Checklist for ExoMars 2020 landing site: Mawrth Vallis

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1. INTERESTING SCIENCE TARGETS

Position of ellipses

The landing ellipse dimensions to be used should be:

- *For Oxia and Mawrth 120 km major axis x 19 km minor axis*

We respect this ellipse size.

Do you use different centres for the various ellipse azimuths?

Three ellipses with three different centers covering the azimuth range of MV are proposed (see Figure 1 and Table 1). The ellipses are located on the plateau of the thick stratified accumulation of a great variety of hydrated minerals dominated by phyllosilicates. Note that there is an additional ellipse with a center located a bit further west (FID #2 and named 129b in the shape file). This ellipse could be an alternative solution for improving the safety criteria (especially the elevation one) counterpart by the fact to have a smaller surface of clay-outcrop coverage.

Table 1. Selected ellipses for the ExoMars2020 mission over the Mawrth Vallis region.

FID	Shape	Azimuth and Name	Center_long	Center_lat
0	Polygon	102	341.9899	22.1694
1	Polygon	129	341.7771	22.1822
3	Polygon	115.5	341.9304	22.1897

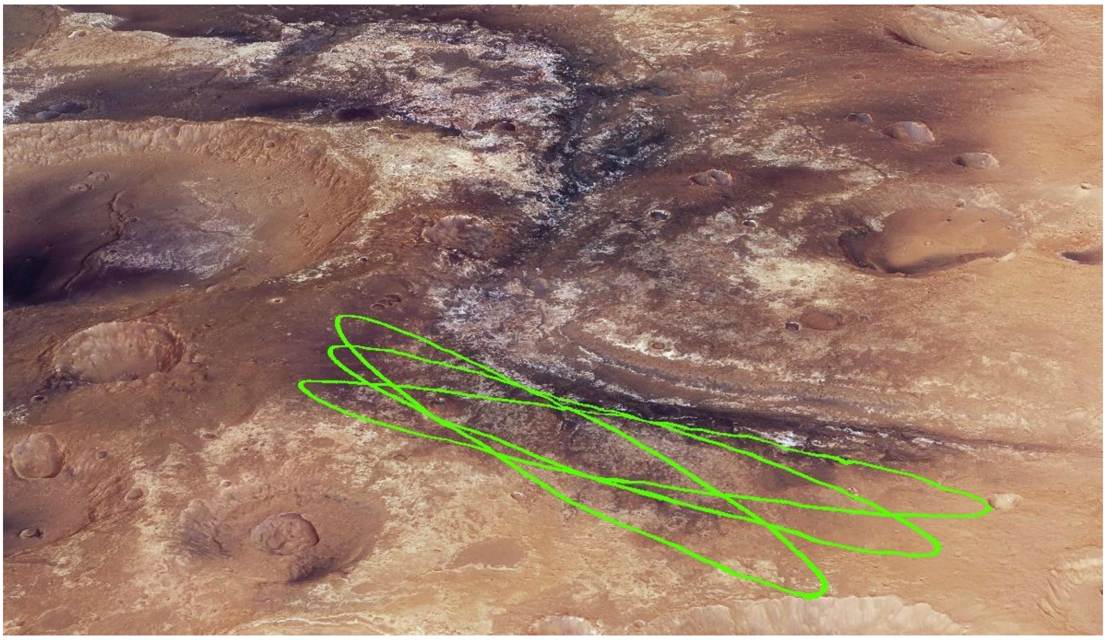


Figure 1. Positions of the three ellipses given to the project over a 3d view of the Mawrth vallis region (HRSC mosaic). Whitish/greyish material corresponds to the hydrated layered outcrops. Vertical exaggeration is 5x.

Arc Files attached?

Yes (attached filename: ellipses_2020_ExoMars_V2)

<u>*Figure of probability within ellipses*</u>

Below are two figures showing the probability for ellipses with azimuth 102° (Figure 2) and 129° (Figure 3). 1σ, 2σ and 3σ ellipses are superimposed over the geological map containing the major units at the HRSC image scale. The size of the probability ellipses were provided by P. Fawdon and E. Sefton-Nash after several iterations by email. Note that the 3σ ellipses slightly differ from the ellipses that we provided.

