be directly assessed through cratering statistics, but the shape of the crater SFD with respect to the crater-production function allows detecting resurfacing events and their strength.

The three sketches in Fig. 5 present examples of crater SFD modifications caused by partial and complete resurfacing episodes. Here we can see how A) a single discrete event (e.g. lava emplacement), B) multiple-events (e.g. several lava flows), and C) continuous deposition (e.g. aeolian dust deposition) may manifest in the crater SFD plot. The interpretation of what exactly caused the deviation in the observable crater record from the expected crater-production function requires a careful photogeological evaluation determined through mapping —to establish whether it was erosion or deposition that erased the small craters. Please note that it is necessary that the images used (for geological mapping and for crater counting) have a resolution significantly higher (e.g. 10 m/pixel) than the smallest crater diameter population (e.g. 100 m) being considered in the analysis.

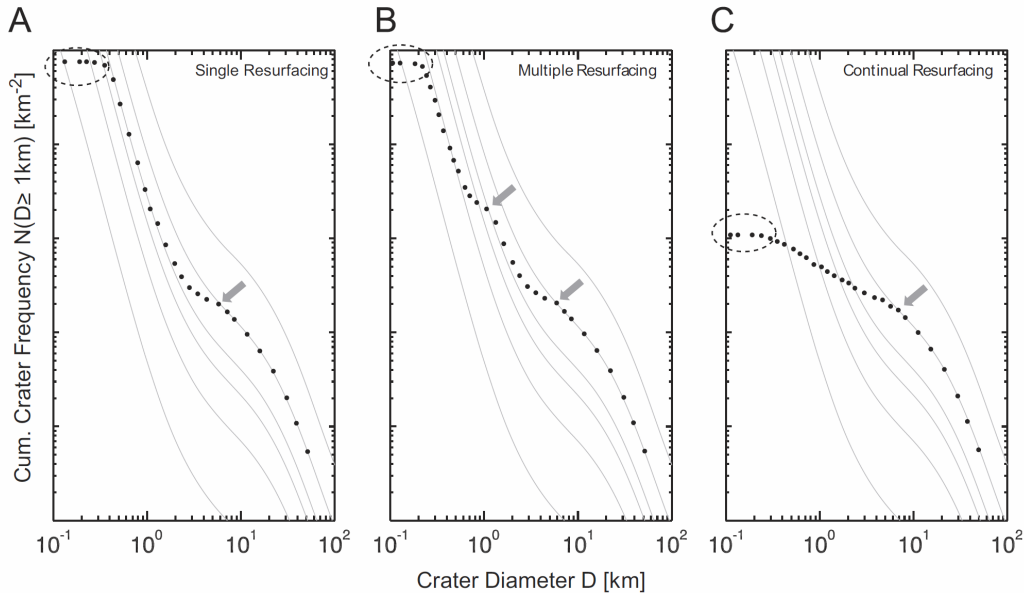


Fig. 5: Three different schematic crater Size-Frequency Distributions (SFDs) displaying the effect of resurfacing events (deposition or erosion): In case A) the resurfacing episode has a distinct timing, visible in the re-steepening of the crater SFD at small crater sizes. In case B) a second distinct event follows the first. The plot in C) corresponds to a case where resurfacing is occurring continuously. At the smallest crater range (dotted ellipse) a flattening of the curve is observed which is related only to the resolution limit of the image data (Figure from Werner et al. 2011). In all cases, the formation age (determined from the larger crater population) is the same.

From the kink in the observed crater SFD one can establish the maximum crater diameter that either got covered or eroded away. Thereafter, by using morphometric rules for the crater depth-diameter relation it is possible to estimate the layer thickness (addition or removal) required to erase the craters (here we have used Tornabene et al. 2013). This gives an estimate for the stratigraphic column thickness that was modified —by deposition, erosion, or a combination of these processes. Again a detailed interpretation can only be accomplished through photogeological evaluation. For ExoMars, in case the SFD kink(s) in our hypothetical example were due to lava emplacement, the likelihood of finding well-preserved organic material in the deposits would be very slim. If, on the other hand, the kinks would result from sedimentary overburden, this should not necessarily constitute an impediment —depending on the nature of the sediments and provided they would be relatively old.

7.2.1 References

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7.3 General Atmospheric Conditions for the 2019 Landing

Excessive winds could affect parachute deployment, parachute performance, and the powered descent phase. As detailed above, the key atmospheric criteria that must be satisfied are:

1. At landing: The precise constraint for the horizontal wind maximum velocity is not known. The preliminary, 3-sigma engineering threshold has been set to 25 m/s from 0- to 10-km above the surface.
2. At landing: Vertical wind speed between 0- and 10-km above the surface: Max $\leq$ 12 m/s (TBC).
3. At landing: Local surface pressure (usually described in terms of altitude): -2.0 km MOLA.
4. During surface rover operations: Surface horizontal ($\leq$ 30 m/s at 1 m) and vertical wind speed ($\leq$ 12 m/s).

Most of these parameters strongly vary with season, latitude, exact location, and amount of airborne dust in the atmosphere (as defined by the dust visible column optical depth).

7.3.1 Expected Atmospheric Dust Loading

A 2019 landing would take place during northern winter ($L_s \sim 324^\circ$), a season characterised by large atmospheric dust inter-annual variability. For the past eight martian years, the visible dust opacity has remained below 1.5. This value is the result of atmospheric loading by local and regional dust events only (Fig. 6). However, atmospheric opacity can be much higher during the peak of a planetary encircling dust storm (“global dust storm”), which is not impossible in this season. For example, in 1977 (Martian Year 12), the atmosphere was still affected by a decaying global dust storm at $L_s=324^\circ$ (Fig. 4). Fig. 5 presents statistics for observed planetary encircling dust storms since 1956 (Martian Year 1).

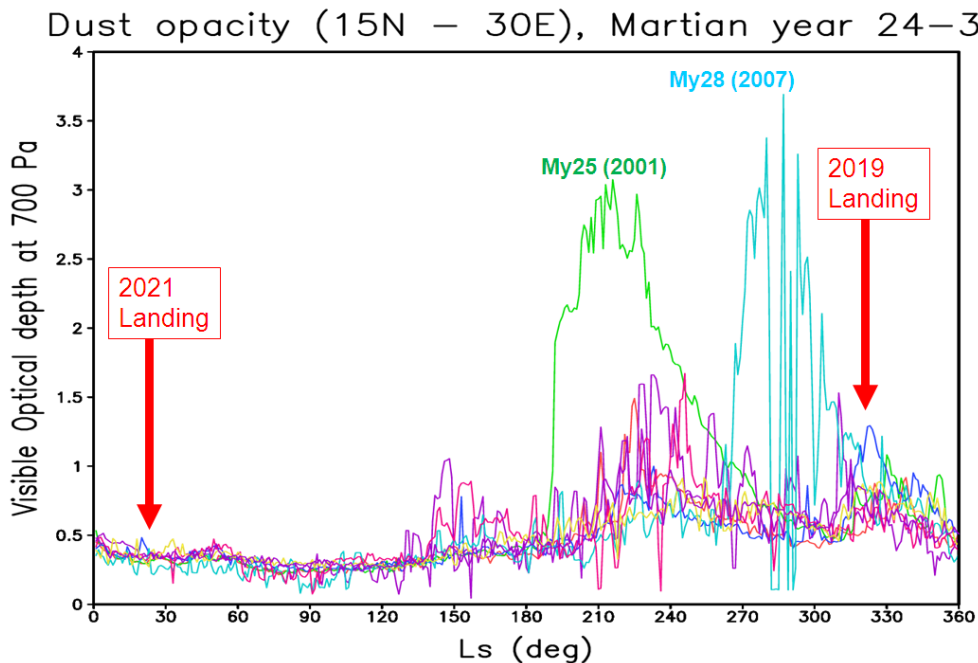


Fig. 6: Visible dust opacity at reference level 700 Pa observed by various instruments during the last eight martian years in Chryse Planitia (15°N , 320°E), near most proposed landing sites (Montabone et al., 2014).

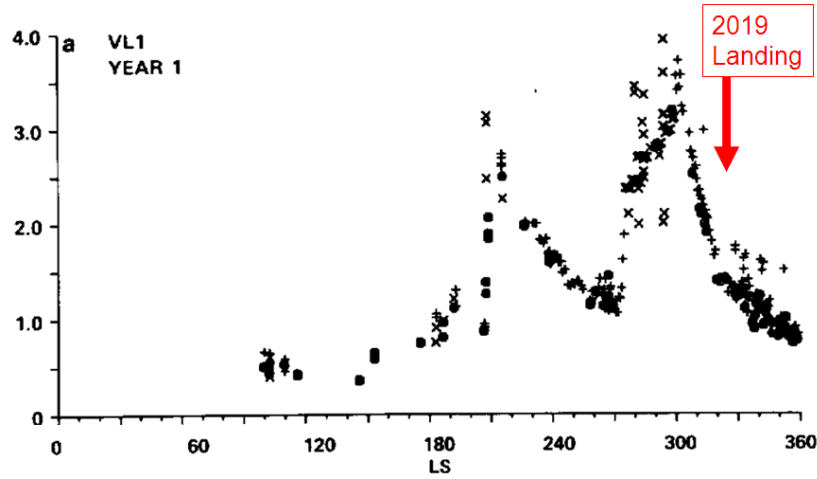


Fig. 7: Visible dust opacity measured by the Viking 1 lander in Chryse Planitia (22.48°N, 310.03°E) during Mars Year 12 (Colburn et al., 1989).

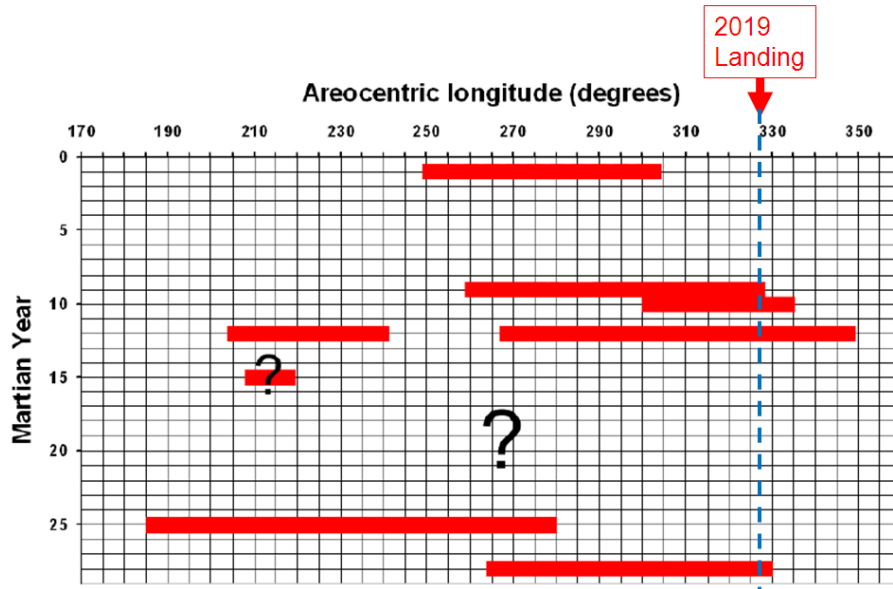


Fig. 8: Statistics for Mars planetary encircling (global) dust storms since 1956. No such dust storms have been recorded prior to 1956. Courtesy of L. Montabone.

7.3.2 Horizontal Winds

To date, no direct measurements of martian winds have been performed from orbit. However, temperature fields can be determined from radio occultation measurements and by monitoring the atmospheric, 15- μm CO_2 band. Using carefully validated Global Climate Models (GCM) we can match the observed atmospheric thermal structure variations. Hereafter, we utilise Laboratoire de Météorologie Dynamique (LMD) GCM simulations (Forget et al., JGR 1999) to predict the atmospheric conditions at the time of landing (Mars Climate Database (MCD) version 5.0, though tests have been performed also with the brand new MCD v5.1 and the results are very similar).

The simulations show that, for a 2019 landing in northern winter (Ls $\sim 324^\circ$), the dominant wind patterns are controlled by Hadley cell circulation. **Above 2–4 km** altitude, the mean meridional flow proceeds from south to north, across the equator, toward the pole. In the northern hemisphere, air masses drawing nearer to the pole (approaching the axis of rotation) tend to conserve their angular momentum, turning faster than the planet, giving rise to a strong westerly jet, analogous to the terrestrial “jet stream”, around the north pole (Fig. 9). **Below 2–4 km** altitude, air follows the reverse path in the returning branch of the Hadley cell, from the winter hemisphere to the summer hemisphere. There again, air trajectory is affected by the rotation of the planet (Coriolis force), which deviates the flow to the right in the northern hemisphere and to the left in the southern hemisphere.

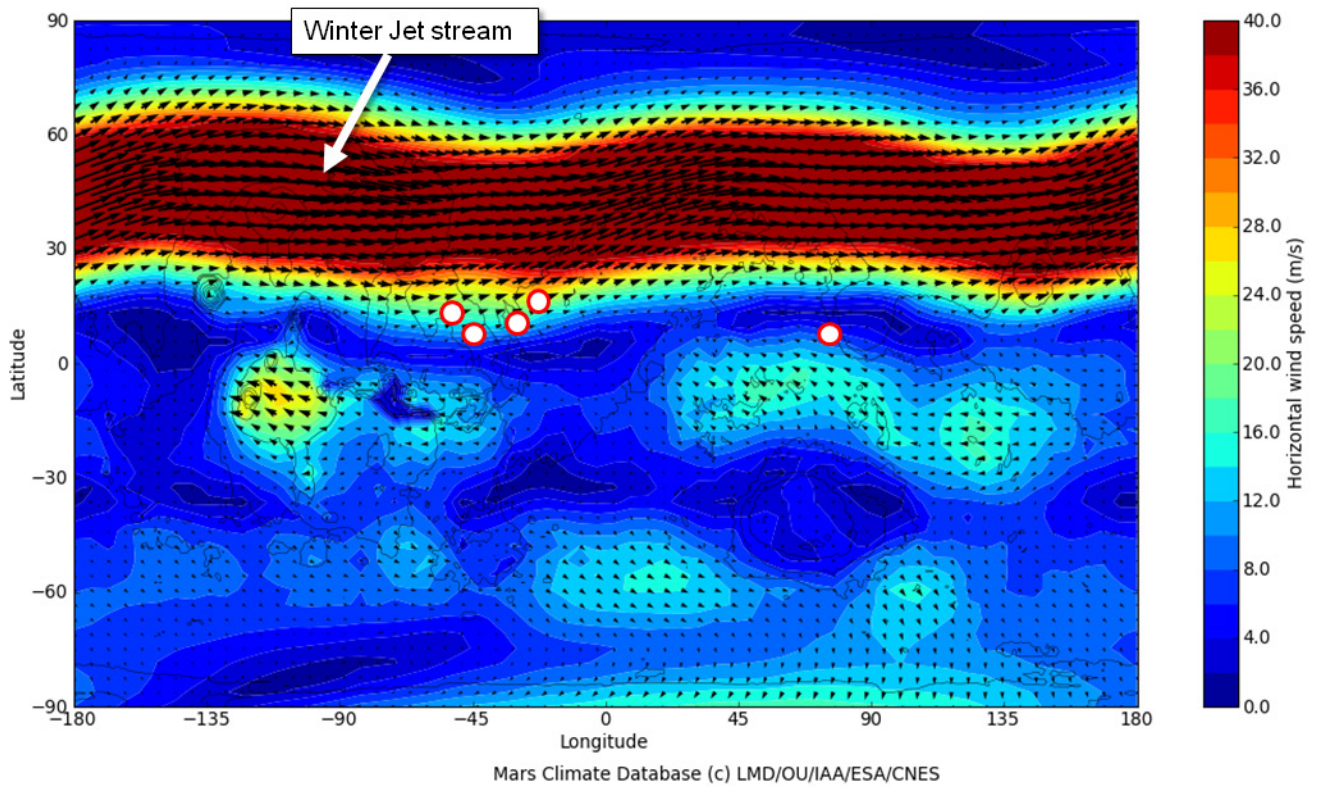


Fig. 9: Mean wind velocity at $z=10$ km above the local surface for the 2019 landing ($L_s \sim 324^\circ$ and Local time=10.5) for typical dust conditions (Mars Climate Database v5.0 climate scenario: $\tau \sim 0.6$). The red circles illustrate the position of several proposed landing sites.

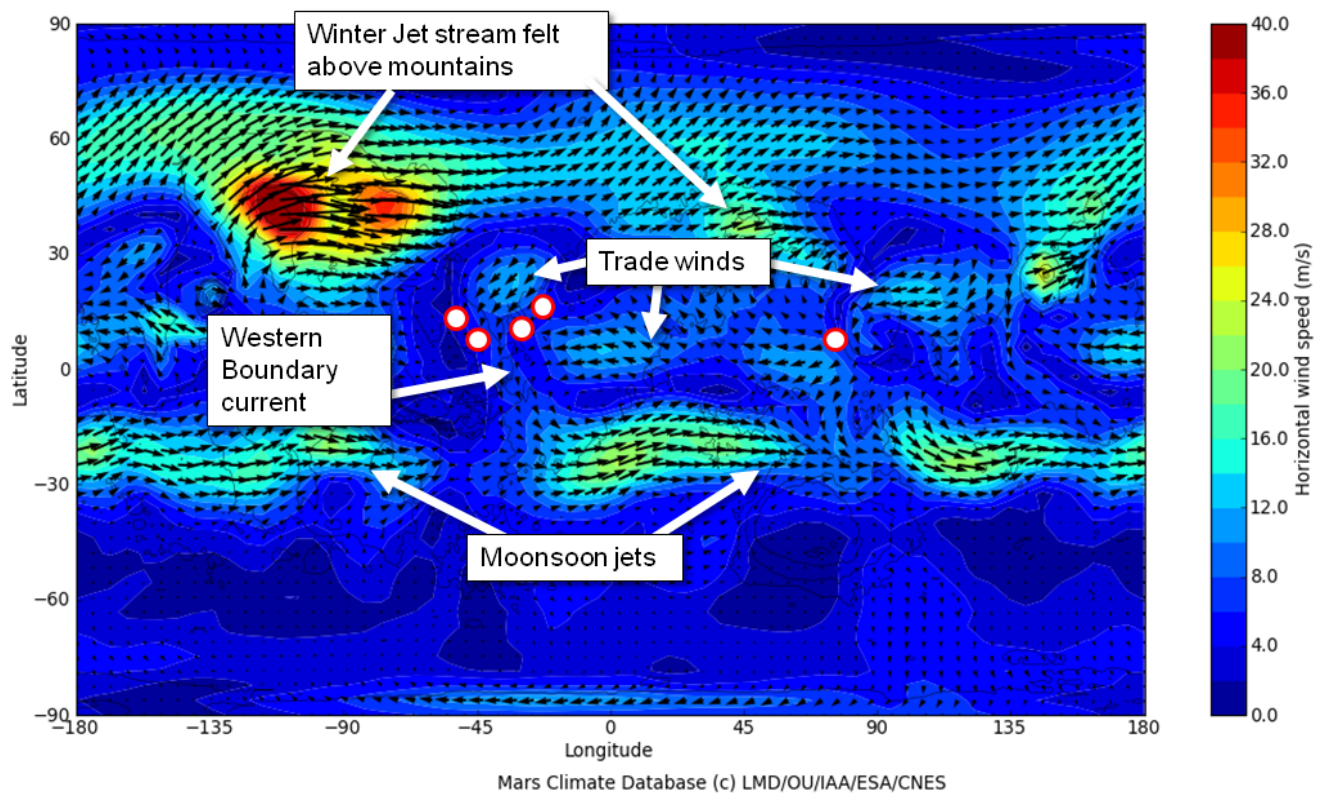


Fig. 10: Mean wind velocity at $z=1$ km above the local surface for the 2019 landing ($L_s \sim 324^\circ$ and Local time=10.5) for typical dust conditions (Mars Climate Database v5.0 climate scenario: $\tau \sim 0.6$). The red circles illustrate the position of several proposed landing sites.

Fig. 10 shows the wind flow 1 km above the local surface. At mid latitudes (30°N–70°N), the martian jet stream has the same effect at the surface as it does on Earth. Martian winter winds tend to be westerly, especially on higher ground. Further south, the southward “return” branch of the Hadley cell affects both north and south hemisphere air circulation in the lower layers. Diverted by the Coriolis force, it creates easterly “trade winds” north of the equator between 0° and 30°N, accelerates on crossing the equator, and then causes strong westerly jets (similar to summer monsoon winds in India and in central Asia) between 15°S and 30°S. Near the equator, the meridional southward flow is shaped by the geophysical fluid dynamic phenomenon of “western boundary currents”.