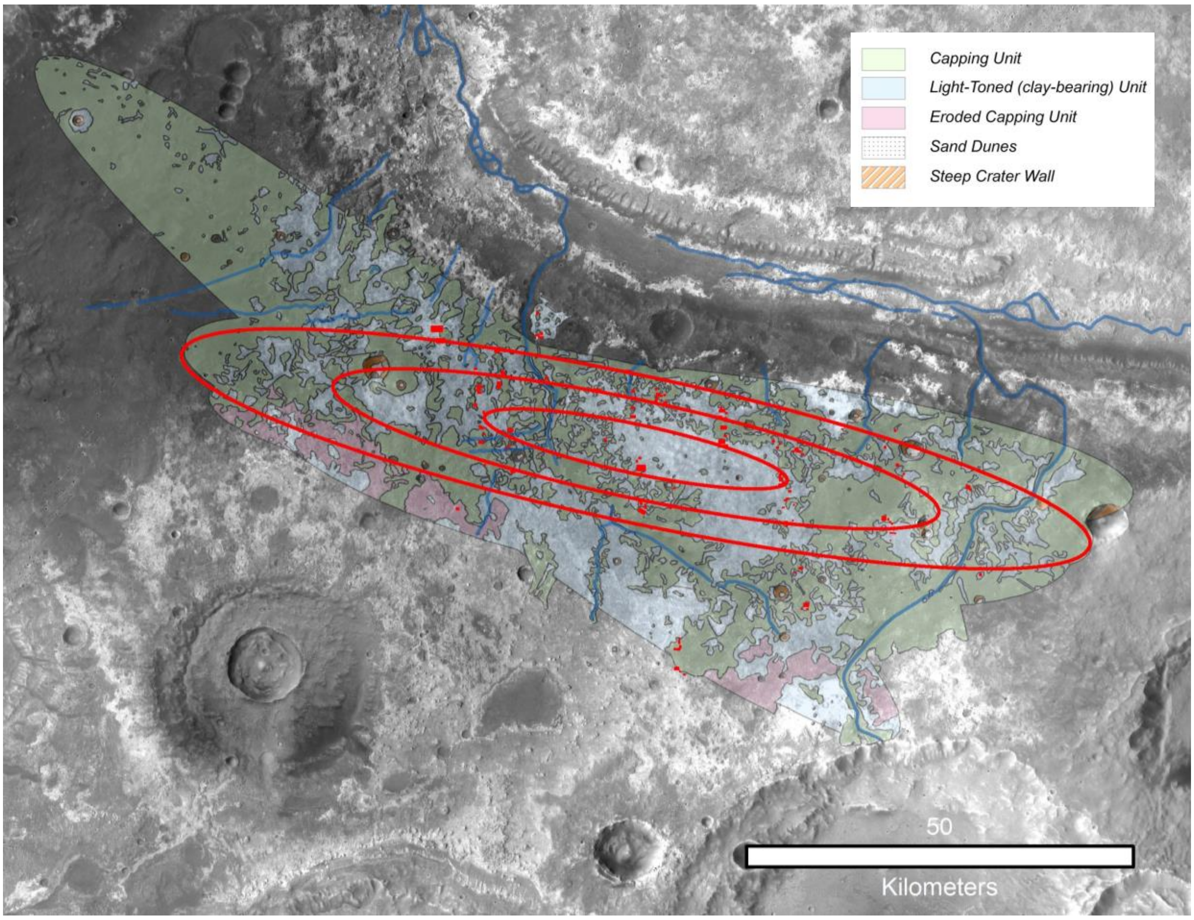


Figure 2. Figures of probability (1σ, 2σ and 3σ) for ellipse FID#0 (AZ102). Blue lines trace the major fluvial channels, and red boxes indicate the locations of the largest mineralized veins.