The strength of the Hadley circulation, and therefore the latitude and intensity of the winds and in particular the winter jet stream, is sensitive to the atmospheric dust loading, which directly controls the atmospheric heating at sunlit latitudes (Fig. 11). The “season mean” global scale wind profiles at landing time for various possible dust conditions are presented in Fig. 12 and discussed in the appropriate section for each landing site.

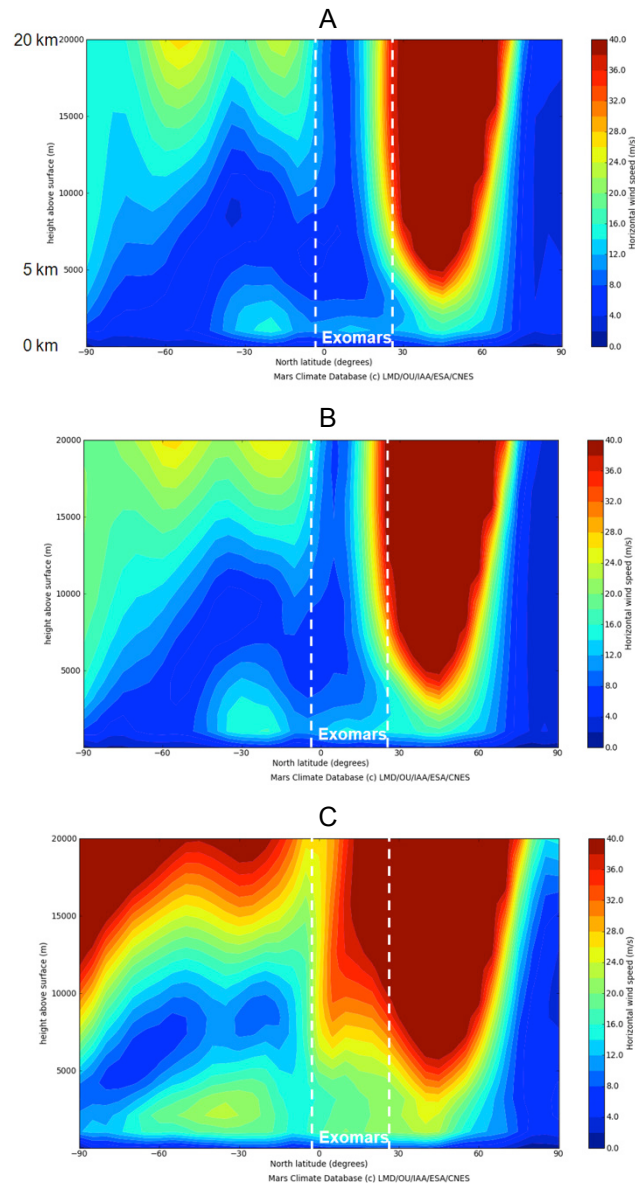


Fig. 11: Zonal mean horizontal wind velocity versus altitude above the local surface for the 2019 landing ($L_s \sim 324^\circ$ and Local time=10.5) for various dust conditions: A) most likely dust conditions (MCD “clim” scenario $\tau=0.6$), B) very dusty conditions outside a global dust storm event (MCD “warm” scenario $\tau=1.2$), and C) severe global dust storm (MCD “storm” scenario $\tau=5$).

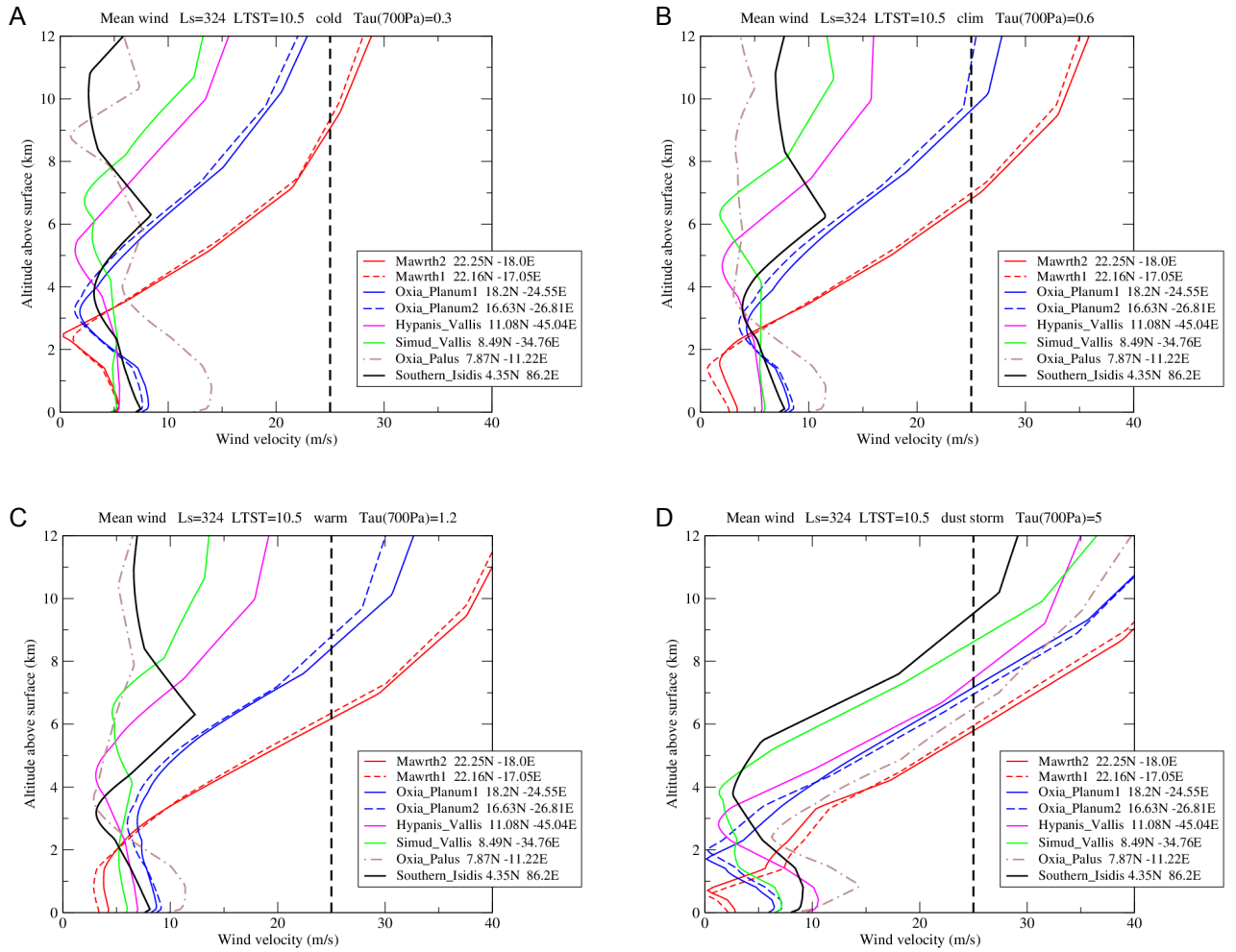


Fig. 12: Season mean horizontal wind velocity versus altitude above the local surface for the 2019 landing (Ls ~324° and Local time=10.5) for various dust conditions: A) (MCD “cold” scenario $\tau \sim 0.3$), B) most likely dust conditions (MCD “clim” scenario $\tau \sim 0.6$), C) very dusty conditions outside a global dust storm event (MCD “warm” scenario $\tau \sim 1.2$), and D) severe global dust storm (MCD “storm” scenario $\tau \sim 5$).

In reality, we should consider that the actual local instantaneous wind encountered by the descent module between 10 km and the surface may be different from the predicted “global scale, season mean” wind provided by the MCD. This is because:

- The actual large-scale wind fluctuates from day to day and from year to year. This fluctuation (as reconstructed using the MCD tools) is illustrated in the case of Oxia Planum on Fig. 13.
- The proposed landing sites are located near the edge of the powerful jet stream. The exact location of the jet is probably model dependent. A detailed sensitivity study, possibly involving several models may be useful to better assess the associated risk.
- At mesoscales (a few kilometres horizontal), the topography can contribute to create significant local winds (“slope winds”, in particular). As for previous missions (MER, Phoenix, Curiosity, Insight, EDM 2016), such winds should be studied using dedicated simulations with mesoscale models. This is especially true for ExoMars 2018, as most sites are located on the edge of a major topographic gradient, the south-north dichotomy.
- In addition, a local or a regional dust storm may be possible near some of the proposed landing sites during the landing season. After evaluating this possibility on the basis of past observations, dedicated mesoscale simulations could be performed.

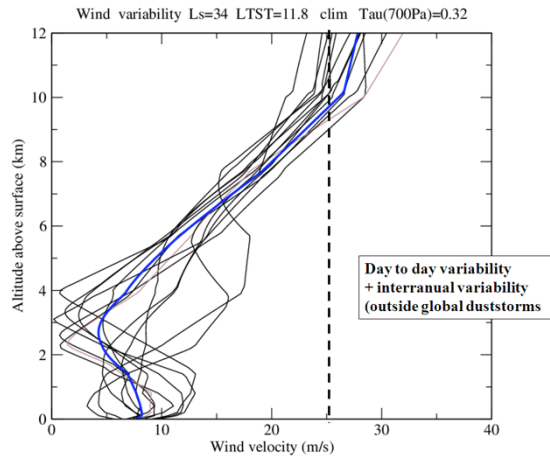


Fig. 13: As in previous figure, horizontal wind velocity versus altitude above the local surface for the 2019 landing ($L_s \sim 324^\circ$ and Local time=10.5) for the Oxia Planum landing site (18.20°N , 24.55°E), but now showing various instantaneous possible wind profiles around the season mean (as reconstructed by MCD 5.0) to illustrate possible day-to-day and inter-annual variability (excluding global dust storm events).

7.3.3 Vertical Winds

Strong vertical wind within a landing ellipse can have two possible origins:

- Local topography (e.g. a crater rim) can induce strong upward slope winds, extending high above the topographic obstacle. Such winds can be estimated using dedicated mesoscale simulations.
- During daytime, solar surface heating results in convection activity that creates updrafts and downdrafts in the boundary layer (and notably dust devils). The intensity of these vertical winds can be estimated using “Large Eddy Simulation” models with a resolution of 12 to 50 m (Spiga et al., 2010). Dedicated simulations must be performed for the landing sites. Fig. 14 shows results obtained to predict the conditions for the 2016 EDM landing site during $L_s=343^\circ$. When surface parameters favouring strong convection are chosen, one can see that the maximum convective updrafts and downdrafts can reach values higher than 12 m/s during the afternoon, but that between 10:00 and 11:00 the convection is not too intense.

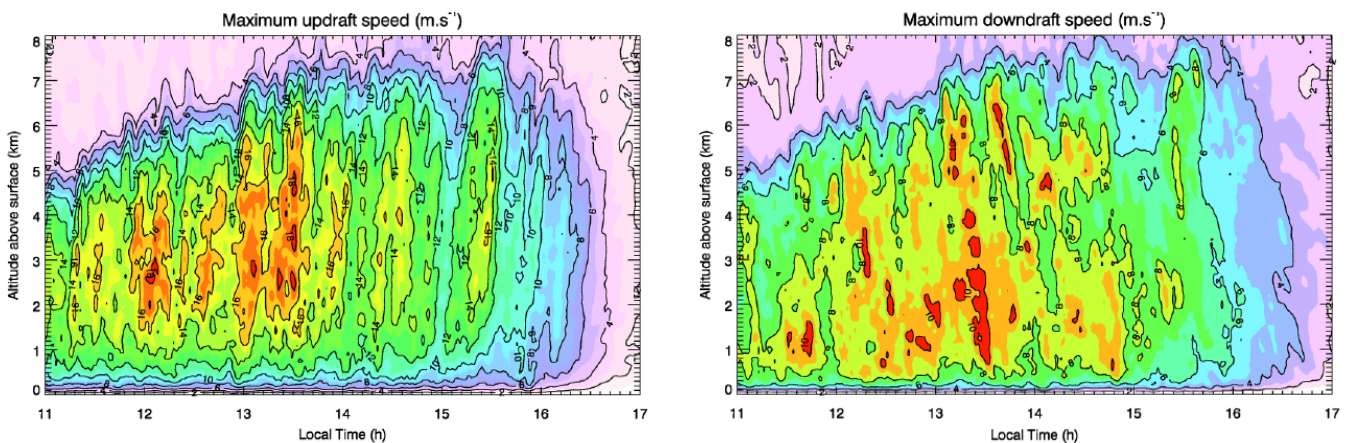


Fig. 14: Maximum vertical velocity for convective updrafts (left) and downdrafts (right), as simulated with a “Large Eddy Simulations” model (Spiga et al., 2010) for the 2016 EDM landing site and landing time ($L_s=343^\circ$), for dust visible optical depth $\tau=0.5$, background wind of 15 m/s, relatively low albedo of 0.13, and thermal inertia of 155 SI, thus maximizing surface temperatures and convection intensity.

7.4 General Atmospheric Conditions for the 2021 Landing

7.4.1 Expected Atmospheric Dust Loading

A 2021 landing would take place during northern spring ($L_s \sim 34^\circ$). This season is relatively dust-free, and, as shown in Fig. 6, with little inter-annual variability.

7.4.2 Horizontal Winds

Compared to the 2019 landing opportunity, the Hadley circulation is less intense. As a consequence, the northern jet stream is located at higher latitudes, $\geq 40^\circ\text{N}$ (Fig. 15). On average, the horizontal winds over the proposed landing sites are < 10 m/s, well below the preliminary engineering threshold (Fig. 16).

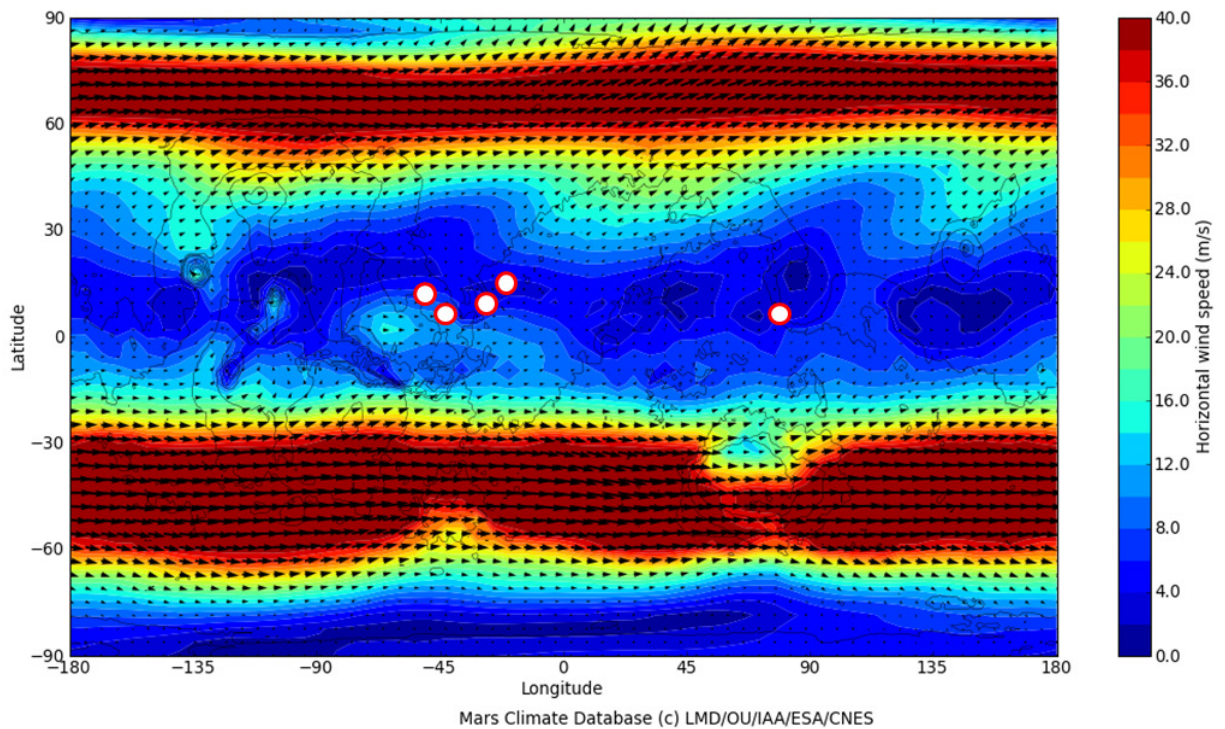


Fig. 15: Mean wind velocity at $z=10$ km above the local surface for the 2021 landing ($L_s \sim 34^\circ$ and Local time=11.8) for typical dust conditions (Mars Climate Database v5.0 climate scenario: $\tau \sim 0.32$). The red circles illustrate the position of several proposed landing sites.

7.4.3 Vertical Winds

A 2021 landing would take place during a clearer season and at a later local time (between 10:55 and 12:40). This results in a more intense convective activity and stronger updrafts and downdrafts than for the 2019 landing. The actual possible vertical velocities will depend on the surface temperature, which in turn will be determined by the surface albedo and thermal inertia of the landing sites.

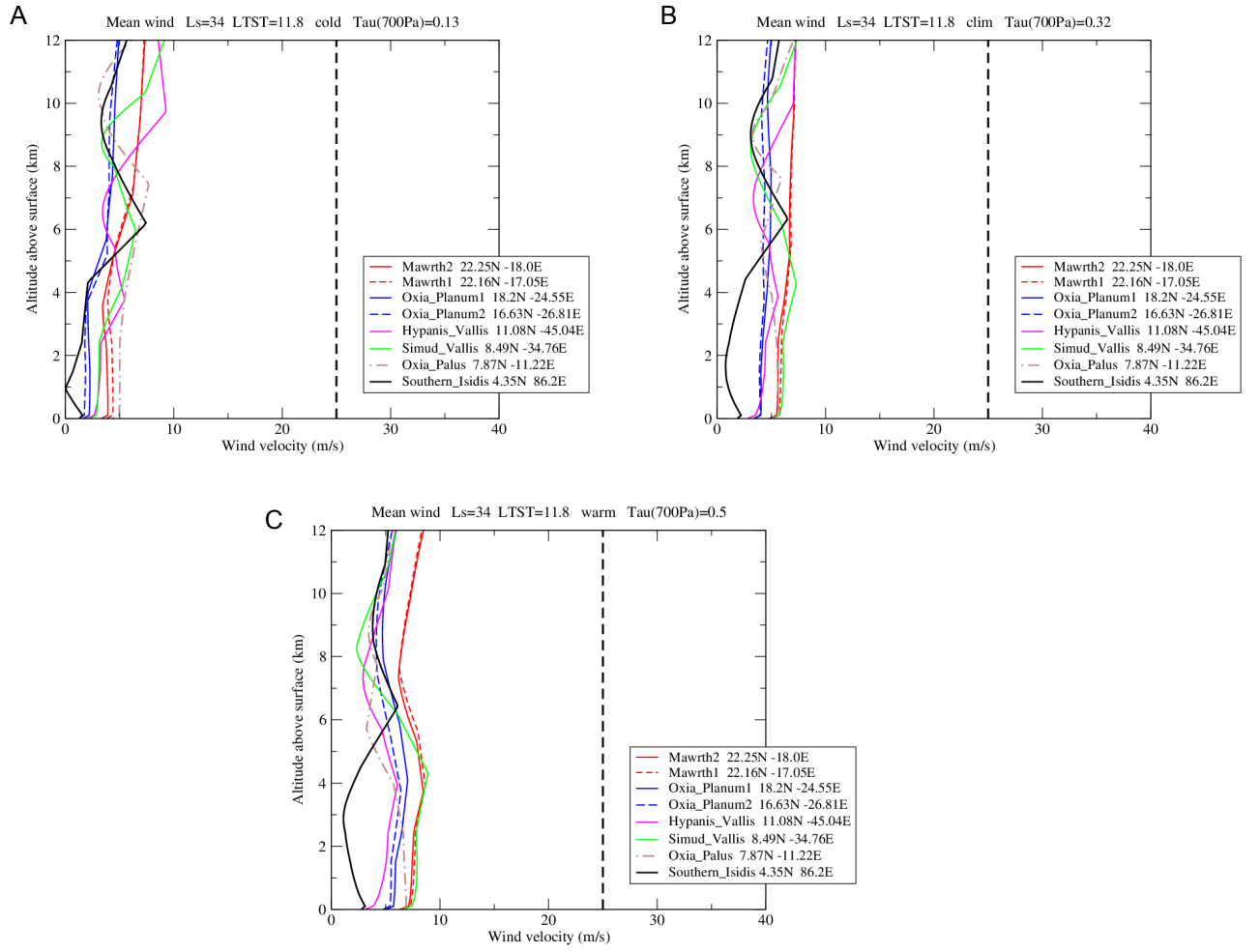


Fig. 16: Season mean horizontal wind velocity versus altitude above the local surface for the 2021 landing ($L_s \sim 34^\circ$ and Local time=11.8) for various dust conditions: A) (MCD “clear” scenario $\tau \sim 0.13$), B) most likely dust conditions (MCD “clim” scenario $\tau \sim 0.32$), and C) very dusty conditions outside a global dust storm event (MCD “warm” scenario $\tau \sim 0.5$).

7.5 Mawrth Vallis

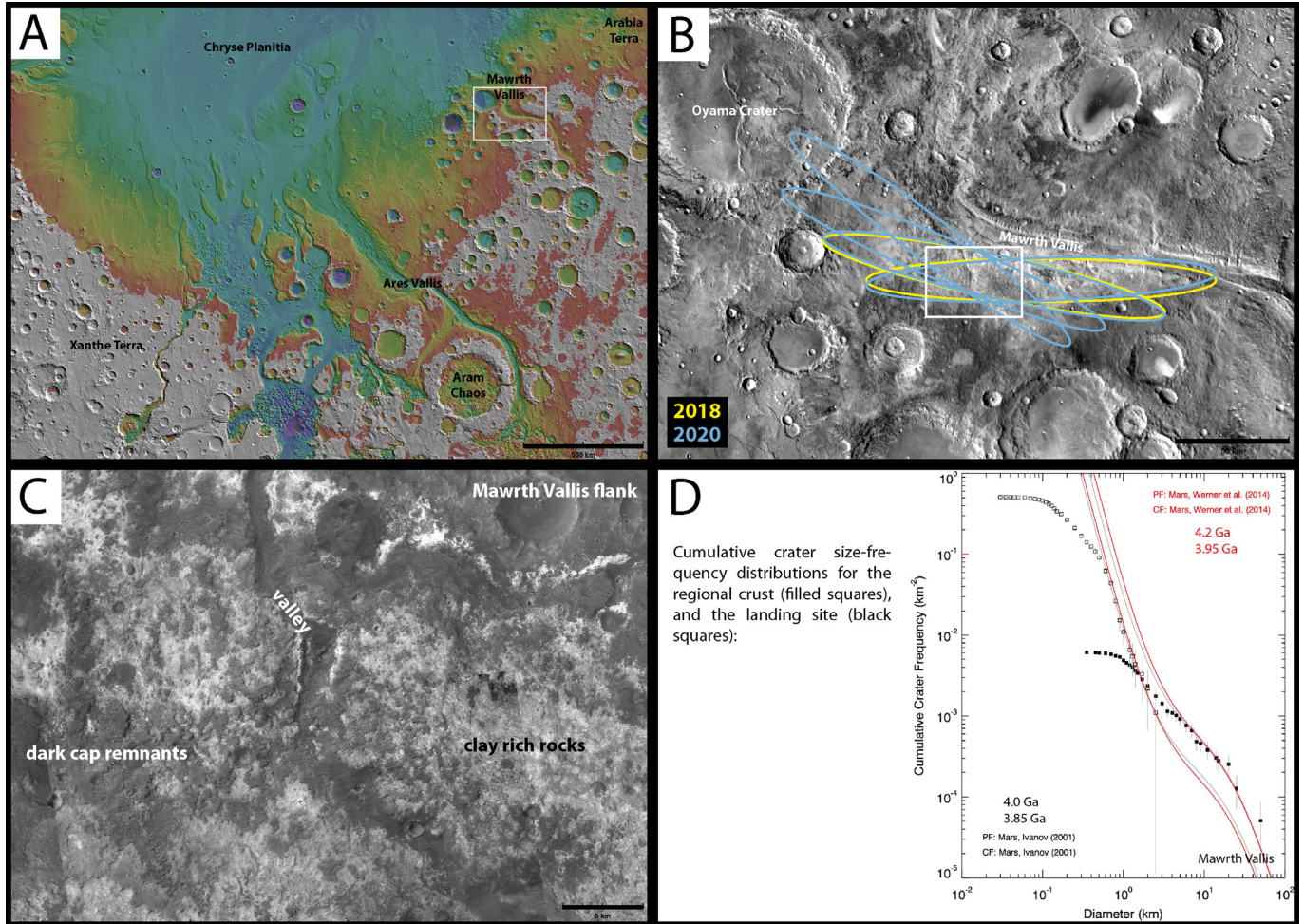


Fig. 17: Documentation images for the Mawrth Vallis landing site. A) Regional context map of Arabia Terra and Chryse Planitia with colourised MOLA topographic data superimposed on MOLA shaded relief. The scale bar is 500 km long. B) Landing ellipse pattern superposed on a THEMIS daytime IR mosaic. The scale bar is 50 km long. C) CTX mosaic close-up of the proposed landing ellipse's centre. The scale bar is 5 km long. D) The analysis of cumulative crater size-frequency distributions resulted in the following ages—Ivanov (Werner et al.): 4.0 Ga (4.2 Ga) for the regional crust (black-filled squares) and 3.85 Ga (3.95 Ga) for the brighter, exposed clay-rich deposits (black squares).

7.5.1 Global Context

The Mawrth Vallis region is located at the contact between the highlands of Arabia Terra and Chryse Planitia, on the martian dichotomy (Fig. 17A). This area is one of the lowest parts of the highlands, with a MOLA elevation between -1.0 and -4.0 km. Mawrth Vallis experienced two major, large scale processes: First, Arabia Terra formed in response to the nearby load of the Tharsis igneous complex, which was emplaced in Noachian times (Phillips et al., 2001). Then, during the late Noachian and the Hesperian, the highlands and the plains of Chryse Planitia were carved by several large outflow events that created the circum-Chryse Planitia outflow channel complex (Carr and Head, 2010).

Mars Express and Mars Reconnaissance Orbiter (MRO) data have been used extensively to study the Mawrth Vallis region for the selection of the MSL landing site. However, the location being proposed for ExoMars lies further south relative to the areas previously investigated; and hence, has less high-resolution data coverage.

7.5.2 Regional Context

The nature and location of the source region that gave rise to the Mawrth Vallis deposits are unknown, but Mawrth Vallis is one of the oldest outflow channels on Mars (Scott and Tanaka, 1986).

Widespread, light-toned outcrops on the intercrater plateau surface show the presence of phyllosilicates (mainly clay minerals) over a region of approximately 300 km x 300 km (Poulet et al., 2005; Michalski & Noe Dobrea, 2007; Loizeau et al., 2007). Most outcrops are large, ranging between 10 and 40 km in size. Many high-resolution images contain evidence of thin layering that, in some crater walls, can exceed 250 m in stratigraphic thickness (Michalski & Noe Dobrea, 2007; Loizeau et al., 2007). Smaller outcrops with similar mineralogy have been observed over a larger, 1000 km x 1000 km, region (Noe Dobrea et al., 2010).

The Mawrth Vallis channel floor also contains clay-rich layers, as does the floor of the nearby crater Oyama. It therefore seems that the Mawrth Vallis outflow carved into ancient, clay-bearing, layered deposits. Later, smaller-scale fluvial processes eroded this material, especially on each side of the Mawrth Vallis channel and on the walls of Oyama crater, thus explaining the origin of the floor deposits (Loizeau et al., 2012).

A thin dark cap (10 m maximum thickness), possibly of volcanic origin, overlies large parts of the Mawrth Vallis plateau. This dark material is younger than the phyllosilicates and does not seem to be hydrated. It probably once covered the entire region (Michalski & Noe Dobrea, 2007; Loizeau et al., 2007; Bishop et al., 2008), but has since been eroded in many places.

7.5.3 Topography and Morphology

The proposed landing site is situated just south of the Mawrth Vallis channel, near 22°N, 342°E (Fig. 17B). The elevation range spans from about -2.0 km to -2.2 km, with a general downward slope trend going from south to north (towards the floor of the Mawrth Vallis channel) accentuated locally by valleys incising the flank of Mawrth Vallis.

A patchy mixture of clay-rich and dark cap outcrops characterises the surface of the ellipse (Fig. 17C), with clay-rich rocks being distributed all over the proposed landing location.

The surface of the clay-rich outcrops is generally characterised by polygonal fracturing, with the largest fractures (generally unresolved with HiRISE, hence < 80 cm wide) often filled by dark material (McKeown et al., 2013). Larger fractures have been mineralized and may stand out, as ridges, due to erosion (Loizeau et al., 2012).

The dark cap remnants constitute mesas, distributed over a large part of the ellipse, with typical sizes varying between 3 km and less than 100 m. Only a few craters are present; the largest of which are very eroded, offering access to deeper layers in their walls.

7.5.4 Mineralogy

As shown in Fig. 18, the composition of the Mawrth Vallis clay-rich sediments shows vertical variation, with Fe-rich clays at the bottom of the sequence and Al-rich clays present towards the top. This progression is typical for many places in the greater Mawrth Vallis region (and elsewhere on Mars). A plausible explanation is that the upper part of this sequence may have formed by top-down weathering from the surface (Bishop et al., 2008; Loizeau et al., 2012; Michalski et al., 2013). The presence of an unidentified ferrous material at the contact between the Al and Fe-rich clays indicates a reaction horizon between the different redox conditions characteristic of the upper and lower sections of the Mawrth Vallis sediments; and hence, different environmental conditions with depth (also detected in other outcrops of the region, Bishop et al., 2008).

Spectral modelling shows that the clay mineral content in Mawrth Vallis is (one of) the highest on Mars, suggesting either the deposition of altered material or a high degree of *in situ* alteration (Poulet et al., 2008; Poulet et al., 2014).

The material in the central part of the landing ellipse is less eroded and consists mostly of Al-rich clays, with smaller outcrops of Fe-rich clays where erosion has been more intense. On the northern and southern edges of the ellipse, higher erosion reveals larger outcrops of Fe-rich clays. Sulphate-bearing outcrops have also been observed locally within the area, although not inside the proposed ellipse (Farrand et al., 2009; Wray et al., 2010).

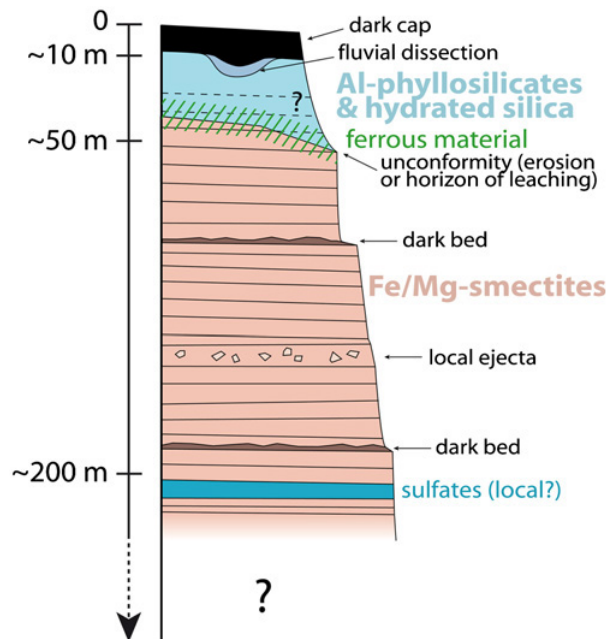


Fig. 18: Schematic stratigraphic profile of layered clays on the plateaus of Mawrth Vallis (Loizeau et al., 2012). The thick, clay-bearing deposits are finely laminated, with Fe/Mg smectites in the lower part of the section and Al-rich phyllosilicates at the top. A dark capping unit, probably volcanic, covers the clay unit.

7.5.5 Ages

Mawrth Vallis was carved into early Noachian plateau units. Loizeau et al. 2012 presented a detailed study of the stratigraphic units north of the ExoMars candidate landing site, estimating plateau ages about 4 Ga old and several phases of deposition and exhumation. They utilised the chronology model by Hartmann and Neukum (2001), which gives slightly younger ages than the chronology by Ivanov (2001) used here.

Regional cratering statistics indicate that the underlying plateau was formed about 4.05 Ga (4.2 Ga) ago (black-filled squares in Fig. 17D), with at least one resurfacing event modifying the plain less than 3.85 Ga (3.95 Ga) ago. Craters smaller than about 3.5 km in diameter have been erased. Based on typical crater aspect ratios, this would imply a modified stratigraphy (due to erosion or deposition) of the order of 700-m layer thickness.

The clay-rich, layered unit was deposited on top of the 4.05-Ga-old plateau and later covered by a dark, cap unit. Wind erosion has removed the dark cap in many places, exposing the clays. The exhumed bedrock is at least 3.85 Ga (3.95 Ga) old (black squares) and, depending on the thickness and duration of the cover layer, maybe older. The image data suggest a complex deposition-exhumation history. Detailed studies of craters smaller than 50 m in diameter would be required to understand the deposition-exhumation history. The two proposing teams report ages of exhumation at 450–500 Ma and ~130 Ma respectively, although exhumation is probably a more or less continuous process.

7.5.6 Atmospheric Conditions

Mawrth Vallis is located around 22°N. For a 2019 landing, horizontal winds are especially weak below 2-km altitude, and are predicted to remain under 20 m/s up to 4 km, whatever the dust loading conditions. Above 5 km, however, this site will be affected by the northern jet stream. Under the most likely dust conditions, the wind is predicted to reach values in excess of 25 m/s above 6 km altitude (Fig. 9). At this stage, this should not be used to reject Mawrth Vallis as a suitable landing site. Firstly, since the strong winds will only occur at altitudes where the engineering threshold is not yet well defined; and secondly, because the jet stream is a robust, consistently west-flowing structure having little variability, which could be taken into account for the EDL plans. To ensure the feasibility of this site, a detailed sensitivity study, possibly involving several models, would be useful to assess risk. In any case, all proposed landing site would be affected by winds above 25 m/s in case of a global dust storm.

There are no problems with horizontal winds at Mawrth Vallis for a landing in 2021.

7.5.7 Geologic History

Finely layered sediments were deposited on the ancient crust of this lower part of the highlands during the early and middle Noachian, although their origin is not known with certainty. Possible mechanisms include: 1) the erosion of the surrounding rocks and concentration of the eroded products in a palaeo-basin; 2) the accumulation of successive palaeosols; and 3) the progressive deposition (and alteration) of pyroclastic material. Another possibility could involve a combination of some of the above mechanisms. For example, as observed on some Archaean Earth settings, swathes of fine-grained, volcanic detrital material deposited at/close to shores interspersed with thin layers of basin-wide contiguous ash fall deposits (in water) (Bréhéret et al., in preparation). Aqueous alteration of the deposits produced the clay-rich lithologies now observed in the greater Mawrth Vallis region.

The thick, clay-bearing deposits are finely laminated, with Fe/Mg smectites in the lower part of the section and Al-rich phyllosilicates at the top (Fig. 18). The Fe/Mg-rich layers are characteristic of the original deposition and alteration environment, whereas the Al-rich deposits are likely the result of subsequent, top-down surface alteration of the Fe/Mg clays (where water leached out the more soluble cations, leaving the Al behind) (Bishop et al., 2008; Loizeau et al., 2012; Michalski et al., 2013). We do not know how deep fluids penetrated into the deposits, although a few mineralised fractures would imply vertical penetration of the fluids over a few tens of metres. Some large meteorites probably impacted the layered unit during its deposition history, although in general the stratigraphy seems well preserved.

The emplacement of the Mawrth Vallis outflow channel eroded the layered unit. Surface water also created valleys and deposited clays on the floor of some large craters throughout the late Noachian. During the early Hesperian, the dichotomy was eroded and covered by what seem lava flows, forming a dark capping unit on the plateaus surrounding Mawrth Vallis. Wind erosion progressively eroded away this dark cap, exhuming the underlying, soft, layered, clay-rich rocks. Exhumation of the clays is an on-going process.

7.5.8 Potential for Biosignature Preservation

Phyllosilicates, and in particular smectites, may have had a role in the origin of life on Earth, as they can provide reaction centres for the synthesis of organic compounds (Ferris, 2005; Meunier et al., 2010; Feuillie et al., 2013). However, origin of life scenarios imply the continuous and concurrent availability of the ingredients of life (liquid water, carbon molecules, nutrients, and energy) in a suitable environment over long periods, ranging from several hundreds of thousands of years to millions of years.

Establishing the habitability potential of the complex Mawrth Vallis deposits is not easy in the absence of a clear geological context. The age and widespread distribution of the thin layers that characterise the stratigraphic sequence suggest that the original sediments may have been ashfall (as it is the case for many ancient terrains on Earth).

If the volcanic sediments were deposited in one or more bodies of water (challenging, considering the extension, 1000's of km², of the clay-rich unit), then the chances that the sediments could have hosted and then preserved the signatures of microbial life would be good. If, on the other hand, the volcanic sediments fell on land, they would not have been directly habitable. However, subsequent alteration of these "dry" deposits by water could have created potentially habitable niches to which viable cells, if they were in the vicinity, could have been transported, e.g. via subsurface aquifers or in flows from one water body to another.

One possible formation scenario could have involved alteration of the first sediment sequence in an aqueous environment to form the lower, Fe-rich, clay section (if so, it would be useful to determine the water/rock ratio). The opportunities for colonisation would have been greater if the deposits had lain under water more or less continuously, but even if the deposits had only been wetted intermittently (for brief periods, but over a long time span), they could still have been colonised, provided viable life existed in their vicinity. A later phase, characterised by top down weathering/leaching, perhaps under an ice sheet, could have produced the upper, Al-rich, clay section. The intermittent habitability concept would also be valid for a leached niche environment in the upper, Al-rich, clay sequence, assuming microbes could have been transported to the ephemeral habitats.

As mentioned above, the origin and history of the clay-rich, layered deposits are not well understood. But whatever the nature of the depositional process, water must have been involved over long periods to alter such a large volume of material, and *in situ* alteration occurred at least for the top most layers (Bishop et al., 2013). In particular,

the many fine layers can be thought of as “tree rings”, each recording an instance of deposition and alteration within a long, sustained sequence.

The exact characteristics of the rocks containing the clays remain unknown. Their grain-size is relatively small, as their thermal inertia is lower than that of sand dunes, for example, and erosion of the clay-rich unit does not create dunes. However, whether the rocks are silt-sized (2–50 µm) or clay-sized (< 2 µm) remains a question. This may have implications regarding the habitability of the material for putative organisms, the environment’s lateral connectivity, and the potential for biosignature preservation. Morphological fossils may be present if the conditions to encase and cement microbial colonies *in situ* existed. In that case, traces of colonies could be found around volcanic clasts (Westall et al., 2011). Although organic traces can be preserved even in sand-sized sediments, they tend to be more concentrated in the finer grain sizes.

No diagenesis is observed that could have degraded potential biosignatures. Additionally, the relatively recent exhumation of the clay-rich, layered deposits means potential chemical biomarkers present in the soil would have been protected from oxidation and ionising radiation damage.

7.5.9 Compliance with Engineering Constraints

Due to an increase of Entry Flight Path Angle (EFPA) dispersion with landing site latitude, the landing ellipse for Mawrth Vallis is larger than for the other sites (its major-axis is 170 km instead of 104 km). It is therefore more challenging to define a safe landing ellipse pattern. High elevation areas exist toward the south and steep slopes to the north, close to the Mawrth Vallis channel flank. Depending on the azimuth, the extremities of some ellipses may include terrain above the prescribed –2000 m MOLA elevation limit. For example, portions of the western end of the 90° ellipse can reach –1700 m. However, for the cases where this occurs, it is a small percent of the ellipse that exceeds –2000 m elevation.

Concerning the slopes at 3-km scale, the Mawrth Vallis channel flank is challenging for almost all azimuths. The wall of the nearby Oyama crater exceeds the stated limit for high azimuth ellipses.

The dust coverage is very low in this area. The thermal inertia is between 180 and 280 TIU. Very few dunes and ripples are present —only in some local depressions. The clay rich rocks do not usually show evidence of boulders, but may be fractured in some places. The dark cap unit is rougher as it retains small impact craters.

For a landing in 2019 under the most likely dust conditions the wind is predicted to reach values in excess of the 25 m/s limit above 6 km altitude. However, the jet stream is a robust, consistently west-flowing structure having little variability, which could be taken into account for the EDL plans. To ensure the feasibility of this site, a detailed sensitivity study, possibly involving several models, would be useful to assess risk. All proposed landing site would be affected by winds above 25 m/s in case of a global dust storm. There are no problems with horizontal winds at Mawrth Vallis for a landing in 2021.

7.5.10 Summary

An initial analysis of the Mawrth Vallis landing site indicates that it is consistent with the scientific objectives of the ExoMars mission, but presents engineering challenges requiring more careful investigations.