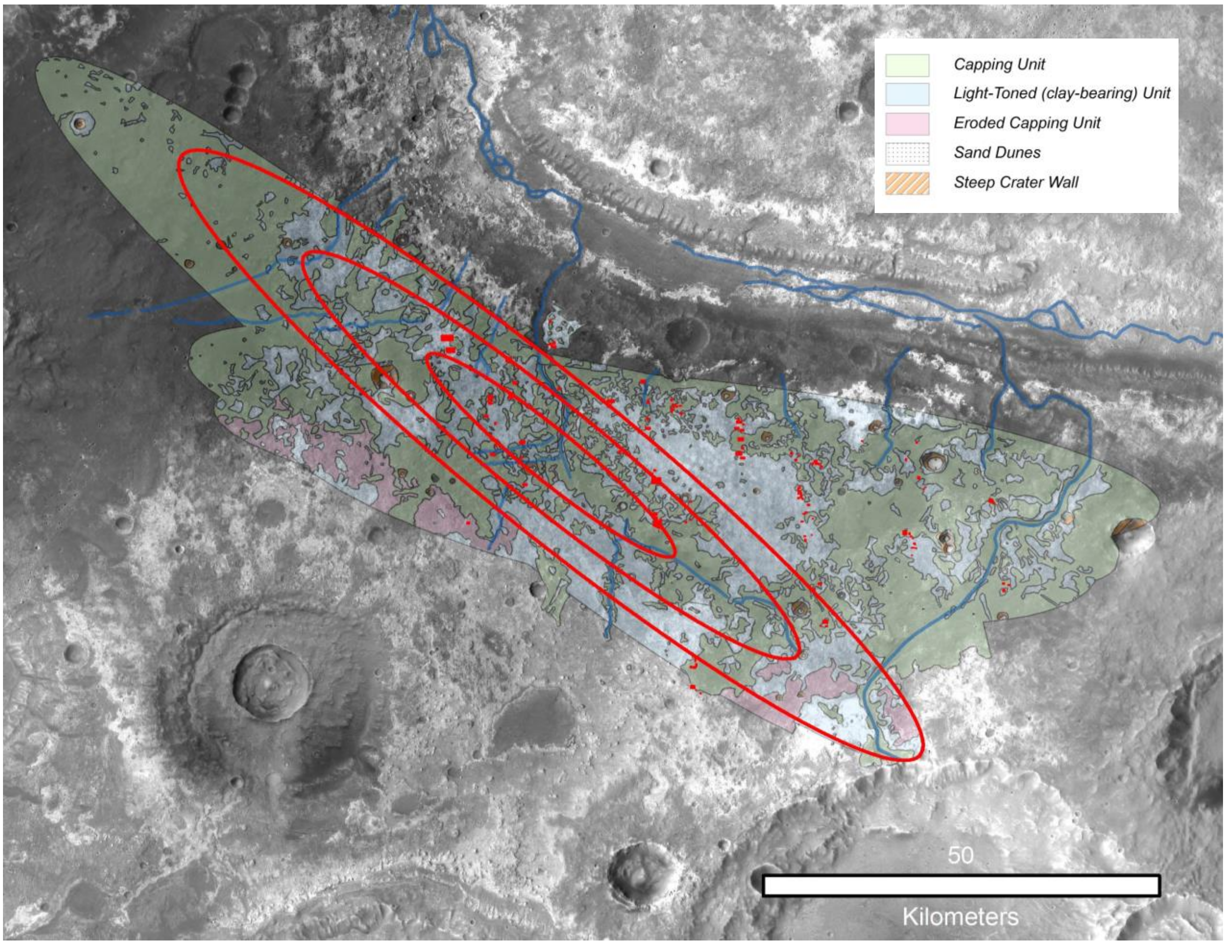


Figure 3. Same as Figure 2 but for ellipse FID#1 (AZ129).

Identification of high priority targets, regions, and formations

The Mawrth Vallis region contains extended outcrops of phyllosilicate-rich rocks. This region receives a lot of attention because OMEGA and CRISM have identified a great diversity of altered minerals in association with light-toned exposures of Noachian bedrock. Specifically, a thick (>300 m) stratigraphic section that exhibits spectral evidence for Fe/Mg-smectites, Al-smectites, iron-hydroxide (ferrihydrite), ferrous phases, amorphous silica, kaolinite, ferrous mica, and sulfate minerals indicates a rich geological history that may have included multiple aqueous environments (see Table 2 for a summary of the mineralogy and Figure 4 for the stratigraphy). Ancient valleys with ponding features are located primarily on the flank of the Mawrth Vallis channel but also cross the ellipses at several locations. Combined with the sulfate deposits, they reveal fluvial activity mostly at the end of the deposition of the entire clay-rich unit. In addition to the large clay unit, several mineralized light-toned fractures/veins indicate another or several other episodes of interaction between the rocks and fluids flowing through the veins, after the formation of the main part of the clay unit. The clays are capped by a regionally-extensive dark mesa-forming unit that exhibits unaltered mineral (pyroxene, plagioclase) spectral signatures. From crater counts, the cap rock is 3.7 Gy old (Early Hesperian) and has play a major role for preservation of the clay-rich deposits.