Mawrth Vallis possesses clear mineralogical indicators for long-lived, liquid water-rock interactions that took place during the Noachian (to form the Fe/Mg smectite layered deposits). There is also evidence for the influence of surface liquid water at a later stage (Al-rich clays, clay-rock erosion and redeposition, and the presence of mineralised fractures). A dark cap, possibly volcanic, protected the finely layered clay unit. The exhumation of the clay-bearing deposits has been relatively recent. Clay-rich outcrops and remnants of the dark cap are spread over the entire landing ellipse.

The ancient age and type of the deposits, coupled with the recent exhumation history and the widespread distribution of primary targets make this location very interesting for the ExoMars 2018 search-for-life objectives. The main scientific concern for this site is the uncertainty of the depositional process that resulted in the clay-rich, layered unit. Nevertheless, phyllosilicate deposits provide a unique opportunity to evaluate aqueous activity on early Mars and point to the possibility that habitable environments may have existed during the Noachian period (Bishop et al., 2013).

Some engineering concerns exist for the high elevation and steep slopes that can be found in some parts of the ellipse, as well as for wind speeds in case of a 2019 landing.

Site	Lat, Lon (year and azimuth dependent)	Avg. Elev. (year and azimuth dependent)	Major elements of interest	Identified minerals
Mawrth Vallis	22.3°N, 342.0°E	−2.0 km	Old, prolonged water/rock interaction. Fine-grained deposits. Thick stratigraphy accessible.	Al-rich and Fe-rich clays, high abundance.

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7.6 Oxia Planum

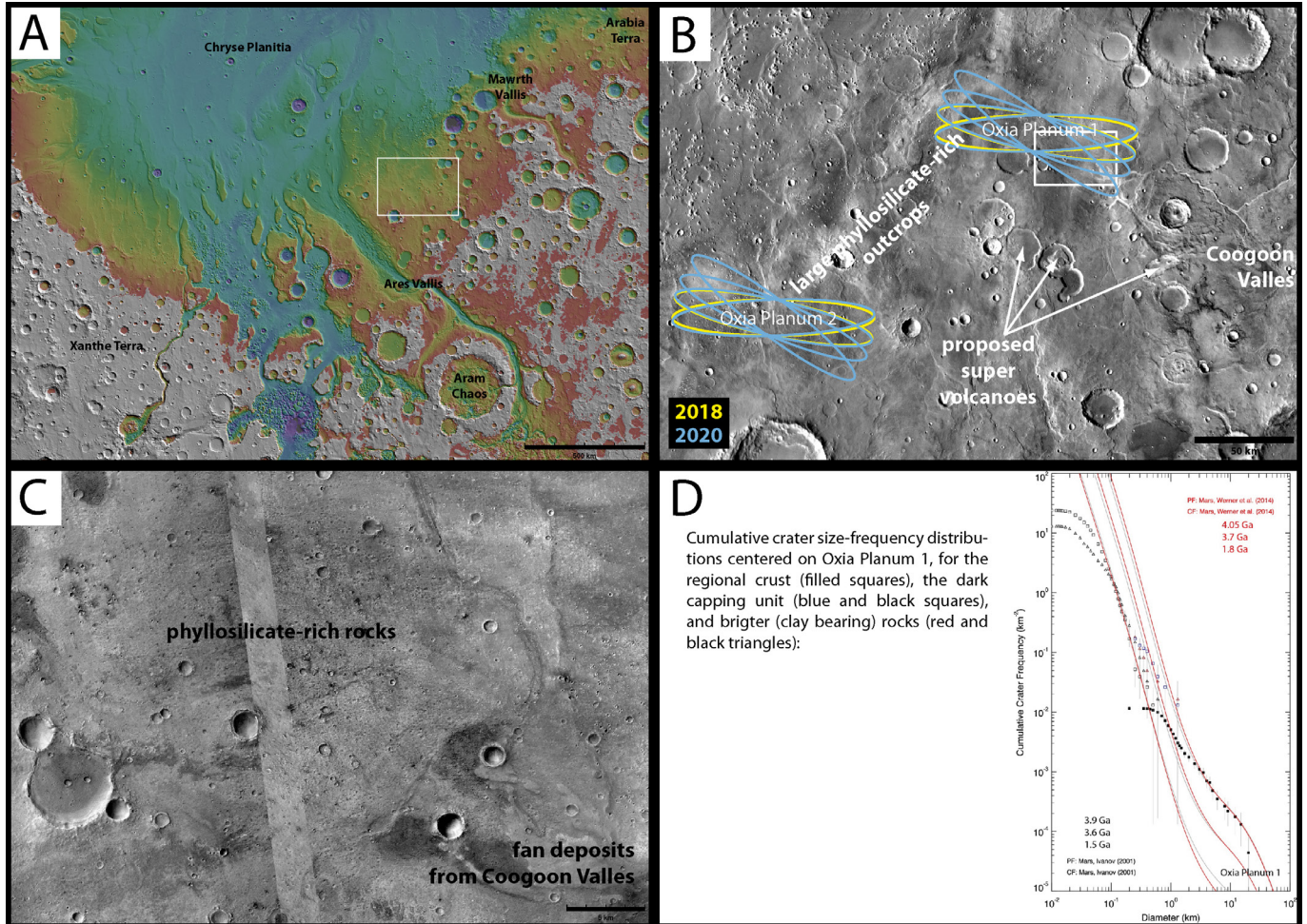


Fig. 19: Documentation images for the Oxia Planum landing site. A) Regional context map of Arabia Terra and Chryse Planitia with coloured MOLA topographic data superimposed on MOLA shaded relief. The scale bar is 500 km long. B) Location of the two proposed ellipses superposed on a THEMIS daytime IR mosaic. The scale bar is 50 km long. C) The key features within and in the vicinity of the landing ellipses are marked on this CTX mosaic. The scale bar is 5 km long. D) The analysis of cumulative crater size-frequency distributions resulted in the following ages—Ivanov (Werner et al.): 3.90 Ga (4.05 Ga) for the regional crust (black-filled squares), 3.90 Ga (4.05 Ga) for the bright, exposed clay-rich deposits (blue squares), and 1.5 Ga (1.8 Ga) for the dark capping unit (black squares, black and red triangles).

7.6.1 Global Context

The Oxia Planum site lies east of the Chryse Planitia region and southwest of the Arabia Terra plains, in the Oxia Palus quadrangle. Chryse Planitia is an area of flat lowland where the largest martian outflow channels converge (Sharp and Malin, 1975) and is thought to be an ancient impact basin (Schultz et al., 1982). Because of its low elevation (−2.5 km MOLA in average) and key location, Chryse Planitia was chosen for the landing sites of the NASA Viking 1 and Mars Pathfinder missions.

7.6.2 Regional Context

The Oxia Planum region is characterised by typical Noachian highland cratered terrains that become increasingly eroded towards the crustal dichotomy (Hynek and Phillips, 2001; Noe Dobrea et al., 2010) (Fig. 19A). Outflows and diverse channels converging toward Chryse Planitia dissect the area (Scott and Tanaka, 1986). Several alluvial fans or deltas have been preserved at the outlets of valleys, often extending into 100's km-wide basins, as is the case in one of the two proposed ellipses.

Oxia Planum exhibits evidence of at least two major aqueous episodes: 1) erosion of the Noachian highlands by valley networks at the end of the Noachian, followed by 2) outflow channel activity and volcanism during the Hesperian discharging into the Chryse basin, which is now filled with Hesperian ridged plains (Carr and Head, 2010). Extensive phyllosilicate-rich deposits have been observed in Oxia Planum and in its close vicinity, over an area approximately 1000 km x 250 km. These phyllosilicate-bearing outcrops might be an extension of those found in the Mawrth Vallis area. As in the case of Mawrth Vallis, the process that resulted in the formation of hydrated minerals over such an extended area remains unclear.

7.6.3 Topography and Morphology

Two ellipses have been proposed in the Oxia Planum area, with MOLA elevations between -2.5 and -3.1 km. Ellipse 1 is located inside a shallow basin at the outlet of the Coogoon Valles system. Ellipse 2 lies south of ellipse 1, on a small plateau (Fig. 19B). Both sites include many phyllosilicate (clay mineral)-rich outcrops distributed over a relatively flat surface with no significant relief, apart from the presence of small impact craters.

The unit composing the main portion of the two ellipses (and associated with the phyllosilicate detections) appears to be finely layered with a thickness of about 200 m, and is sometimes blanketed by a dark, indurated capping unit—similarly to that observed in the Mawrth Vallis region. Single, sinuous, deep valleys, 100's of km long, are present within and around the ellipses.

The eastern part of ellipse 1 includes the relic of a 15-km-wide, 21-km-long, fan-shaped deposit lying at the outlet of the Coogoon Valles system and at the entrance of the palaeobasin in ellipse 1. This fan has a flat surface, many divergent finger-like terminations, and shows no obvious channel; it could potentially correspond to a sub-aqueous delta deposit, but it could equally be a subaerial (alluvial) fan or a terminal fan (Fig. 19C).

7.6.4 Mineralogy

As derived from IR observations acquired by OMEGA and CRISM, Mg/Fe phyllosilicate signatures (most likely saponite, nontronite, and/or vermiculite) dominate the composition of the rocks of the dichotomy in Chryse Planitia. These hydrated mineral observations occur within Noachian-aged units in circum-Chryse and extend further west, toward the edge of Arabia Terra, including the Mawrth Vallis region. Oxia Planum represents one of the largest and strongest Mars phyllosilicate detections. Based on conservative mapping at low resolution, clay-rich outcrops cover at least 74–78% of both ellipses (Fig. 20A). CTX, HRSC and THEMIS observations suggest that the Fe/Mg-phyllosilicate bearing unit is continuous over the entire region.

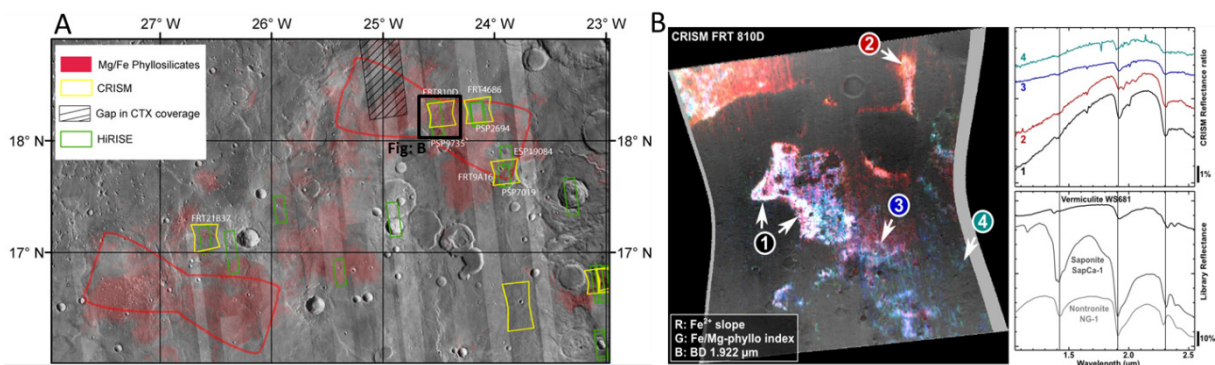


Fig. 20: Phyllosilicate detections in Oxia Planum. A) The two proposed ellipses (red outlines) encompass a large area rich in phyllosilicates (red) on this THEMIS daytime IR mosaic. B) Close-up of a CRISM observation in ellipse 1 showing phyllosilicate signatures. Best library matches are shown on the lower right for comparison.

Locally, additional absorption bands are found at ~ 2.2 μm , indicating a spectral mixture at the > 200 -m scale between Mg/Fe phyllosilicates and other hydrated silicates (e.g. Al-rich clays). Southeast of the proposed sites, some better-preserved outcrops exhibit a more complete stratigraphic sequence, similar to that at Mawrth Vallis (Bishop et al., 2008, Loizeau et al., 2010). This sequence includes Fe/Mg-phyllosilicate-rich bedrock, covered by an Al-phyllosilicate-bearing unit (including Al/Fe-smectite and kaolinite), overlain by material enriched in hydrated silica, topped by a cap unit, and locally exhibiting weak jarosite signatures.

7.6.5 Ages

The two Oxia Planum landing ellipses (like the one in Coogoon Valles) lie in a mid- to late-Noachian region near the martian dichotomy. Ellipse 1 is mainly late Noachian. Ellipse 2 has been mapped as mid Noachian.

Regional cratering statistics for the preferred Oxia Planum 1 landing site suggest a surface age of about 3.90 Ga (4.05 Ga) (black-filled squares in Fig. 19D) with episodic modifications of the distribution for craters smaller than about 2 km in diameter about 3.6 Ga (3.7 Ga) ago. The disturbance of the stratigraphic column is at a layer thickness of about 450 m. At smaller, landing site scale, two different types of unit can be identified based on albedo and morphologic structure: 1) Prevalently dark with some exposed light areas, interpreted to consist mainly of dark capping material with some brighter, clay-rich deposits exposed. The dark layer was formed about 1.5 Ga (1.8 Ga) ago (black squares), but the lighter, underlying strata are recognized from their crater record, suggesting an original deposition age of ≤ 3.90 Ga (≤ 4.05 Ga) (blue squares) for the plains. 2) Prevalently light with some areas of dark material, interpreted as regions where the dark capping material has been removed by erosion, exposing the underlying clay-bearing deposits. The same ≤ 3.90 Ga (≤ 4.05 Ga) ages are found for the lighter deposits. Craters smaller than about 100 m in diameter are strongly modified on the dark thin layers, which together with the smallest crater record (< 100 m in diameter) suggest an age of 1.5 Ga (1.8 Ga) (red and black triangles).

7.6.6 Atmospheric Conditions

Oxia Planum is located at approximately 18°N. For a 2019 landing, the horizontal winds are predicted to be below 25 m/s. Above 5-km altitude, the site will be affected by the northern jet stream. For the usual dust loading conditions, winds will remain close to (sometimes slightly exceeding) the specified limit up to 10 km (Figs. 9 and 10). Winds will reach values above 25 m/s in very dusty conditions (Fig. 9). As for Mawrth Vallis, further studies are required to determine the risk and establish the high-altitude engineering threshold.

There are no problems with horizontal winds at Oxia Planum for a landing in 2021.

7.6.7 Geologic History

Similarly to Mawrth Vallis, the origin of the clay-rich, finely layered sediments observed in the Oxia Planum region remains undetermined. This area is still relatively unexplored, but could correspond to the base of the same sequence that is found further east in Coogoon and Mawrth Vallis. The layered sediments were deposited on top of a 4.0-Ga old highland crust. This unit was eroded by impacts and outflows until the end of the Hesperian (3.0 Gy ago).

In general, the valleys observed within Oxia Planum are not part of a well-developed network. They are, most likely, the result of sapping or local outflow processes. The catchment area to the south (outside) of ellipse 1, however, contains more developed valleys that could stem from a possible valley runoff system. A fan located east of ellipse 1 could correspond to a subaqueous deposit, a potential repository for organics transported to the outlet of the Coogoon Valles.

The dark, indurated capping material (possibly volcanic) overlying the clay-rich unit appears to have been eroded only recently (< 100 Ma). There is no evidence for thermal or metamorphic alteration of the clay-bearing deposits.

7.6.8 Potential for Biosignature Preservation

The potential for biosignature preservation of this area is similar to that of the Mawrth Vallis and Coogoon Valles regions. The ancient clay-rich outcrops present all over Oxia Planum and in the ellipse 1 depositional basin may have formed in aqueous settings that could have hosted microorganisms. The fine-grained sediments could have preserved the signatures of the putative microorganisms. The potential for habitability of the Oxia Planum sediments will depend on their mode of formation. The same reflections made regarding the habitability of the clay-rich sediments in Mawrth Vallis are valid here.

The available data show no evidence of low-grade metamorphic reactions that could have degraded potential chemical biosignatures. In addition, the geologic history of prolonged burial (and therefore protection from radiation and oxidation) and the recent exhumation ages of the clay-rich unit result in a strong potential for biosignature preservation at Oxia Planum, depending upon the origin of the deposits.

7.6.9 Compliance with Engineering Constraints

The preferred Oxia Planum 1 landing ellipse lies well below the –2000 m limit, with typical elevations in the order of –3000 m. No slope-specific concerns have been identified at the larger scales. A few higher slope spots exist at 7-m scale in association with some small craters.

The dust coverage is very low in this area. The thermal inertia is between 250 and 480 TIU. Very few dunes and ripples are present—only in some local depressions. The clay rich rocks do not usually show evidence of boulders, but may be fractured in some places. The dark cap unit is rougher as it retains small impact craters.

For a landing in 2019 under the most likely dust conditions the wind could reach values slightly in excess of the 25 m/s limit above 10 km altitude. However, the jet stream is a robust, consistently west-flowing structure having little variability, which could be taken into account for the EDL plans. A detailed sensitivity study, possibly involving several models, would be useful to assess risk. All proposed landing site would be affected by winds above 25 m/s in case of a global dust storm. There are no problems with horizontal winds at Oxia Planum for a landing in 2021.

7.6.10 Summary

An initial analysis of the Oxia Planum landing site indicates that it is broadly consistent with the scientific objectives and engineering constraints of the ExoMars mission.

The region exhibits one of the widest Mg/Fe phyllosilicates exposures, as mapped globally with OMEGA and with CRISM multispectral data. The Mg/Fe phyllosilicate signatures are associated with a regionally extended Noachian sedimentary unit, therefore two potential landing ellipses fitting the engineering criteria have been proposed. The current understanding is that the clay-rich unit exposed in Mawrth Vallis extends further southwest to the Oxia Planum and Coogoon areas.

The Noachian-aged, phyllosilicate-rich sedimentary rocks that constitute the prime target are ubiquitous across both landing ellipses, ensuring immediate accessibility to sites of scientific interest regardless of the exact landing location.

The clay-rich rocks that have been buried under a dark capping unit show no evidence for subsequent alteration and have a young exhumation age—a favourable scenario for biosignature preservation. Sinuous valleys and inverted channels are observed at both locations, but overall, ellipse 1 is preferred because it includes a palaeobasin and a fan, indicating that a sustained aqueous depositional environment existed at the outlet of the Coogoon Valles system.

The ancient age and type of the deposits, coupled with the recent exhumation history and the widespread distribution of primary targets make this location very interesting for the ExoMars 2018 search-for-life objectives. As for Mawrth Vallis, the main scientific concern for this site relates to the lack of precise information regarding the geologic context and origin of the clay-bearing unit. Nevertheless, phyllosilicate deposits provide a unique opportunity to evaluate aqueous activity on early Mars and point to the possibility that habitable environments may have existed during the Noachian period (Bishop et al., 2013).

The preferred Oxia Planum 1 landing ellipse has no elevation problems and contains very few topographic obstacles or challenging slopes.

Site	Lat, Lon (year and azimuth dependent)	Avg. Elev. (year and azimuth dependent)	Major elements of interest	Identified minerals
Oxia Planum	18.2°N, 335.5°E	–3.0 km	Old, prolonged water/rock interaction. Fine-grained deposits. Thick stratigraphy accessible.	Fe-rich clays, high abundance.

7.6.11 References

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7.7 Coogoon Valles

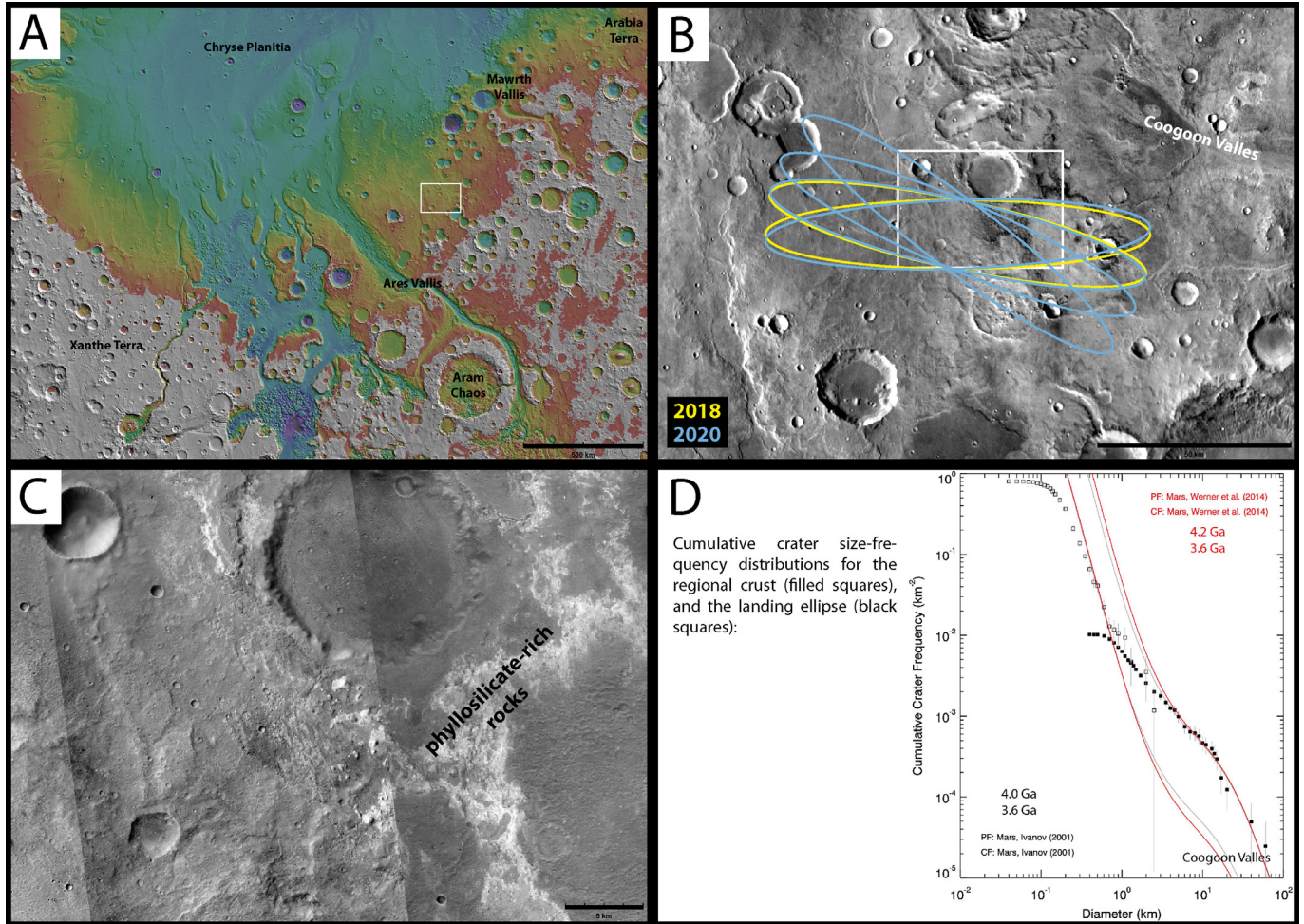


Fig. 21: Documentation images for the Coogoon Valles landing site. A) Regional context map of Arabia Terra and Chryse Planitia with coloured MOLA topographic data superimposed on MOLA shaded relief. The scale bar is 500 km long. B) Location of the proposed ellipse superposed on a THEMIS daytime IR mosaic. The scale bar is 50 km long. C) The key features within and in the vicinity of the landing ellipse are marked on this CTX mosaic. The scale bar is 5 km long. D) The analysis of cumulative crater size-frequency distributions resulted in the following ages —Ivanov (Werner et al.): 4.0 Ga (4.2 Ga) for the regional crust (black-filled squares) and ≥ 3.6 Ga (≥ 3.6 Ga) for the landing site's exposed clay-rich deposits (black squares).

7.7.1 Global Context

The Coogoon Valles region is situated between Mawrth Vallis and Ares Vallis, in one of the lowest parts of Arabia Terra, an area of Mars hitherto practically unexplored (Fig. 21A).

7.7.2 Regional Context

The Coogoon Valles area shows plentiful morphological and mineralogical evidence of aqueous activity. The main units are dissected by an ancient fluvial system. Numerous, high-albedo, sedimentary rock outcrops are distributed in different locations of the proposed landing ellipse (Fig. 21C). Mineralogical analysis suggests the presence of phyllosilicates and polyhydrated sulphates. It is likely that they correspond to the same type of extensive, hydrated deposits encountered in the Mawrth Vallis and Oxia Planum regions.

7.7.3 Topography and Morphology

The Coogoon Valles landing ellipse is centred at 16.5°N, 336.5°E (Fig. 21B), in terrain averaging -2.7 km MOLA elevation devoid of large obstacles. Ancient water flow channels exist within the proposed landing ellipse, with some short ones located within rover traverse distance from the ellipse centre.

7.7.4 Mineralogy

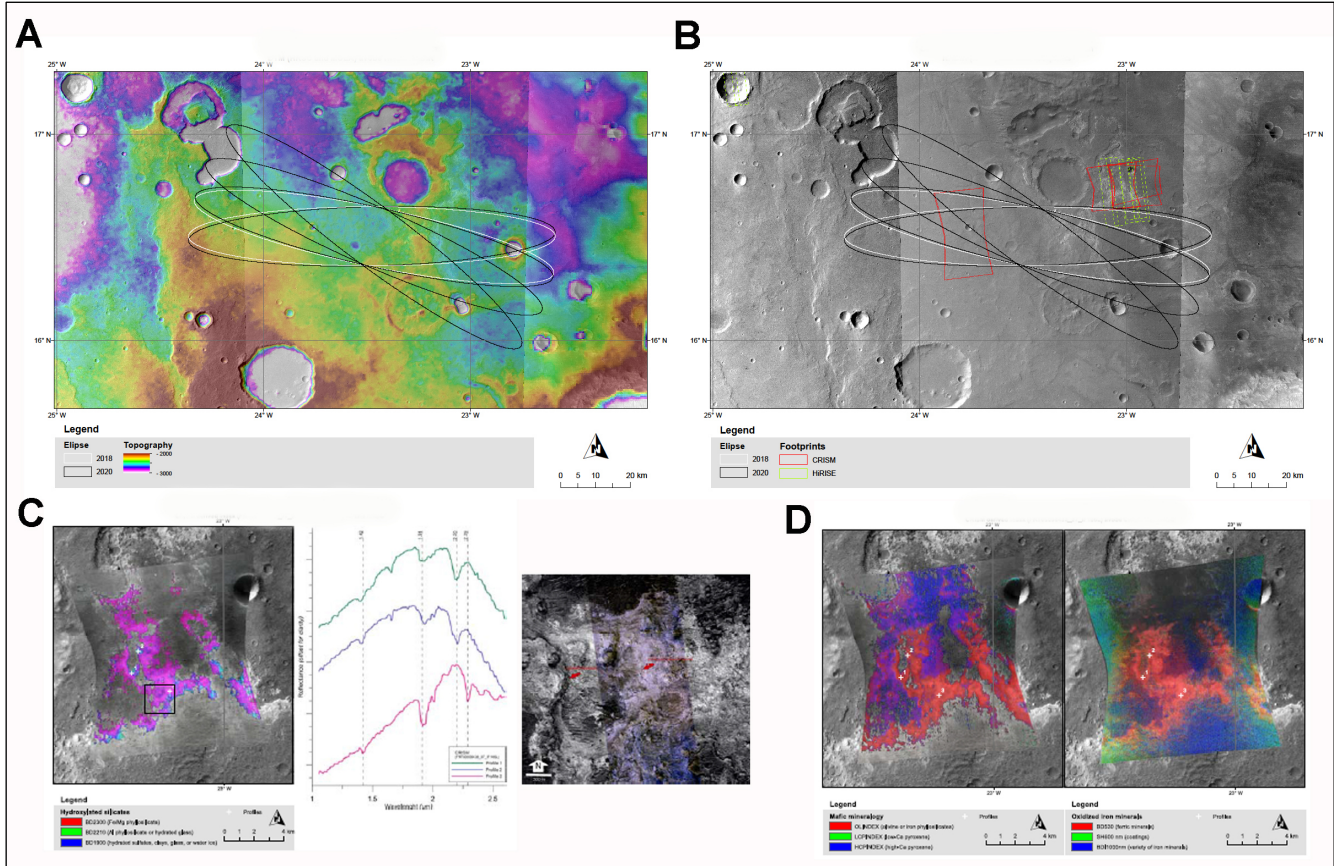


Fig. 22: Documentation images for the Coogoon Valles landing site. A) Topographic map of proposed ellipse—DTM computed from HRSC and MOLA data projected over an HRSC Nadir view. B) Location of existing HiRISE and CRISM images for the landing area. C) Left: CRISM-derived index (FRT00008438_07_IF166L) overlaid on an HRSC image; Centre: CRISM data; Right: HiRISE image (corresponding to the black-outline rectangle on the left). D) Distribution of Fe-rich phyllosilicates, derived using the same data as in C (Gomez, F. et al. 2014).

The mineralogical sequence of Coogoon Valles is similar to that found in Mawrth Vallis and Oxia Planum. Light-toned materials, extending from the centre to the northeastern section of the ellipse, can be observed in HiRISE images. These deposits are characterised by absorption bands at 1.43 and 2.29 μm , consistent with phyllosilicate-bearing material, such as nontronite (Fe-smectite, pink coloured areas in Fig. 22C). Other outcrops, with absorption bands at 1.41 and 2.21 μm , have been tentatively identified as Al-rich smectites (green patches in Fig. 22C) (Bishop et al., 2002, 2008; Clark et al., 1990). Polyhydrated sulphates might be present in this region as well (blue colour in Fig. 22C). However, the clay-bearing, light-tone deposits are less well exposed and distributed than on Mawrth Vallis or Oxia Planum.

7.7.5 Ages

The Coogoon Valles highland sector includes crustal units formed during the early, mid, and late Noachian, with the oldest units occupying the highest topography. Regional crater counts, however, suggest a more homogeneous picture with all units formed about 4.0 Ga (4.2 Ga) ago (black-filled squares in Fig. 22D). Craters with a diameter smaller than 3 km in diameter have been erased, indicating a modified stratigraphic column of about 650 -m layer thickness.

Intense resurfacing took place up to 3.6 Ga (3.6 Ga) ago (black squares), which may correspond to the deposition and alteration process that resulted in the clay-rich unit. Craters and pits smaller than about 150 m in diameter are very numerous, and suggest an old age as well. Detailed studies on the nature of these pits are required to distinguish remote secondary crater clusters, pits formed in rough volcanic or sedimentary terrain, and primary craters.

7.7.6 Atmospheric Conditions

Coogoon Valles is very close to Oxia Planum, and the same general wind regime conditions are applicable for this location. For a 2019 landing, the horizontal winds are predicted to be below 25 m/s. Above 5-km altitude, the site will be affected by the northern jet stream. For the usual dust loading conditions, winds will remain close to (sometimes slightly exceeding) the specified limit up to 10 km (Figs. 9 and 10). Winds will reach values above 25 m/s in very dusty conditions (Fig. 9). As for Mawrth Vallis, further studies are required to determine the risk and establish the high-altitude engineering threshold.

There are no problems with horizontal winds at Coogoon Valles for a landing in 2021.

7.7.7 Geologic History

The Coogoon Valles area exhibits clear indications of past water activity, including 1) layered, clay-rich sedimentary deposits, 2) high-albedo material whose origin was likely associated with water solutions, 3) numerous flow channels, 4) craters with fluidised ejecta patterns, and 5) scablands (landscapes scoured clean by cataclysmic outflows).

The geologic history of the area probably follows a scenario similar to that of Mawrth Vallis. Layered sediments were deposited on the ancient highland crust during the early and middle Noachian. After their formation, the combined action of surface water and impacts eroded the layered unit, creating valleys and depositing clays in depressions through the late Noachian. Later, during the Hesperian, the large outflows that eroded the dichotomy boundary modified the area, as did probable lava flows. A dark cap unit covered the plateau. Wind erosion progressively eroded away this dark cap, exhuming the soft, layered, clay-rich rocks. Exhumation of the clays is likely a still ongoing process.

7.7.8 Potential for Biosignature Preservation

The potential for biosignature preservation of this area is similar to that of the Mawrth Vallis and Oxia Planum regions. The ancient clay-rich outcrops present all over Coogoon Valles system may have formed in aqueous settings that could have hosted microorganisms and then helped preserve their putative biosignatures.

7.7.9 Compliance with Engineering Constraints

Coogoon Valles landing ellipse elevations are in the order of –2500 m, always below the –2000 m limit. Slope-specific concerns on approximately 6% of the ellipse pattern area have been identified at 330-m and smaller scales, typically in association with craters.

The dust coverage is expected to be low in this area, but needs to be checked.

Coogoon Valles is very close to Oxia Planum, so the same general wind regime will be applicable for this location. For a landing in 2019 under the most likely dust conditions the wind could reach values slightly in excess of the 25 m/s limit above 10 km altitude. However, the jet stream is a robust, consistently west-flowing structure having little variability, which could be taken into account for the EDL plans. A detailed sensitivity study, possibly involving several models, would be useful to assess risk. All proposed landing site would be affected by winds above 25 m/s in case of a global dust storm. There are no problems with horizontal winds at Coogoon Valles for a landing in 2021.

7.7.10 Summary

An initial analysis of the Coogoon Valles landing site indicates that it is broadly consistent with the scientific objectives of the ExoMars mission. However, it presents some engineering challenges requiring more careful investigations.

The proposed landing ellipse lies at the end of the Coogoon Valles ancient fluvial system, between Mawrth Vallis and Ares Vallis. Coogoon Valles is a poorly studied area of Mars that shows clear indications of abundant past water activity. The numerous finely layered, phyllosilicate- and sulphate-bearing deposits are similar to those in Mawrth Vallis and Oxia Planum, but less well exposed and distributed.

The Coogoon Valles landing ellipse has no elevation problems, but includes some topographic obstacles and difficult slopes.

Site	Lat, Lon (year and azimuth dependent)	Avg. Elev. (year and azimuth dependent)	Major elements of interest	Identified minerals
Coogoon Valles	16.5°N, 336.5°E	−2.7 km	Old, prolonged water/rock interaction. Fine-grained deposits. Thick stratigraphy accessible.	Fe-rich clays, relatively high abundance.

7.7.11 References

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7.8 Hypanis Vallis

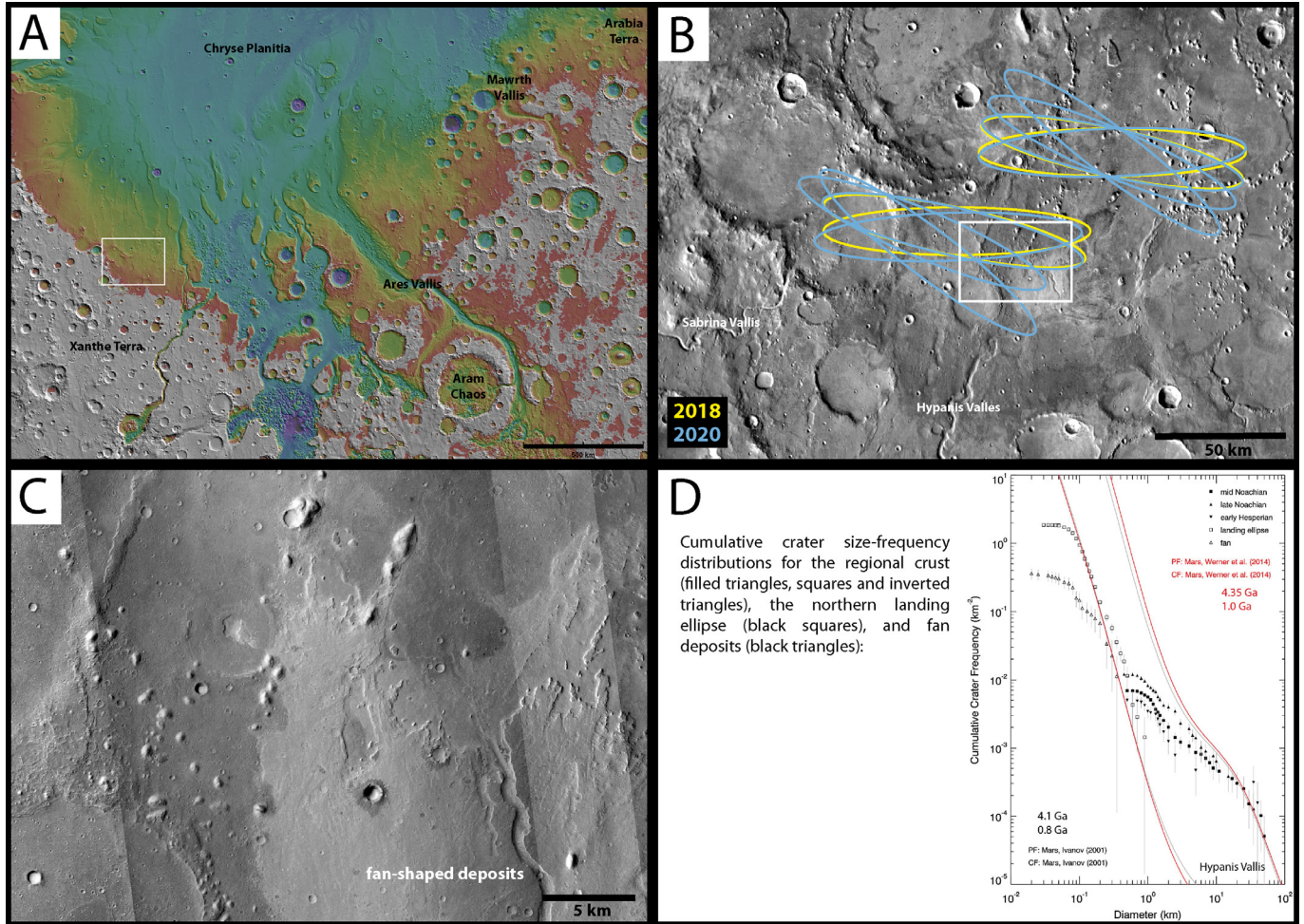


Fig. 23: Documentation images for the Hypanis Vallis landing site. A) Regional context map of Xanthe Terra and Chryse Planitia with colourised MOLA topographic data superimposed on MOLA shaded relief. The scale bar is 500 km long. B) Landing ellipse pattern superposed on a THEMIS daytime IR mosaic. The scale bar is 50 km long. C) CTX mosaic close-up of the proposed landing ellipse's centre. The scale bar is 5 km long. D) The analysis of cumulative crater size-frequency distributions resulted in the following ages —Ivanov (Werner et al.): 4.10 Ga (4.35 Ga) for the regional crust (black-filled squares and black-filled triangles) and ≤ 0.8 Ga (≤ 1.0 Ga) for the fan deposits' exposure age (black squares and triangles).

7.8.1 Global Context

The Hypanis Valles and the large fan-shaped deposits at their termini are located in the Noachian terrain part of the Xanthe Terra region (Rotto and Tanaka, 1995). Specifically, the units on which the Hypanis Valles are incised are of middle Noachian age, but the western branch of the Hypanis Valles originates in early Noachian terrain (Tanaka et al., 2014a; Platz et al., 2014). These units are believed to contain undifferentiated impact, volcanic, fluvial, and basin materials that are moderately- to heavily-degraded and tectonically deformed in places (Tanaka et al., 2014b). The terminal deposits are also located on middle Noachian material. To the north of the deposits, the middle Noachian material transitions into late Noachian highland material, interpreted as undifferentiated impact, volcanic, fluvial, and basin material that has been lightly to moderately degraded and (or) deformed (Tanaka et al., 2014b).

7.8.2 Regional Context

The Hypanis Valles are located in Xanthe Terra near the global dichotomy boundary, thus corresponding in that region with the western margin of Chryse Planitia, thought to be an ancient impact basin (Fig. 23A). The Hypanis

Valles are one of several valleys situated between two large outflow channels, Maja Vallis in the west and Shalbatana Vallis in the east. These valleys are deeply incised into the Noachian plateaus, have more or less constant widths, and possess few tributaries. They display amphitheatre-shaped valley heads, with some evidence for small shallow valleys connecting to these head scarps. At least one of these valleys (Nanedi Vallis) contains an inner channel. These valleys have been interpreted as sapping valleys (i.e. formed by seepage as a result of groundwater emergence; Sharp and Malin, 1975), but this interpretation has been challenged based on terrestrial research carried out on analogue valleys, which were shown to receive significant surface runoff (Lamb et al., 2008). Several of these valleys (e.g., Sabrina, Tyras, and Hypanis Valles) exhibit fan-shaped deposits at their termini (Di Achille et al., 2006, 2007; Hauber et al., 2009). The valleys have been dated as Late Noachian in age (Hauber et al., 2009; Platz et al., 2014), whereas the fan-shaped deposits seem to be younger, of Hesperian age (Hauber et al., 2013). Several wrinkle ridges cross the region and imply contractional tectonic deformation.