The Mawrth Vallis site would therefore enable:
(1) investigation of some of the most ancient outcrops of sedimentary and clay-bearing rocks on Mars;
(2) investigation of rocks with one of the greatest mineral diversities of Mars. Because phyllosilicates are strong indicators of ancient aqueous activity, and the preservation potential of

biosignatures within sedimentary clay deposits is high, martian phyllosilicate deposits are desirable astrobiological targets;

(3) sampling and analysis materials from the mineralized veins and fractures of possible low-T hydrothermal origin. These features will enable access to an additional environment that could have been favourable for the development of past life;

(4) investigation of fluvial activities. Small regional mineral variations (sulfates) possibly due to localized processes (e.g. ponds, evaporates) are also indicator of wet, poorly drained conditions at the top of the layered unit.

Table 2. Summary of hydrated and unaltered minerals at Mawrth Vallis.

Mineralogy at Mawrth Vallis region
Fe^{3+}/Mg smectites
Fe^{2+}/Mg-clays
Hydrated silica
Ferrous micas (celadonite)
Ferrihydrite/FeOx
Sulfates (bassanite, jarosite,alunite)
Zeolites
Allophane
Pyroxene
Plagioclase

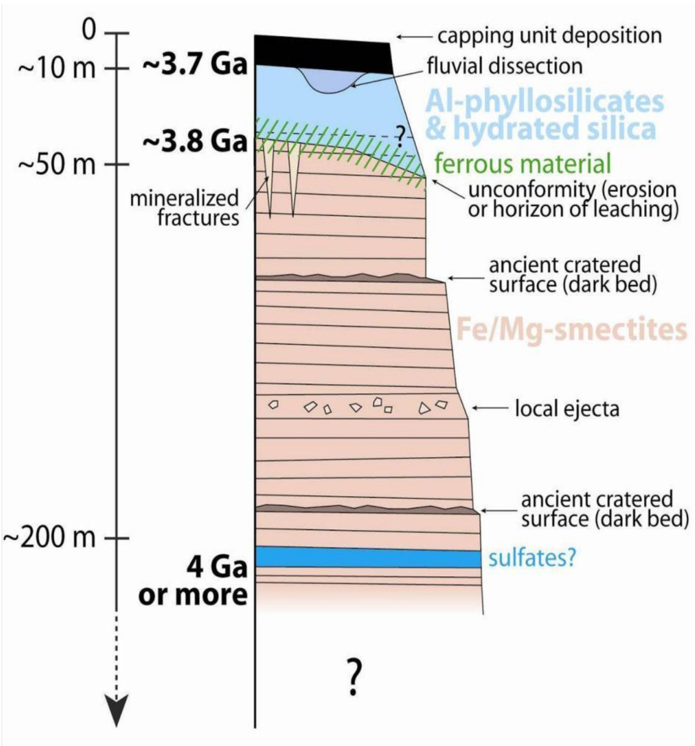


Figure 4. Schematic stratigraphic column of the main clay-bearing layered unit on the plateau around Mawrth Vallis channel (Loizeau et al. 2012). The thickness of individual layers is not drawn to scale. The total thickness of the layered unit is also unknown but reaches 200+ m at single outcrops on crater walls (Loizeau et al., 2010). Local sulfate deposits are also observed, with jarosite present at the very top of the sequence (Farrand et al. 2009), and bassanite identified in deeper layers (Wray et al. 2010). The Al–phyllosilicate zone in blue is sometimes seen to truncate the Fe/Mg-smectite zone in red (e.g. Loizeau et al., 2010). A ferrous suggesting redox change is found at the transition (green dashed zone). Some fluid circulation have mineralized some fractures going through the clay-rich layers after their deposition. All these major mineral phases/features of astrobiological interest are present inside the proposed landing site ellipse.

Below we present the major regions of interest that reveal different types of palaeoenvironments. Their possible formation as well as their potential in terms of habitability and presence of ancient life are described.

<u>Fe/Mg phyllosilicate-bearing layered deposits</u>

The clay-bearing units correspond to exposures of thick (>300 m), finely layered (layer thickness <<10 m) sedimentary rocks extending across a 300*300 km wide region. This unit is dominated by Fe/Mg smectites with local interbeds of sulfates. OMEGA and CRISM unmixing models suggest clay mineral abundances as high as 50 w.t% (the largest content on Mars). The Fe/Mg-smectites are possibly related to the global population of crustal Noachian Fe/Mg-smectites that are notably mapped around Chryse planitia.

The rocks are layered essentially everywhere they have been observed (see Figure 5 for an example inside the ellipse); and, within this layered section, they contain evidence for buried impact craters and folding or channeling (i.e., evidence for unconformities within the stratigraphic package). Therefore, these rocks were deposited over a duration of time rather than in a single catastrophic event.

The rocks are intact and relatively flat-lying. Although they have been buried to some depth and later exhumed, they have not been buried very deeply, nor have they been severely deformed by regional stresses, which is consistent with the absence of compositional diagenesis.

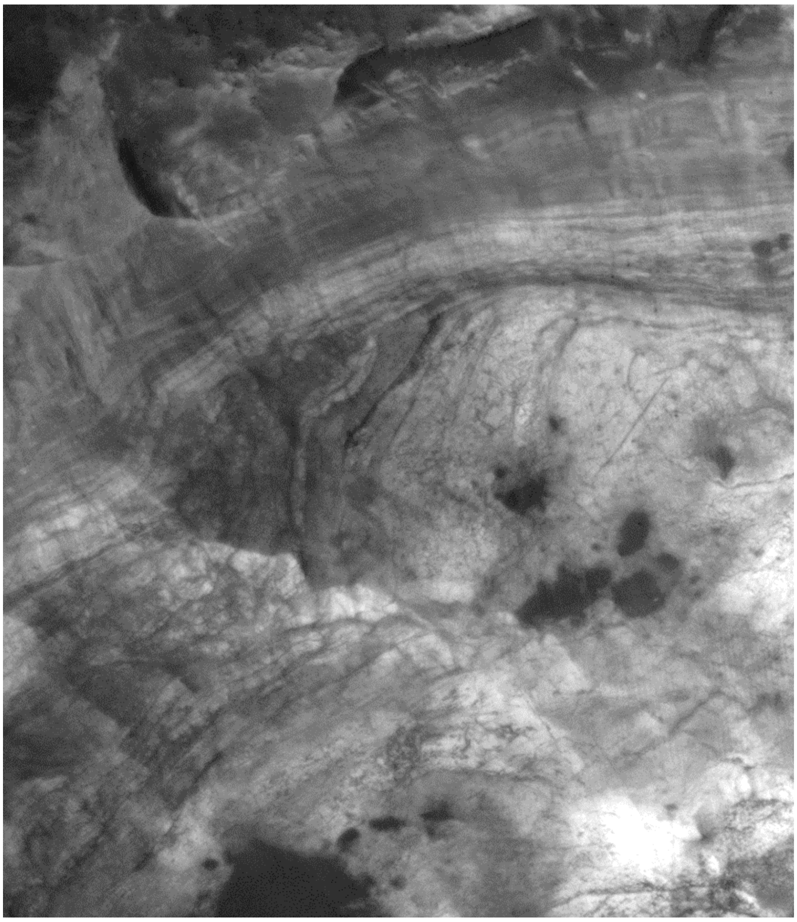


Figure 5. Example of clay-bearing layers inside AZ129 ellipse (2σ) (HiRISE image). The width of the image is about 350 m, and it corresponds to an eroded plain.

The formation of this expansive deposit would have required sustained water activity (sub-surface or surface). Alteration of basaltic rocks on Earth typically produces Fe-bearing dioctahedral

smectites such as montmorillonite and nontronite in high water/rock ratio environments with moderate silica activity (Velde, 1995 and Caillaud et al., 2006). The abundant Fe/Mg-smectite found on Mars in regions like Mawrth Vallis likely formed via aqueous alteration of mafic to ultramafic rocks (Chevrier et al., 2007 and Meunier et al., 2010). Fe/Mg-smectites are commonly formed in marine, lacustrine, and hydrothermal submarine environments on Earth and the different mineralogies formed in each of these environments can provide information about the geochemical formation environment (e.g. Chamley, 1989 and Velde, 1995). Fe-rich saponite (Fe/Mg-smectite) commonly forms in sediments derived from basaltic volcanic material (Desprairies et al., 1989 and Parthasarathy et al., 2003). More recently, synthetic nontronites were formed under hydrothermal conditions (150 °C, pH∼12) from both ferric chloride and ferrous chloride (Andrieux and Petit, 2010). Farmer et al. (1994) synthesized nontronite at 90 °C and found that reduced conditions during the early phase of synthesis produced better crystallized products. Decarreau et al. (2008) also used a ferrous starting gel to form synthetic nontronites and produced crystalline nontronites at temperatures over the range 75–150 °C. Cuadros et al. (2011) analyzed natural Fe-rich smectites formed under low-temperature submarine hydrothermal conditions via slow reaction of Fe^{3+} hydroxides, detrital silicates and silica. This study indicates that poorly crystalline Fe-rich smectites containing Al and/or Mn as well as Fe in octahedral sites could form via this mechanism.