7.8.3 Topography and Morphology

The Hypanis Vallis landing ellipse is centred at approximately 11.9°N, 314.0°E (Fig. 23B). Overall, the elevation is rather constant across the landing ellipse (the MOLA range is -2.7 to -2.8 km). However, significant relief exists locally, in association with outcrop cliffs that are finely layered and have a brighter albedo than the plains. A lack of boulders at the foot of scarps indicates that the layered deposits are likely constituted by fine-grained material. Other, fan-shaped deposits (both at Hypanis and Sabrina) appear darker relative to their surroundings in THEMIS night time infrared data, suggesting a (surficial) composition of finer-grained and/or more unconsolidated material. In plain view, the deposits form several lobes, the margins of which appear to be eroded, as layering is clearly visible in the steep cliffs (scarps). Their layered geometry suggests (sub)horizontal layering. Some inverted channels seem to be associated with the fan-shaped deposits. The surrounding plains are relatively smooth and do not display any noticeable textural peculiarities. Aeolian bedforms (ripples) are sparsely distributed across the entire area. The landing ellipse is not directly located on the fan deposits, but is distal (i.e. basin-ward) to them, in a region where very fine-grained materials may have been deposited (Fig. 23C). Isolated, km-sized hills with rounded shapes in plan view suggest that the entire area has been exhumed. Irregular pitted cones in the nearby Lederberg crater have been hypothesized to be of igneous volcanic origin, representing either scoria and/or tuff cones (Brož and Hauber, 2013).

7.8.4 Mineralogy

No alteration minerals have been identified so far within the ellipse, neither in association with the Hypanis deposits nor in the distal plains, possibly due to the lack of high-resolution spectroscopic data (no CRISM targeted observations are available). However, hydrated minerals are detected in outcrops of other deposits, possibly laterally continuous to the Hypanis delta ones, to the south of the ellipse, as well as in the rims of the nearby Magong Crater and of a smaller crater south-west of the ellipse. A weak phyllosilicate signal has been detected in CRISM spectra of another, fan-shaped deposit at the terminus of Sabrina Vallis, in Magong Crater.

7.8.5 Ages

The Hypanis Vallis landing site is located at the transition between mid- and late Noachian units, where fan deposits appear to overlie a late-Noachian unit. The regional crater counts suggest that several resurfacing events took place. The original highland unit formed about 4.1 Ga (4.35 Ga) ago. The late-Noachian unit may be only slightly younger —4.05 Ga (4.25 Ga)— with at least one resurfacing event having removed parts of the record for craters smaller than about 2.5 km in diameter, implying a modified stratigraphy (erosion or deposition) of the order of 500-m layer thickness, which was disturbed in several episodes (as indicated by the presence of several different slopes in the crater count distribution).

Another possible ellipse, north of the fan is situated at the transition between late Noachian to early Hesperian (3.75 Ga) units, with a cratering record disturbed for craters smaller than 1.3 km in diameter (layer of about 300 m). The fan sedimentary deposits appear to have been exposed, at most, for the last 0.8 Ga (1.0 Ga), with loss of smaller craters due to dune activity or other aeolian sedimentation.

7.8.6 Atmospheric Conditions

Hypanis Vallis is located around 11.8°N. For a 2019 landing, this location is less disturbed by the northern jet stream than either Mawrth Vallis or Oxia Planum. Under most dust loading conditions, the predicted horizontal

winds will remain below 15 m/s (Fig. 9). For a global dust storm, however, the jet stream would extend down almost to the equator (Fig. 8), with wind velocities exceeding 25 m/s below 10 km altitude.

There are no problems with horizontal winds at Hypanis Vallis for a landing in 2021.

7.8.7 Geologic History

The main scientific interest for this site is the investigation of layered deposits containing very old (i.e. Noachian) material eroded from the cratered highlands to the south. This material, dating back to the very early history of Mars, when habitability was probably most likely, accumulated in fan-shaped deposits during the early Hesperian. The proximal environment is likely to consist of coarser particles, whereas finer particles would have been carried further to the north, where the proposed landing site is located. If the sediments were formed in a standing body of water, then this aqueous environment would have been directly habitable and traces of potential *in situ* life may be recorded in the strata exposed at the fan-shaped deposits. The location of these deposits at the margin of Chryse Planitia implies that a standing body of water could have been hosted in the huge northern lowlands basin (the closed basin defined by a contour line with the same elevation as the Hypanis deposits). Thus, the investigation of these sediments would also constitute a test of the northern ocean hypothesis (i.e. a true delta would imply the presence of an ocean-sized body of water). The possibility of a long-standing body of water in conjunction with volcanic activity (scoria/tuff cones), with which hydrothermal activity was most certainly associated, opens up a window for the emergence of life in the area (Westall et al., 2013).

7.8.8 Potential for Biosignature Preservation

This landing site has high potential for having hosted microbial life and for preserving its biosignatures. If life emerged in the area, its traces could be found in the fine-grained sediments. Even if life did not emerge locally, the longevity of the standing body of water would have allowed sufficient time for viable cells to be transported there, either by flowing water and/or by subsurface aquifers tapped by (impact) fractures. Biosignatures in the form of fossilized morphological structures and/or organic remains could be present, e.g. coating volcanic particles and/or adsorbed to the surfaces of phyllosilicates (Westall et al., 2011).

The fine-grained sediments could also contain allochthonous biosignatures, i.e. transported fragments containing morphological and/or organic remains eroded off from more ancient Noachian units in the hinterland, or transported particulate organic matter from extant life forms living elsewhere. This is also a possibility for any of the other sites, but here we have positive evidence for lateral aqueous transport.

The successful preservation of the potential biosignatures would require rapid encasing in anaerobic, fine-grained sediments and/or a precipitated mineral (e.g. silica—available from nearby hydrothermal activity, or if the body of water had high silica content as did oceans in the early Earth, Westall et al., 2011). The degree of degradation of eventual organic biosignatures will also depend on how long ago the area was exhumed.

7.8.9 Compliance with Engineering Constraints

The Hypanis Vallis landing ellipse elevation is rather constant and in the order of –2700 m, well below the –2000 m limit. Slope-specific concerns on approximately 3% of the ellipse pattern area have been identified at 2-km and smaller scales, typically in association with outcrop cliff walls.

Based on IRTM data, it would appear that rock abundance, thermal inertia, and albedo criteria are met throughout the landing ellipse. However, this needs to be further checked with HiRISE images. Frequent aeolian bedforms (ripples) may pose a challenge to rover traversability, though. There are insufficient data at present to evaluate radar reflectivity.

7.8.10 Summary

The initial analysis of the Hypanis Vallis landing site is broadly consistent with the scientific and engineering constraints of the ExoMars mission.

The site has a clear geomorphic context indicating that Noachian-aged rocks from the ancient highlands were eroded and deposited as layered sediments in low-energy, aqueous environments (alluvial and possibly lacustrine

settings) in the early Hesperian. The proximal sediments, exposed at distinct cliffs, are finely layered, probably coarse-grained material that is not incompatible with life and biosignature preservation. However, it is the more distal, fine-grained deposits that provide the best scenario for biosignature preservation potential.

With sites of scientific interest spread throughout the landing ellipse, and with minimal obstacles to driving (except possibly aeolian ripples), Hypanis offers accessibility to rocks that formed in aqueous depositional environments. Old rocks from a wide catchment area in the Noachian highlands accumulated in the deposits, a scenario favourable for gaining insight into diverse source lithologies.

Scientific concerns with this site relate to 1) an Hesperian age (younger than preferred) of formation of the sedimentary body (however, if the delta was spreading into an already long-standing body of water, this may not matter); 2) very weak, and possibly ambiguous, phyllosilicate detection (in nearby deposits only); and 3) uncertainty about the exact nature of the presumed distal, fine-grained deposits.

The Hypanis Vallis landing ellipse has no elevation problems, but includes a few topographic obstacles with difficult slopes (steep terrains at some cliffs) and frequent aeolian bedforms (ripples) that may pose a challenge to rover traversability.

Site	Lat, Lon (year and azimuth dependent)	Avg. Elev. (year and azimuth dependent)	Major elements of interest	Identified minerals
Hypanis Vallis	11.9°N, 314.0°E	−2.7 km	Layered sediments, part of fine-grained deposits at the termini of Hypanis and Sabrina Valles.	Weak phyllosilicate signals (CRISM) nearby.

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7.9 Simud Vallis

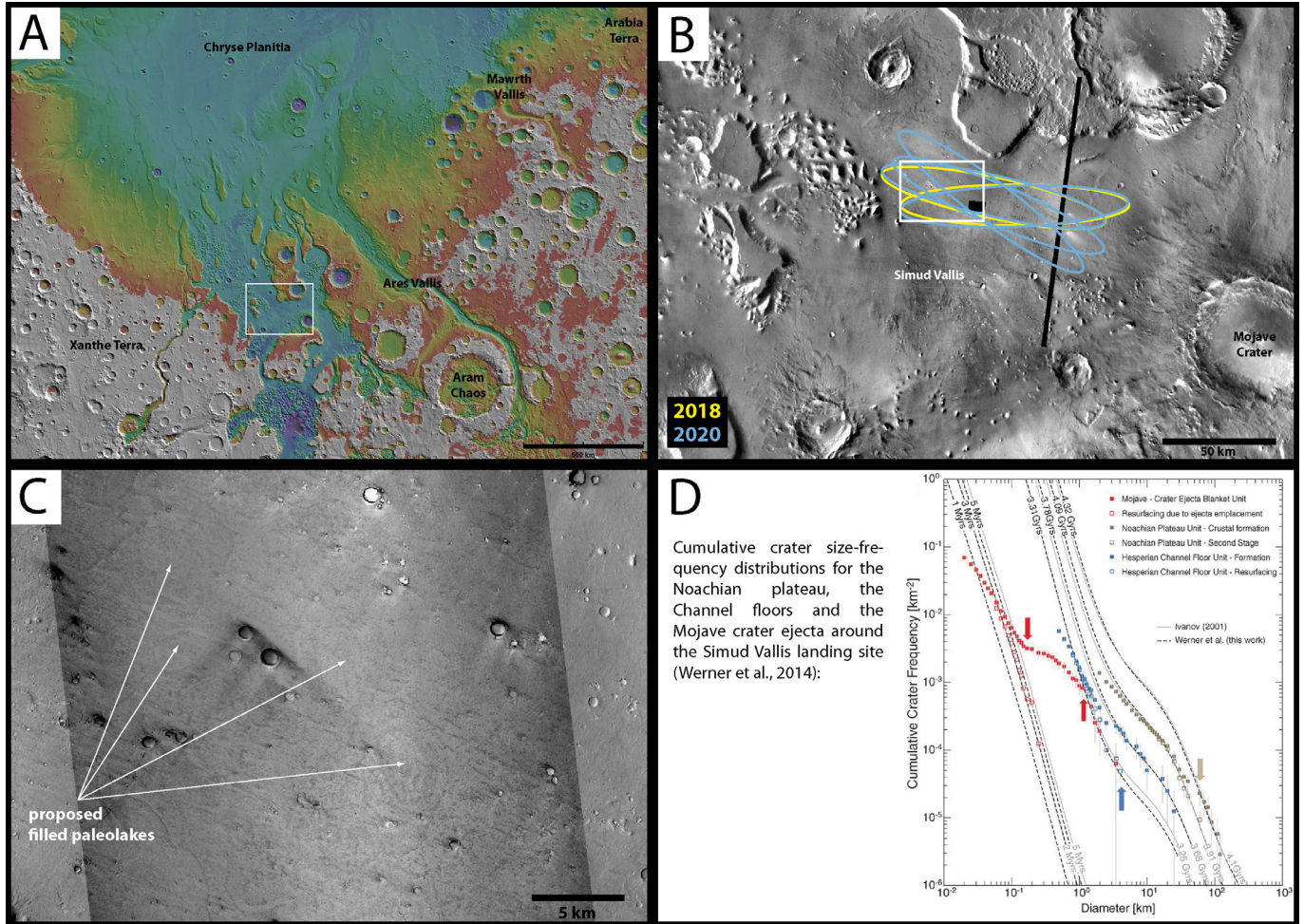


Fig. 24: Documentation images for the Simud Vallis landing site. A) Regional context map of Chryse Planitia with coloured MOLA topographic data superimposed on MOLA shaded relief. The scale bar is 500 km scale. B) Landing ellipse pattern superposed on a THEMIS daytime IR mosaic. The scale bar is 50 km scale. C) CTX mosaic close-up of the proposed landing ellipse's centre. The scale bar is 5 km scale. D) The analysis of cumulative crater size-frequency distributions resulted in the following ages —Ivanov (Werner et al.): 4.10 Ga (4.32 Ga) for the surrounding plateau, and 3.68 Ga (3.78 Ga) for the channel floor.

7.9.1 Global Context

The Simud Vallis candidate site is located in the outflow channel complex connecting Valles Marineris with Chryse Planitia (Fig. 24A). Large outflow channels and basins dominate this area. The basins are probably the product of erosion by catastrophic flows and by large-scale liquefaction and collapse typical of the martian chaotic terrains. The study of this region is key for understanding the post-Noachian history of the planet, as it preserves evidence of the processes that shaped Valles Marineris and the Northern lowlands.

7.9.2 Regional Context

The proposed landing ellipse lies in the plain formed by the confluence of the Simud and Tiu Valles. Mojave Crater, although unrelated with the Simud channel complex formation, dominates this part of the basin. The basin itself is part of a complex system including several other basins; such as Chryse, Hydraotes, and Aurorae Chaos; all linked by outflow channels. This system of chaos/basins and catastrophic channels served partly as a route for emptying the Valles Marineris basin. However, this region has a more complex aqueous history. The topography of the channel system and related basins in the entire region displays local evidence of southward flow in some channel segments. Therefore, apart from the general northward trend from Valles Marineris to Chryse Planitia, the

presence of thresholds matched by channel floors dipping southward suggests that, during particular periods of activity, flows funnelled water to the South, at least in some stretches of the channel system. Water ponding in the basins has been proposed (e.g. at Hydroates Chaos) on the basis of topographic morphology and geological features. However, definitive evidence for the presence of long-standing bodies of water in the Simud Vallis area has not been demonstrated yet.

7.9.3 Topography and Morphology

The Simud Vallis landing ellipse lies close to 8.5°N, 325.0°E (Fig. 24B), in terrain averaging –5 km MOLA elevation. An alternative ellipse to the west of the first ellipse has also been proposed, providing better coverage of putative “closed basins”. However, the characteristics of both ellipses are similar. The ellipses are located in the northern part of the basin that originates at the confluence of the Simud and Tiu Valles. The area is extremely flat and basically devoid of aeolian bedforms. Ellipse 1 includes some ejecta from Mojave Crater. Ellipse 2 has some butte-like relief, representing the southern portion of Chryse Chaos.

Erosional signatures dominate the surface morphology at the scale of MOC and CTX observations (a few m/pixel). They seem to be the product of unidirectional, turbulent flow, with high erosional capabilities. The proposers classify some faint, quasi-circular features scattered in the region as “closed basins” (Fig. 24C). These features, however, do not display the characteristics of lacustrine basins. No clear shoreline morphologies can be observed, deltaic deposits are absent, and there is no evidence of basin infill. Smaller channels, up to 200-m wide, can be found in various places. These channels probably represent a late phase of hydrological activity, postdating the formation and flooding of the much larger outflow channels. These smaller channels are possibly associated with mound-like structures that the authors suggest could be mud-volcanoes. A relation of these channels with the purported “closed basins” is absent or, at least, not clear.

7.9.4 Mineralogy

There is no high-resolution spectroscopic information (CRISM targeted data) available for the Simud Vallis landing ellipse. However, OMEGA and CRISM multispectral products, as well as TES data, do exist. So far, no hydrated mineral detection has been reported in this area. The proposers state the presence of hematite, sulphates, and carbonates, based on TES mineral maps from Bandfield (2002), but the values are very low and not conclusive. CRISM multispectral data analysis does not provide confident evidence of hydrated minerals.

7.9.5 Ages

The Simud Vallis candidate landing site is located on the Hesperian channel floor. The surrounding plateau unit is about 4.10 Ga (4.32 Ga) old (mid Noachian). It experienced resurfacing 3.91 Ga (4.09 Ga) ago, with craters smaller than about 4 km erased. The small-crater record of the plateau has been highly influenced by secondary impacts from Mojave Crater.

The channel floor was formed (excavated) approximately 3.68 Ga (3.78 Ga) ago, with at least one resurfacing event occurring about 3.25 Ga (3.31 Ga) ago. Mojave Crater formed only about 3–5 Ma ago. Its ejecta and secondary craters disturbed both the crater record and the strata. The crater record of the Mojave Crater ejecta, when considered relative to all other crater-size frequency distributions, suggests a slow but relatively steady infill by aeolian deposits at a rate of ~3 m/Ma. All ages described here are derived from Werner et al. (2014).

Further detailed studies of this landing site will be rather difficult due to the Mojave ejecta.

7.9.6 Atmospheric Conditions

Simud Vallis is located at 8.5°N. For a 2019 landing, this location is not disturbed by the northern jet stream. Under most dust loading conditions, the predicted horizontal winds will remain below 15 m/s (Fig. 9). Only for a global dust storm, the jet stream would extend down almost to the equator (Fig. 8), with wind velocities exceeding 25 m/s below 10 km altitude.

There are no problems with horizontal winds at Simud Vallis for a landing in 2021.

7.9.7 Geologic History

The Simud outflow channel system formed during the early Hesperian. It is not clear whether the system functioned as a single conduit from Valles Marineris to Chryse Planitia since the onset of its formation. Nevertheless, there is evidence that flows affected the entire region from an early stage. Subsequently, probably during the late Hesperian and possibly the early Amazonian, some water ponding occurred due to the presence of topographic thresholds and southward dipping channel floors. However, it is not clear if this modification of drainage was due to a change in the morphologies of the systems or to a variation of the hydrological magnitude of the events. What is important is that surface features have been preserved indicating that, during this later stage, probably low-energy flows, and possibly standing bodies of water occurred in this hitherto active outflow channel system. The potential scientific targets in the Simud landing site belong to this late period. Additional interest for this site comes from the fact that the ejecta from Mojave crater cover the eastern portion of the landing ellipse. Mojave crater has been recently hypothesised to be the source impact for the Shergottites (Werner et al., 2014), a class of meteorites believed to have come from Mars.

7.9.8 Potential for Biosignature Preservation

It is unlikely that outflow channels could have harboured life or preserved its signatures. High-energy flows, the relatively short presence of water, and the rapid accumulation of coarse-grained detrital deposits would have inhibited the colonisation of sediments by microbial communities. Furthermore, the strong, turbulent currents could have eroded biotic material either already emplaced at an earlier time, or potentially present in transported clasts. Hence, this high-energy, outflow channel phase of activity cannot be considered promising for the mission's scientific objectives.

The low-energy channels and possible small bodies of standing water could represent a later stage of activity in this area. Although, by then, the planetary habitability conditions were rapidly degrading, provided life could have been transported to these more tranquil wet environments, microbial communities could have developed. Rapid burial by fine-grained sediments, such as wind-blown dust settling from suspension, would have been necessary to preserve potential biosignatures. No large cover of wind-blown sands has been recognised, though.

7.9.9 Compliance with Engineering Constraints

The Simud Vallis region has the lowest elevation among the various candidate landing sites, averaging -5000 m. Ellipse 1 (shown in Fig 22B) complies with slope (at 2-km and 463-m scales), albedo, and thermal inertia constraints, but exceeds the rock abundance limit of 7%, with values of 11% in some areas, as determined from Viking Infrared Thermal Mapper (IRTM) data. A second ellipse, Ellipse 2, displaced toward the west to have the putative standing bodies of water at the centre, does not respect slope requirements at 2-km and 463-m scales and exhibits high rock abundances, though lower than for ellipse 1. The analysis of recently obtained HiRISE images reveals that part of the terrain is covered by wind-remobilised material (dominantly aeolian ripples) that may significantly hamper navigation and obscure bedrock.

7.9.10 Summary

An initial analysis of the Simud Vallis landing site has identified important concerns regarding its suitability for addressing the scientific objectives of the ExoMars rover mission and some engineering issues.

The depositional environment of the Simud Vallis region is characterised by relatively young, turbulent catastrophic outpours that cannot be considered ideal either for the potential colonisation of sediments or for the preservation of biosignatures. Some evidence exists, however, for a later phase with episodic, slower-flow regimes, accompanied by some small standing bodies of water. These targets, however, are not well distributed in the landing ellipse. The available information, in particular the mineralogy data, does not reveal the presence of outcrops having a high exobiology interest.

The Simud Vallis landing site has no elevation problems. The nominal Ellipse 1 seems to comply with slope requirements. Ellipse 2, on the other hand, presents challenging slopes toward the west. Viking IRTM data suggest that both ellipses may have high rock abundance. HiRISE images reveal that aeolian ripples that may hamper rover navigation cover part of the terrain.

Site	Lat, Lon (year and azimuth dependent)	Avg. Elev. (year and azimuth dependent)	Major elements of interest	Identified minerals
Simud Vallis	8.5°N, 325.2°E	−5.0 km	Possible, relatively young small basins present in some areas.	Weak mineral signals (CRISM).

7.9.11 References

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7.10 Aram Dorsum (Oxia Palus)

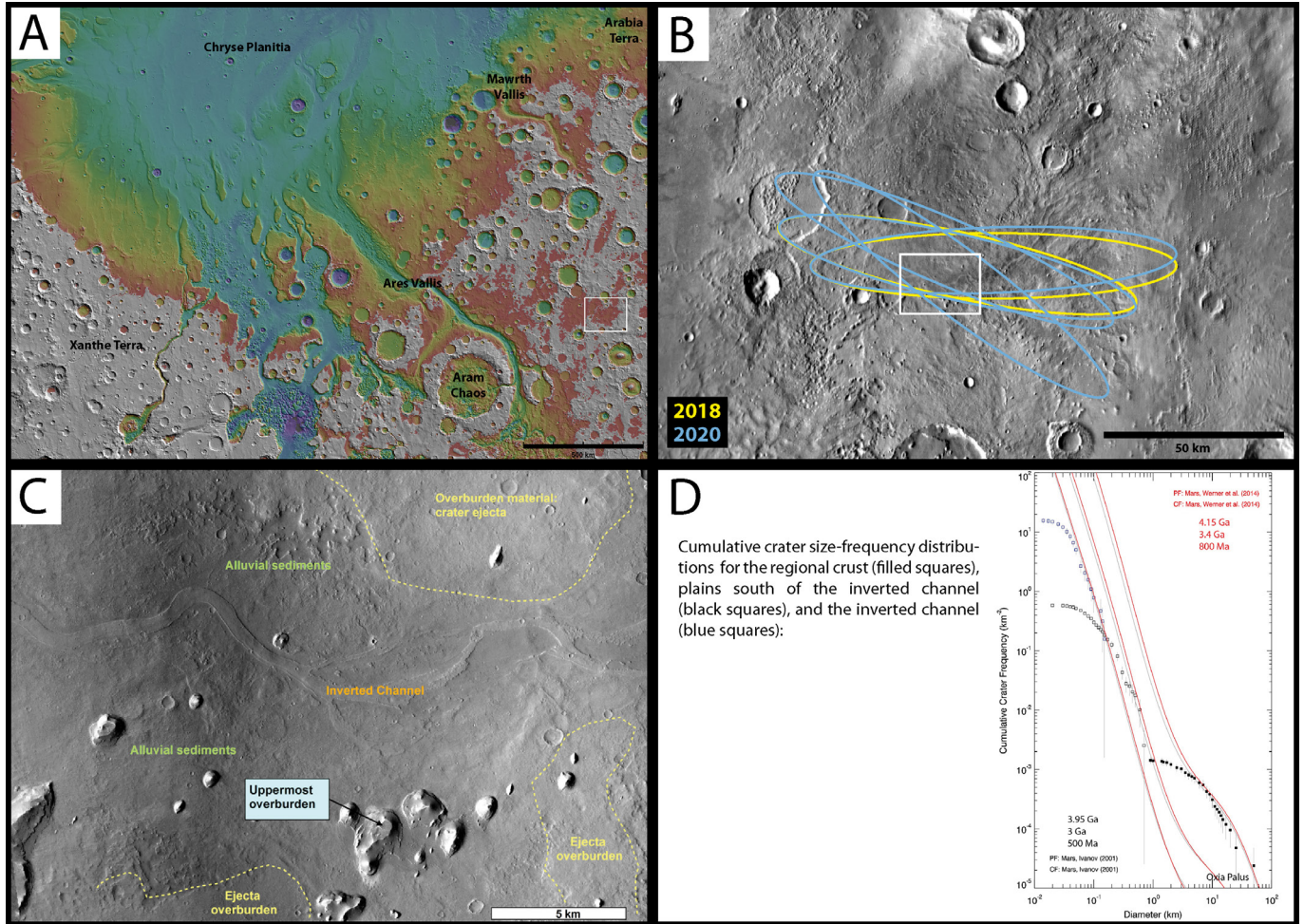


Fig. 25: Documentation images for the Aram Dorsum landing site. A) Regional context map of Arabia Terra with colourised MOLA topographic data superimposed on a THEMIS daytime IR mosaic. The scale bar is 500 km long. B) Landing ellipse pattern superposed on a THEMIS daytime IR mosaic. The scale bar is 50 km long. C) Key features are marked in this detail view obtained from a CTX image located near the ellipse centre. The scale bar is 5 km long. D) The analysis of cumulative crater size-frequency distributions resulted in the following ages —Ivanov (Werner et al.): 3.95 Ga (4.15 Ga) for the regional crust, 3.0 Ga (3.4 Ga) for the southern unit plains, and ≤ 0.5 Ga (≤ 0.8 Ga) for the inverted channel and plains' exposure age.

7.10.1 Global Context

The Aram Dorsum landing site (originally referred to as 'Oxia Palus') is located on plains of middle Noachian age (Tanaka et al., 2013) in a region that has been sculpted by two major aqueous periods (Fig. 25A). The Arabia Terra highlands formed in response to the Tharsis igneous complex load, which was emplaced during Noachian time (Phillips et al., 2001). Extensive fluvial networks carved these plains during the Noachian (Carr and Head, 2010). The far western portion of Arabia Terra underwent significant erosion in the late Noachian (Hynek and Phillips, 2001). As a result, this region possesses a large concentration of inverted channels (Williams, 2007; Williams and Chuang, 2012). The record of this early fluvial period includes the Aram Dorsum inverted channel (after which the landing location received its name). A second, later aqueous phase occurred during the Hesperian, when outflow channels carved the plains and terminated in the Chryse basin (Carr and Head, 2010).

Complete CTX coverage is available for the proposed landing ellipse but only 6 HiRISE frames (1 stereo image pair) and 2 CRISM frames exist. Additional sub-meter resolution HiRISE images and CRISM targets have been requested with an emphasis on further documenting the ellipse centre.

7.10.2 Regional Context

The prominent Aram Dorsum inverted channel curves from northeast to west across the landing site region (Fig. 25C). Aram Dorsum is one of several such systems and is a representative example of a widespread, ancient alluvial landscape. Flow direction is inferred to be to the west based on the regional drainage patterns and on modern topography. Outside the landing ellipse, Aram Dorsum originates abruptly as a full width plateau with no evident contributing drainage network. It is unclear if the source region represents a former lake, or if the drainage basin is buried, or has been erased by erosion.

Ground exploration of the rock units at this site would continue the stratigraphic succession of *in situ* observations made at the Sinus Meridiani MER landing site. Outcrops at the landing site are near the base of a regional pile of sediments, the top of which was analysed by Opportunity (Edgett, 2005).

7.10.3 Topography and Morphology

The Aram Dorsum landing ellipse is located at approximately 7.9°N, 348.8°E (Fig. 25B). Although the total relief is minimal (< 70 m), some areas exist that exceed the -2 km elevation threshold.

The palaeogeomorphology of the Aram Dorsum sedimentary system consists of four terrains (Fig. 25C): 1) A primary ~80-km long, 1–2 km wide, trunk channel, preserved as a prominent inverted feature (Aram Dorsum); 2) Smoother, channel marginal deposits, up to ~10-km across, found on either side of the main trunk; 3) Various smaller channel segments, up to a few tens of kilometres in length, and ~100–200 m across, that form a branching network and are also preserved as inverted features; and 4) Depositional fans/deltas at the termini of the smaller inverted channels. The stratigraphy within the landing ellipse includes thick remnant mesas (~100 m relief) overlying a smooth unit, a pitted, layered unit, and a basal, polygonally fractured surface. Superposing channel deposits record the development of the river system, which included both lateral and vertical channel migration, and indicate a long duration history of aqueous activity. The majority of the landing ellipse is covered by polygonally fractured terrain extending from either side of the inverted channel. The proposing team interprets this material to consist of marginal floodplain deposits (labelled alluvial sediments in Fig. 25C), consistent with the vertically aggrading fluvial environment and with texture similar to that of rocks investigated by the Curiosity rover in Gale Crater. However, an alternate hypothesis is that these rocks could instead be exposed terrain, lying stratigraphically beneath (i.e. pre-dating), and therefore unrelated to the inverted channel system.

7.10.4 Mineralogy

Only two CRISM targeted observations exist for the Aram Dorsum landing ellipse and the data do not show evidence of hydrated minerals. CRISM multispectral data suggest the possible presence of limited (ambiguous) phyllosilicate outcrops (Fig. 26). However, even a modest dust cover can hinder such observations, as recently demonstrated by MSL's positive *in situ* detection of hydrated minerals in Gale Crater that had not been seen from orbit (Grotzinger et al., 2013; Vaniman et al., 2013). Additional CRISM data have been requested, which could reveal evidence for specific aqueous alteration processes, depending on their spatial distribution and mineral composition. Proposed scenarios for phyllosilicate formation in this area include 1) hydrothermal alteration associated with impact processes, 2) deep alteration products brought up and distributed by impact events, 3) allochthonous deposits associated with the fluvial channel eroding and depositing Noachian material, and 4) autochthonous deposits reflecting *in situ* alteration in a low-energy environment. This latter mechanism for forming phyllosilicates would be the most favourable for biosignatures preservation (Ehlmann et al., 2008) and is supported by the geomorphic evidence indicative of channel migration consistent with a long-lived river system.

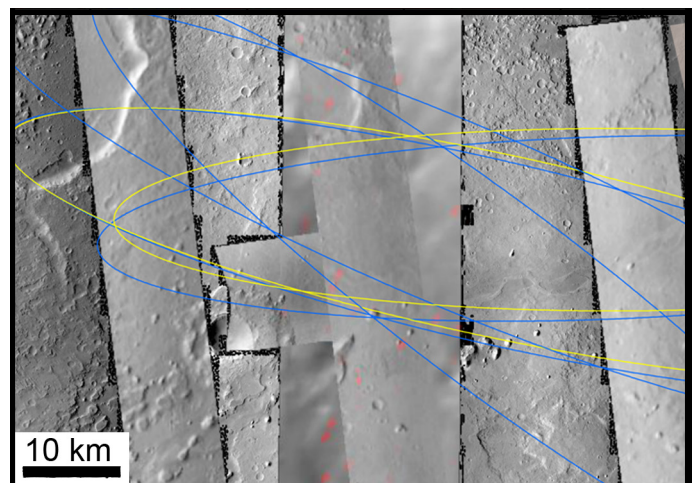


Fig. 26: CRISM multispectral data suggest sporadic occurrences of phyllosilicates (red dots) within the landing ellipse.

7.10.5 Ages

The Aram Dorsum landing site is located in a mid-Noachian unit, one of the most extensive highland units on Mars. The regional age is in agreement with a formation before 3.95 Ga (4.15 Ga) (black-filled squares in Fig. 25D). Craters smaller than 4 km in diameter have been removed from the cratering record. This suggests a relatively complex evolutionary history characterised by deposition and possible exhumation episodes having a modified stratigraphy of the order of 700-m layer thickness.

The plains around the Aram Dorsum inverted channel have been significantly influenced by secondary cratering north of the channel, thus determining an age for these plains is difficult. For the southern unit, ages could be up to 3.0 Ga (3.4 Ga) (black squares) with a resurfacing event occurring less than 1.0 Ga ago. The inverted channel shows a crater record that suggests it has been exposed since 0.5 Ga (0.8 Ga) or less (blue squares). A similar time could apply for the plains' latest resurfacing event.

7.10.6 Atmospheric Conditions

Aram Dorsum is located southeast of the other sites proposed in Chryse Planitia. For a 2019 landing, the predicted winds above 3-km altitude are particularly weak. Only for a global dust storm, when the jet stream would extend down almost to the equator (Fig. 8), would wind velocities exceed 25 m/s above 6-km altitude.

The models predict strong winds at altitudes below 2 km (Figs. 7 and 9) because Aram Dorsum lies within a “trade winds” corridor. In case this proves problematic, further studies with a mesoscale model would be necessary.

There are no problems with horizontal winds at Aram Dorsum for a landing in 2021.

7.10.7 Geologic History

The sediments in the Aram Dorsum landing ellipse are of alluvial origin and likely include a range of aqueous depositional environments, including lacustrine, fluvial-channel, and floodplain settings. The Aram Dorsum region experienced burial of at least 100 m (possibly substantially more) after the early aqueous period recorded in the landing ellipse. The primary science target, the channel margin material, which is interpreted to reflect a low-energy floodplain setting, was exhumed relatively recently. There is minimal evidence for alteration of sediments, although this should be further assessed with forthcoming spectral data.

Noachian-aged sedimentary rocks with a rich aqueous history are present across the landing ellipse, with few topographic obstacles or steep slopes, ensuring ready accessibility to sites of scientific interest regardless of the exact landing location. Preliminary mapping shows that the prime science targets (inferred floodplains and inverted channel) occur throughout the central parts of the ellipse. Erosional windows reveal other interesting targets throughout the ellipse.

7.10.8 Potential for Biosignature Preservation

The aqueous environments at this site (lakes and rivers) would have been favourable for the development of potential autochthonous life, as well as for the preservation of its biosignatures: Lacustrine and floodplain settings result in the concentration of fine-grained sediments and therefore would constitute excellent targets for biomarker preservation potential. The long-lived aqueous conditions recorded in the migrating channel pattern would have been critical for establishing a habitable environment at the Aram Dorsum site. The geologic history revealing ancient, sustained water activity, followed by burial (and therefore protection from radiation and oxidation for most of Mars' geological history), and young exhumation ages are important factors that make Aram Dorsum a site with strong biosignature preservation potential.

7.10.9 Compliance with Engineering Constraints

For the most part, the Aram Dorsum landing location has elevations ranging between –2200 and –2000 m. However, there exists an area at the west end of the ellipse pattern that reaches –1900 m. This higher elevation terrain is located up-range and constitutes between 0.5% (for azimuth values ~90°) and 5% (for azimuth values 113–127°) of the landing ellipse surface. This region also has slopes that exceed the 2-km baseline slope criteria. Roughly

one-third of the landing ellipse area has CTX DTM coverage, showing ~1% of that region exceeds the 330-m baseline slope criteria.

In general, the landing ellipse meets the elevation and slope criteria, with some regions outside of the desired values. These concerns could be mitigated if the landing ellipses' long-axis were to shrink 10% —perhaps possible for a location lying this close to the equator. Based on IRTM data, it would appear that rock abundance, thermal inertia, and albedo criteria are met throughout the landing ellipse. However, this needs to be further checked with HiRISE images. There is insufficient information at present to evaluate radar reflectivity. Traversability at the site is favourable, with minimal regions having steep slopes, topographic obstacles, or dunes.

7.10.10 Summary

An initial analysis of the Aram Dorsum landing site is broadly consistent with the scientific objectives of the ExoMars mission. Some elevation and slope concerns affecting a small area in the far western portion of the ellipse pattern require a more careful evaluation.

The site has a clear geomorphic context indicating that alluvial sediments were deposited in low-energy, aqueous environments (fluvial and possibly lacustrine settings). Noachian-aged rocks formed in aqueous depositional environments lay buried for the majority of Mars' geologic history and were exhumed relatively recently, resulting in a favourable scenario for biosignature preservation potential. With interesting scientific targets spread throughout the landing site and with minimal obstacles to driving, Aram Dorsum can be considered a promising candidate landing location.

Site	Lat, Lon (year and azimuth dependent)	Avg. Elev. (year and azimuth dependent)	Major elements of interest	Identified minerals
Aram Dorsum	7.9°N, 348.8°E	-2.07±0.07 km	Alluvial sediments proximal to inverted channel (primary science target). Inverted channel terminal fan/delta deposits.	Weak phyllosilicate signature (CRISM).

7.10.11 References

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7.11 Southern Isidis

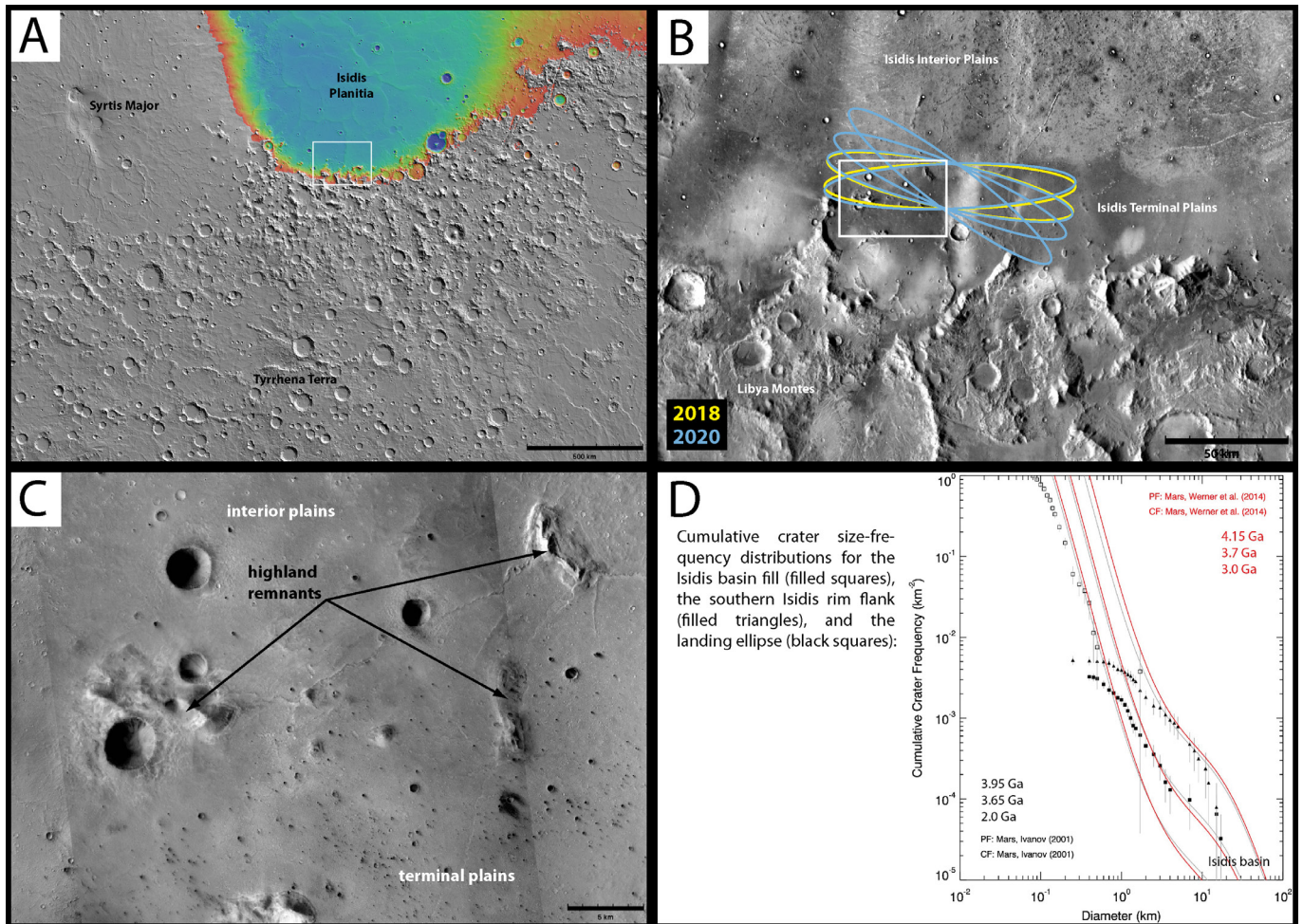


Fig. 26: Documentation images for Southern Isidis landing site. A) Regional context map of Isidis Planitia, Libya Montes, and Tyrrhena Terra with colourised MOLA topographic data superimposed on a THEMIS daytime IR mosaic. The scale bar is 500 km long. B) Landing ellipse pattern superimposed on a THEMIS daytime IR mosaic. The scale bar is 50 km long. C) CTX image, located near the ellipse centre, showing the highland remnant inliers that could constitute targets for the rover. The scale bar is 5 km long. D) The analysis of cumulative crater size-frequency distributions resulted in the following ages—Ivanov (Werner et al.): 3.95 Ga (4.15 Ga) for the regional Isidis basin fill material; 3.65 Ga (3.70 Ga) for the older, southern Isidis rim flank; but just 2.0 Ga (3.0 Ga) for the exposed material within the landing ellipse proper.

7.11.1 Global Context

Isidis Planitia is one of the four great basins in the northern lowlands, along with the Vastitas Borealis, Utopia Planitia, and Chryse Planitia. Isidis Planitia was probably created by a very large impact, which produced a particularly sharp boundary between the northern lowlands and the southern highlands. It has a 1500-km diameter outer ring, a 1100-km diameter inner ring (Frey et al. 2000), and overlies the crustal dichotomy (Fig. 26A). In common with the rest of the northern lowlands, there is evidence of a Noachian surface underlying near-surface deposits (e.g. Frey et al. 2001). The impact excavated very deep crust, and possibly mantle material that could be present as local deposits in and around the basin (Mustard et al. 2007).