Abundant Fe^{3+}-bearing nontronite forms in dysoxic and anoxic regions in the ocean on Earth where oxygen is depleted due to reaction with Fe^{2+} released into solution from basaltic rocks (Bischoff, 1972 and Arrhenius, 1986). Further, smectites are well-known as the dominant clay mineral forming in deep-sea environments where volcanic activity is prevalent (e.g. Odin, 1986). Once the nontronite forms, some oxidation is necessary to produce Fe^{3+} and stabilize the nontronite (Lonsdale et al., 1980). The oxygen-poor atmosphere on the early Earth, similar to past and present Mars, supported formation of Fe-rich smectites such as nontronite from basaltic-composition material in sedimentary environments (Harder, 1988). Thermodynamic considerations support formation of smectites on Mars only if liquid water was present; solid or vapor phase H_2O could not have supported formation of smectites (Gooding, 1978). The silica content in solution is also important for Fe-smectite formation, such that lower Si/Fe ratios give hydroxides and only poorly crystalline nontronite, while higher Si/Fe ratios produce only amorphous products (Harder, 1976).

The origin of the Fe/Mg phyllosilicate layering will be thus evaluated by in situ observations since the orbital facies as seen from the orbit does not allow a definitive interpretation. The possible and favoured formation mechanisms based on orbital observations that will be tested by Exomars are: 1- Clay deposits in sedimentary basin as primarily chemical weathering produces mineral assemblage similar to the observations (smectites and mica-celadonite). We would expect strong connection between clays and rocks at basin if this scenario is the right one. 2- In situ aqueous alteration of basaltic ash-fall. This scenario implies open body of water and/or subsurface aquifers and seeps. 3- The patchy distribution and correlation with topographic lows of the ferrous unit could support the interpretation that this unit represents soils that were poorly drained and altered to ferrous mica upon burial. Furthermore, the decrease in ferrous absorptions with stratigraphic position in unit also supports increasing crystallinity of this unit through time and therefore also increasing humidity through time.

By contrast, aqueous transport of sediments or impact ejecta is unlikely as these deposits was deposited over a period of time, so a single event or even several large impact events cannot explain the origin of the whole section of rocks. Also primarily physical weathering produces illites and siliceous sediments, which are not observed. If the alteration occurred due to some localized hydrothermal phenomenon (e.g., associated with an igneous intrusion or impact structure), we would expect to see alteration products tied to fluid conduits, such as faults and fractures, and we would not expect to see such a widespread and consistent distribution of alteration minerals through a large area within flat-lying units. A strictly hydrothermal interpretation for the origin of the mass of altered, layered rocks can be thus eliminated, although the occurrence of a late-stage

and localized hydrothermal event associated with these light-toned mineralized fractures/veins is likely (see section "Veins/fractures").

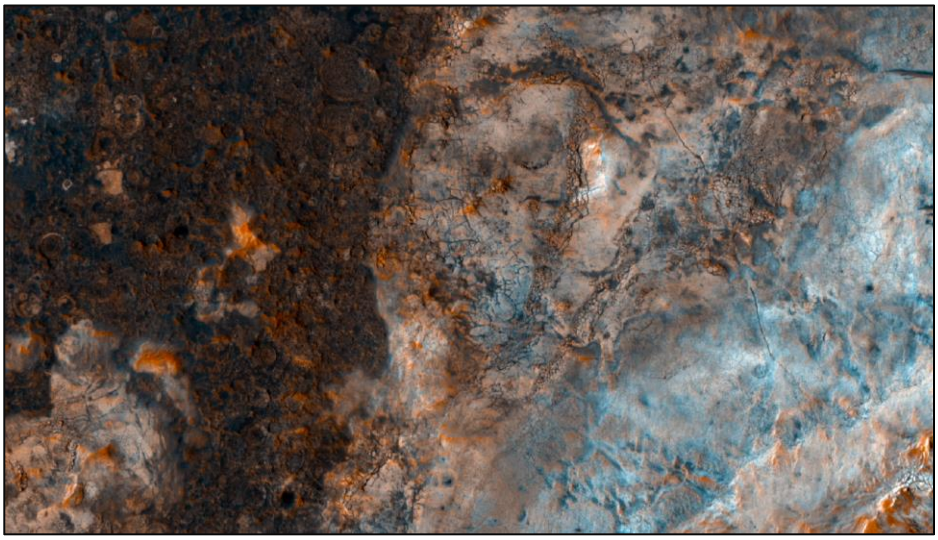


Figure 6. Part of HiRISE image (inside 3σ ellipse) showing the transition from lower Fe/Mg-clays unit (reddish and rugged, left) to upper Al/Si-OH phases unit (blueish and smoother, right).

<u>Al/Si hydrated phases and ferrous phases</u>

Al-rich clays, grading from Al-smectite and silica into kaolinite and possibly allophane, dominate the top 10-30m of the section (Fig. 4). As shown on Figure 6, the textures of the clay-rich outcrops (from rugged and eroded texture to smoother surface, meter-scale polygonal cracks) are pretty diverse indicating different types of lithologies that capture multiple environments and variation of deposition with time. The Al-clays are interpreted to have formed during sub-aerial weathering (pedogenic leaching, see below). Significant mineralogical variability as well as features interpreted as inverted channels suggest that this section also supported aqueous environments. The kaolinite is concentrated near the top of the section, and may either have been formed due to (a) localized acid leaching in a wetlands environment, (b) regional or global acid surface leaching, (c) long term, more neutral leaching (a laterite). Possible alunite detections at the top of the section support either scenario (a) or (b). Strong spectral signatures consistent with Fe^{2+}-bearing phyllosilicates associated with the kaolinite may support reducing, poorly drained conditions, but the spectral signature is non-unique. A ferrous phase is also present at the transition between the Fe^{3+}/Mg-smectite and the upper Al/Si-rich unit (Fig. 4). This ferrous phase cannot be uniquely constrained, but is likely due to reduction of some of the Fe^{3+} in the nontronite or formation of another Fe^{2+} phase at the boundary of the major phyllosilicate units.

Subsequent aqueous alteration and leaching of Fe and Mg from the smectite or ash precursor material could have produced amorphous hydrated Al/Si-rich phases, Al-smectite, Al/Mg-rich mica, and kaolin-group minerals. Alternatively, a change in the aqueous chemistry (e.g., hydrothermal activity or more acidic conditions) or a change to a less basaltic (more Si-rich) volcanic material or sediment precursor material could have produced the Al/Si-rich upper clay unit. Another possible scenario is alteration of interbedded source rocks with different chemistries, resulting in changing alteration profiles from Fe/Mg-smectites in more mafic to ultramafic lower rocks to more Si-rich upper rocks. However, there are several lines of evidence that syn-depositional surface alteration (pedogenesis) to form a sequence of preserved soil profiles (paleosols) is supported rather than post-depositional leaching to form a deep weathering profile (Horgan et al. 2016). The Mawrth Vallis deposits exhibit lateral and vertical diversity beyond the overall Fe/Mg-smectite-Al/Si-phase trend, as demonstrated by the heterogeneous distribution of units and the presence of isolated color units.

This diversity is inconsistent with a deep weathering profile, but consistent with paleosols, which exhibit diversity in composition and color on the meter scale. Finally, relic fluvial landforms are present throughout the units. In the context of pedogenesis on Earth, the overall trend from smectites to Al-Si phases at Mawrth Vallis would indicate an increasingly humid climate through time. The Al-Si phases in unit appear to increase somewhat in crystallinity and iron oxide content with position in the stratigraphy, consistent with a general maturation trend of allophane/halloysite-kaolinite/hematite in a sub-humid to humid climate.