7.11.2 Regional Context

Isidis is bound to the west by the Hesperian shield volcano Syrtis Major and to the south by the Noachian Libya Montes. Most of the Isidis floor is covered with Amazonian and Hesperian plains material. These sediments were deposited predominantly on top of Hesperian lava flows, partially obscuring underlying wrinkle ridge topography.

Two types of material are present on the floor of Isidis, separated by the “Deuteronilus Contact”. They are named Terminal Plains at the southern edge, near the Noachian Lybia Montes, and Interior Plains toward the centre of Isidis Planitia (Fig. 26B&C). They have different thermal inertia and roughness. The reason for this difference between the two plains is not completely understood, though it is likely that highland-derived deposits may cover the terminal plains. Some inliers of Noachian age are present in the south as eroded hills surrounded by the plains; they are considered the main science targets for rover exploration at this site (Fig. 26C). The crater retention age by Erkeling et al. (2012) for the terminal plains is consistent with a Hesperian age (Fig. 26D).

The Isidis and Utopia basins have large positive mass anomalies (Smith et al. 1999). Zuber et al. (2000) and others have interpreted the combined gravity and topography data to reflect basin infill by sediments or lavas and/or thinning of the crust underlying the basin.

7.11.3 Topography and Morphology

The Southern Isidis landing ellipse is located at approximately 4.35°N, 86.20°E (Fig. 26B), at the boundary between the smooth terminal plains and the interior plains, and has an average elevation of –3.8 km MOLA. The ~6-km-wide Noachian inliers stand out from the plains, reaching an altitude of –3.5 km. Also, there are two ~3-km diameter impact craters in the western part of the ellipse, and an 8-km crater to the south (Figs. 24A & B). The ejecta from these craters may result in rougher terrain and localised high rock abundances. The northwest part of the 127°-azimuth 2020 landing ellipse contains chains of conical landforms. Several valleys extend through the terminal plains, from south to north.

7.11.4 Mineralogy

Existing CRISM targeted data have been obtained to the south, near the Libya Montes/terminal plains boundary. They show the presence of Al-rich phyllosilicate (e.g. montmorillonite) and Fe/Mg smectite-like clays associated with the Libya Montes, Noachian inliers and with deposits at the base of the Libya Montes.

7.11.5 Ages

The Isidis landing ellipse is located in the late Hesperian plains that have filled the Noachian Isidis basin. It is possible that material from the nearby, mid Noachian basin rim has been transported and deposited on top of the late Hesperian basin fill.

The Hesperian unit is about 3.65 Ga (3.70 Ga) old (black-filled squares in Fig. 26D), craters smaller than about 1 km in diameter may have been modified to some extent. Age estimates for the older southern Isidis rim flank are at least 3.95 Ga (4.15 Ga) (black-filled triangles). Craters smaller than 2.8 km in diameter are partially erased, suggesting a disturbed stratigraphic column of about 600-m thickness. Within the landing site ellipse only smaller craters (< 500 m) can be observed. Cratering statistics suggest a very young age of less than 2.0 Ga (3.0 Ga) (black squares), with possibly one small resurfacing event, but a nearly undisturbed cratering record for craters between 100–500 m in diameter.

Most of the old material is likely to be the inliers of inferred Noachian age and float rocks on the terminal plains brought down from Libya Montes.

7.11.6 Atmospheric Conditions

Southern Isidis is located close to the equator. For a 2019 landing, this location is less disturbed by the northern jet stream than any of the others. Under most dust loading conditions, the predicted horizontal winds will remain below 15 m/s (Fig. 9). For a global dust storm, however, the jet stream would extend down almost to the equator (Fig. 8), with wind velocities exceeding 25 m/s below 10 km altitude.

There are no problems with horizontal winds at Southern Isidis for a landing in 2021.

Isidis Planitia is not a frequent centre for major, localized dust storm activity. In a survey of 120 regional dust storms observed between 1894 and 1984, Martin and Zurek (1993) listed just two of them centred on Isidis.

7.11.7 Geologic History

The proposing team base some of their interest in Southern Isidis on the idea of a hypothesised shoreline appearing as a series of possible cliffs (at approximately -3600 and -3700 m) at the edge of the basin. This shoreline would indicate the presence of a palaeosea in the Early Hesperian. They also suggest another (Deuteronilus) shoreline at -3800 m MOLA that they interpret as the sublimation residue of a frozen sea that might have filled the Isidis basin. They propose that the morphologic–geologic setting and associated mineral assemblages of the Libya Montes/Isidis Planitia boundary are the result of fluvial activity, lake-size standing bodies of water, and a subsequent environmental change toward decreasing water availability followed by a cold and dry climate (Erkeling et al. 2012). The morphological and mineralogical signs of water activity are less clear than in some of the other sites. For instance, there are no clear lacustrine, deltaic, or large-scale fluvial systems in the landing ellipse, although they have been described in the adjacent Libya Montes (Carr and Chuang, 1997; Di Achille and Hynek, 2010).

The thickness of deposits in the terminal plains is likely to be no more than a few hundred metres because the low elevation of the basin (-3.5 to -3.9 km MOLA) and the surface expression of the basement wrinkle ridges do not allow for km-thick accumulations of sediments.

Areas of higher elevation within the central part of the landing ellipse are likely to be Noachian inliers (Fig. 26C), of similar origin to the Libya Montes, surrounded by the smoother plains material.

Conical landforms (Fig. 27), sometimes organised in long chains, are present to the north of the proposed landing ellipse. The 127° -azimuth landing ellipse includes this terrain in its northwestern part. These have been interpreted to be mud volcanoes that could have deposited volatile-rich material, or tuff cones of up to ~ 100 -m height (Bridges et al. 2001; Ori et al. 2001) and may offer access to a potential hydrothermal terrain.

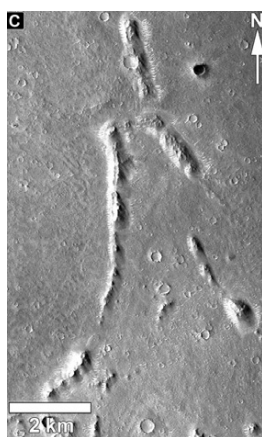


Fig. 27: Example of conical landform chains. These may be tuff cones, formed by magma-ice interaction, or mud volcanoes (Erkeling et al., 2012).

7.11.8 Potential for Biosignature Preservation

The absence of clear, water-related, morphological structures within the landing ellipse (such as deltaic systems) complicates the biosignature potential assessment. Similarly, the lack of widespread mineralogical signatures of water-rock interaction does not result in a clear case of high biosignature preservation potential.

The possibility of volcanic and/or hydrothermal activity tapping ground water or interacting with ice would be interesting for habitability. The fluids could have brought viable cells to the surface where they could have colonised the briefly habitable environment. The muds/hydrothermal deposits could have preserved potential biosignatures. However, these features (Fig. 27) are present in a small part of the landing ellipse and are very localised.

7.11.9 Compliance with Engineering Constraints

The proposed landing site ellipse is located in low terrains. This site generally satisfies the average slope and wind constraints, though the rock abundance, based on the IRTM model, is greater than the 7% maximum. Localised high rock abundances may be expected near the larger impact craters, for instance, or in the eastern part of the ellipse.

7.11.10 Summary

An initial assessment of the Southern Isidis landing site has found this location not scientifically compelling enough for addressing the objectives of the ExoMars rover mission. The Southern Isidis proposal includes a stimulating set of ideas based on the landing ellipse's proximity to the clay bearing, Noachian Lybia Montes. However, the morphological basis for establishing the nature of the process transporting material down into the Isidis plains is less

certain than for some of the other sites. If the Noachian inliers are the prime justification for considering this site, then there is a risk that ExoMars may land too far away to be able to reach them. The putative shorelines lie outside the ellipse.

From an engineering point of view, the only concern regards the existence of transported rocks in the landing site that may difficult landing and roving. This would require detailed further checking on HiRISE images.

Site	Lat, Lon (year and azimuth dependent)	Avg. Elev. (year and azimuth dependent)	Major elements of interest	Identified minerals
Southern Isidis	4.4°N, 86.2°E	−3.8 km	Noachian inliers. Detrital material deposited over terminal plains from clay-bearing Libya Montes, to the south.	AL- and Fe/Mg- phyllosilicates in the region of the ellipse, but not identified within it.

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7.12 Compliance with Planetary Protection Constraints

None of the candidate landing sites contains gullies, bright streaks associated with gullies, or pasted-on terrain currently classified as Mars Special Regions.

The evaluation of RSL associated with the candidate landing sites is on going based on already existing HiRISE images (though some of them have been obtained at times and seasons not ideal for observing RSL). A first assessment did not reveal any candidate RSL. However, confirmation that the proposed landing sites comply with planetary protection requirements, i.e. no candidate RSL in association with the sites, requires more HiRISE images and more detailed analyses to be conducted in the next phase of the landing site selection process.

8 RECOMMENDATION FOR THE NARROWING OF EXOMARS 2018 LANDING SITES

8.1 Scientific Interest

Considering the mission's search-for-life objectives, the LSSWG has identified four landing sites that possess a clear, higher scientific interest —Mawrth Vallis, Oxia Planum 1, Hypanis Vallis West, and Aram Dorsum (Oxia Palus)— which can be grouped into two categories:

Noachian, Clay-Bearing, Layered Deposits

Mawrth Vallis and Aram Dorsum have preserved a rich record of sustained, ancient deposition and alteration episodes involving liquid water. Although the origin and history of the clay-bearing deposits are not well understood, water must have been involved over long periods to alter such a large volume of material (~200-m section distributed over many 1000's km²). The fine layering probably resulted from the progressive deposition (and alteration) of frequently deposited sediments of thin individual thickness. By analogy, in some Archaean Earth settings, swathes of fine-grained, volcanic detrital material were deposited at or close to shores interspersed with thin layers (mm to cm) of basin-wide, contiguous ash fall deposits (in water). The active volcanic/hydrothermal background prevailing during the Noachian, acting in combination with the above deposition and alteration context, would have contributed ingredients and conditions favourable for life.

The type and the ancient age of the deposits, the recent exhumation history, and the widespread distribution of primary targets make Mawrth Vallis and Oxia Planum 1 very appropriate locations for pursuing the ExoMars 2018 search-for-life objectives.

Early Hesperian Alluvial Deposits

Hypanis Vallis and Aram Dorsum provide access to large areas of alluvial deposits. The aqueous conditions recorded in the migrating channel and fan patterns could have established habitable environments. The geomorphic setting indicates that large areas of these ellipses are likely to be fine-grained sediments, ideal for preserving chemical biomarkers.

The age and type of the deposits, coupled with the recent exhumation history and the widespread distribution of primary targets make also these locations very appropriate for the ExoMars 2018 search-for-life objectives.

The Other Sites

The Coogoon Valles region can be considered as somewhat similar to Mawrth Vallis and Oxia Planum, although the distribution of potential targets within the landing ellipse is sparser, and may therefore entail long driving distances, which are risky and would have to be undertaken at the expense of science observations.

The Simud Vallis candidate site is located in an outflow channel complex possessing attributes that can be associated with episodic, violent outflows and not with a long-standing, water rich environment that could have hosted life. The area's floor seems the product of unidirectional, turbulent flow, with high erosional capabilities. Though the latter stages of the catastrophic flooding could have resulted in quieter environments more favourable for life, these environments were probably very short lived. No clear mineralogical targets of interest have been found and those identified, based on somewhat ambiguous morphological information, are few and widely scattered. The LSSWG therefore concludes that landing in Simud Vallis would result in a low probability of achieving the mission's search-for-life objectives.

The Southern Isidis site contains clay-bearing detrital material eroded from the nearby Noachian Lybia Montes. These materials are likely to be diverse and would constitute interesting targets for studying the ancient aqueous history of Mars. However, the morphological basis for establishing the nature of the processes transporting this material down into the Isidis plains is less certain than for some of the other sites. If the Noachian inliers are the prime justification for considering this site, then there is a risk that ExoMars may land too far away to be able to reach them. This concern also applies to the localised features interpreted to be mud volcanoes or tuff cones, in the northwestern part of the landing ellipse. The LSSWG considers that this site does not offer as compelling a case as some of the other locations.

8.2 Landing and Roving Suitability

To date, the level of engineering assessment performed on the various candidate sites can best be described as preliminary. To proceed with the next level of detailed analysis it is necessary to concentrate on a reduced number of locations. Considering the various candidate sites' compliance with the applicable landing and roving constraints, the following statements can be made:

Between the two Noachian, clay-bearing sites, Mawrth Vallis and Oxia Planum: The former presents many more challenges for landing than the latter. The Mawrth Vallis ellipse pattern is much larger and has some elevation and slope problems. The Oxia Planum ellipse is smaller, is situated in low-elevation terrain (providing an increased margin of safety) and does not contain obvious relief obstacles.

Though, as seen from orbit, the stratigraphic profile of layered clays appears to be more complete in Mawrth Vallis than in Oxia Planum, the LSSWG considers that Oxia Planum would provide access to most of the same science—in case landing in Mawrth Vallis would prove too challenging.

The Hypanis Vallis landing ellipse has no elevation problems, but includes a few topographic obstacles with difficult slopes (steep terrains at some cliffs) and frequent aeolian bedforms (ripples) that may pose a challenge to rover traversability.

For the most part, the Aram Dorsum site has elevations ranging between –2200 and –2000 m. However, there exists an area at the west (up-range) end of the ellipse pattern reaching –1900 m with slopes exceeding the thresholds. These concerns could be mitigated if the landing ellipses' long-axis were to shrink 10%—perhaps possible for a location this close to the equator. Traversability at the site is favourable, with minimal regions having steep slopes, topographic obstacles, or dunes.

The Coogoon Valles landing ellipse has no elevation issues, but contains some topographic obstacles and difficult slopes.

Simud Vallis is an outflow, detrital accumulation site. It is therefore expected that the surface could include transported boulder fields and sands. HiRISE images reveal that aeolian ripples that may hamper rover navigation cover part of the terrain. This site does not present elevation or slope problems.

Southern Isidis is a sedimentary site that has collected material transported down from the Lybia Montes. The rock distribution estimate exceeds the threshold, but this would have to be studied in detail to determine if this is indeed a threat. This location does not have elevation or slope issues.

8.3 Recommendation

In agreement with the procedure established by ESA and Roscosmos for the evaluation of candidate landing sites for the ExoMars 2018 mission, and considering the ExoMars mission's search-for-life scientific objectives, the LSSWG recommends that further analysis concentrate on the four landing sites possessing higher scientific interest—Mawrth Vallis, Oxia Planum 1, Hypanis Vallis West, and Aram Dorsum.

Table 8 summarises the major conclusions for the proposed landing sites. Whereas the assessment performed has clearly identified four landing sites that are better suited to the mission's scientific goals, the verification of how well they meet the present engineering constraints is still on going—engineering constraints may be updated as the mission and spacecraft designs evolve. The landing and roving engineering constraints are satisfied to different degrees in each of these locations, although our preliminary evaluation indicates that Oxia Planum exhibits fewer problems than any of the other sites. However, we would expect that, upon closer inspection, all sites will have a certain amount of non-compliance, including Oxia Planum. It is therefore very important to proceed quickly to the next stage of analysis, which will allow performing Monte Carlo simulations to predict the probability of landing success based on the entry profile, atmospheric, and terrain properties at each of the candidate sites.

The LSSWG proposes to defer further evaluation of the relative science and engineering compliance merits among the four recommended sites to this next stage, once sufficient high-resolution images, spectral data, and landing performance simulations will have become available, allowing us make a more informed decision—perhaps narrowing down the recommendation to one main and one backup landing site.

Landing Site	Science	Engineering
Mawrth Vallis	Sustained, ancient deposition of sediments and alteration involving liquid water. Biosignature potential.	Some elevation and slope concerns
Oxia Planum	Sustained, ancient deposition of sediments and alteration involving liquid water. Biosignature potential.	No elevation or slope concerns
Hypanis Vallis	Large area of early Hesperian alluvial deposits including fine-grained sediments. Biosignature potential.	No elevation concerns, some slope concerns, aeolian ripple concerns
Aram Dorsum (Oxia Palus)	Large area of early Hesperian alluvial deposits including fine-grained sediments. Biosignature potential.	Some elevation and slope concerns
Coogoon Valles	Similar to Mawrth Vallis and Oxia Planum, but targets are less well distributed over landing ellipse	No elevation problems, but some topographic obstacles and difficult slopes
Simud Vallis	High-energy outflow environment with biosignature preservation potential	No elevation or slope problems, concerns about possible boulder fields and coarse sand
Southern Isidis	Old material transported from highlands into lowlands. Targets are not well distributed within landing ellipse and may be hard to reach	No elevation or slope problems, concern about rocks and coarse sand

Table 8: The LSSWG recommends the four top candidate landing sites for further, detailed evaluation. The following colour scheme has been used: Green to show when a site is considered to have a high science interest or good compliance with engineering constraints. Yellow to denote medium science interest or some problems satisfying engineering constraints. Red for locations whose science potential is not considered well suited for the mission's search-for-life objectives.

The LSSWG wishes to acknowledge the excellent work performed by the proposing teams in preparing their proposals and subsequent presentations for the first LSS workshop. We also thank the Mars Reconnaissance Orbiter and Mars Express science teams for their assistance and support during this work.

9 LIST OF ACRONYMS AND ABBREVIATIONS

AO	Announcement of Opportunity.
ALD	Analytical Laboratory Drawer.
CM	Carrier Module. The spacecraft element transporting the DM to Mars.
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars —IR imaging spectrometer in MRO for mineralogical studies.
CTX	Context Camera in MRO.
DEM	Digital Elevation Model.
DM	Descent Module. The part of the spacecraft composite that enters the atmosphere for landing—typically a capsule.
DTM	Digital Terrain Model.
EDL	Entry, Descent, and Landing.
ESA	European Space Agency.
ESAC	European Space Astronomy Centre, in Madrid (ES).
ESOC	European Space Operations Centre, in Darmstadt (DE).
ESTEC	European Space Technology and Research Centre: ESA's largest establishment, located in Noordwijk (NL).
ESWT	ExoMars Science Working Team: The group of scientists that advises ESA on all aspects of the Programme affecting its scientific performance.
Ga	Giga-annum = 1 billion years.
GCM	Global Climate Model.
GCMS	Gas Chromatograph / Mass Spectrometer: Two analytical instruments that, combined, are very useful to analyse complex gas mixtures. They can provide elemental, molecular, and isotopic abundances and composition.
HiRISE	High Resolution Imaging Science Experiment —High-resolution camera in MRO.
HRSC	High Resolution Stereo Camera in Mars Express.
IKI	Russian Academy of Sciences organism conducting space research.
ITU	Inertial Thermal Units, shorthand for $\text{J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$.
IR	Infrared.
IRTM	Infrared Thermal Mapper. An instrument in the Viking orbiters used to produce high-resolution Thermal Inertia (TI) maps of the martian surface.

LSS	Landing Site Selection.
LSSWG	Landing Site Selection Working Group.
Ma	Mega-annum = 1 million years.
MER	Mars Exploration Rovers, Spirit and Opportunity.
MEX	Mars Express.
MGS	Mars Global Suveyor.
MOC	Mars Orbiter Camera —camera on board MGS.
MOLA	Mars Orbiter Laser Altimeter: An instrument for measuring relief height in NASA's Mars Global Suveyor (MGS). The 0-MOLA ellipse has become the <i>de facto</i> reference for measuring altitude on Mars.
MRO	Mars Reconnaissance Orbiter.
MSL	Mars Science laboratory: A NASA programme that landed the Curiosity rover on Gale crater in 2012.
NASA	National Aeronautics and Space Administration—the space agency of the United States of America.
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité —IR imaging spectrometer in Mars Express for mineralogical studies.
PP	Planetary Protection.
Pyr	Pyrolysis is a technique to render organic compounds volatile by subjecting them to high temperatures. It is usually employed as a first stage in combination with a GCMS, resulting in a Pyr-GC-MS instrument. This method is sometimes also called Thermal Volatilisation (TV), and can be performed with or without involving derivatisation agents—chemical compounds that attach to small molecules to help render them volatile.
ROCC	Rover Operations Control Centre, to be located at ALTEC, in Turin (ITA).
RSL	Recurring Slope Lineae: Small-scale surface manifestations of present-day liquid water activity.
SFD	Size Frequency Distribution. Refers to the crater SFD model used for estimating the ages of geologic units.
SOC	Science Operations Centre.
SP	Surface Platform. The science element, part of the lander, that becomes active after Rover egress.
SPDS	Sample Preparation and Distribution System.
TGO	Trace Gas Orbiter.
TI	Thermal Inertia.
UV	Ultraviolet, usually used for ultraviolet radiation or ultraviolet light.