<u>Fluvial activities and ponding events</u>

Fluvial erosion (ancient valleys) is visible on many outcrops on the region's plateau. Numerous km-long to tens-of-km-long fluvial valleys incise the surface of the clay-bearing unit, generally indicating ancient flows towards Mawrth Vallis (or a former valley pre-existent to the outflow channel) and towards craters south of the ellipses (some are indicated in Figures 2 & 3). They are all more or less filled by the dark capping unit. Many of them are strongly eroded and often appear as inverted relief in other locations of the region outside the ellipses (Loizeau et al., 2007, Mangold et al., 2010). This actually supports earlier fluvial activity possibly during the layers' deposition period. We also observe a large ponding geological feature in the eastern part of the landing site (Figure 7). This zone is covered by capping unit material so that the access of the floor may not be accessible, but the age of the alteration and its relationships with the fluvial activity will be a fundamental aspect to be studied with ExoMars for estimating the timing of aqueous activity and duration of the habitability in this region, and on Mars. However, the largest likelihood of ponding environment that should easily accessible with the rover occurred in the Al-clay unit. Indeed, the presence of hydrated, poorly crystalline materials sometimes associated with sulfates at the top of the stratigraphic column likely marks a change in climate or aqueous environment. A scenario explaining the observed mineralogy would involve ponding of water up in localized areas in the strata containing Al-phyllosilicates.

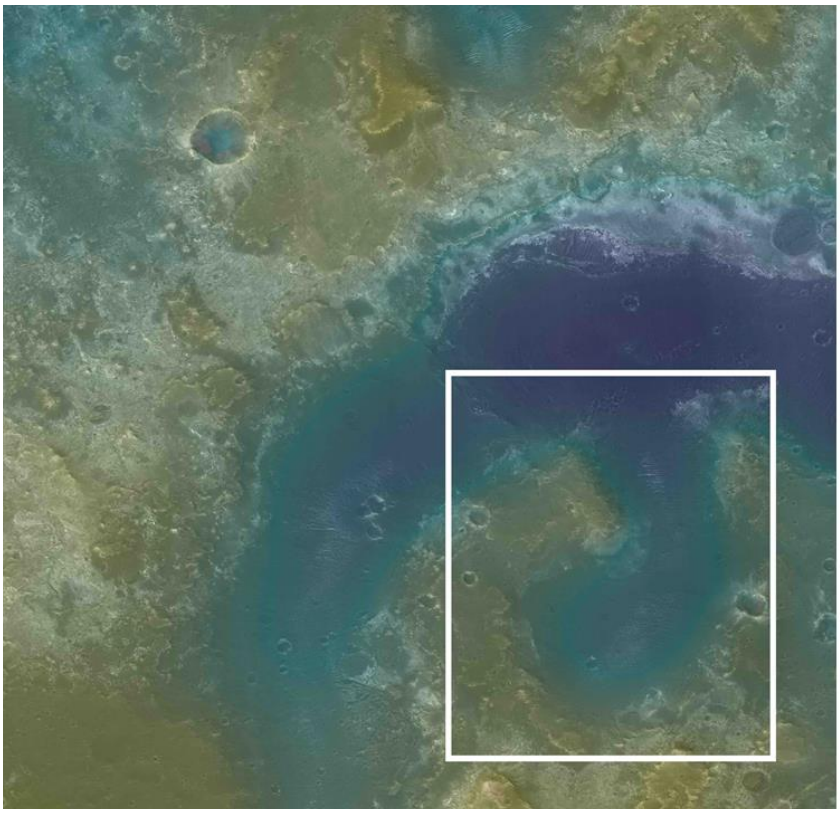


Figure 7. Pool located in the eastern part of the ellipse (3σ AZ102). The pond width is ~1.1 km.

Veins/fractures

Some portions of the Fe/Mg-unit exhibit large resistant filled fractures and numerous veins (Figures 2, 3 & 8a). These features were mapped from strips of HiRISE color images so there is much more than it is shown on Figures 2 and 3. These structures are typically spaced by about a few 10s m. Their size is several meters, and some can reach 10 m. We interpret these features as the result of fluids circulating inside fractures in the subsurface of the plateau. They precipitated minerals and indurated material inside fractures and in the rocks close to the fractures through circulation in the porous space of the rocks, forming light-toned veins/fractures. The same observation has been made in another part of the MV region (Loizeau et al., 2012) and elsewhere on Mars (Okubo and McEwen, 2007). The densest set of veins is observed on the flank of Mawrth Vallis, in deeper layers. This may be explained by the presence of an ancient aquifer circulating at this level in the ancient subsurface. This indicates that fluid circulation was still happening, at least in the subsurface, after the formation of the fractures, thus well after the cementation of the layers. Although most of these veins are found in the clay-rich deposits, some are found related to crater rims of a few km size and thus likely impact-induced hydrothermal veins (Figure 8b).

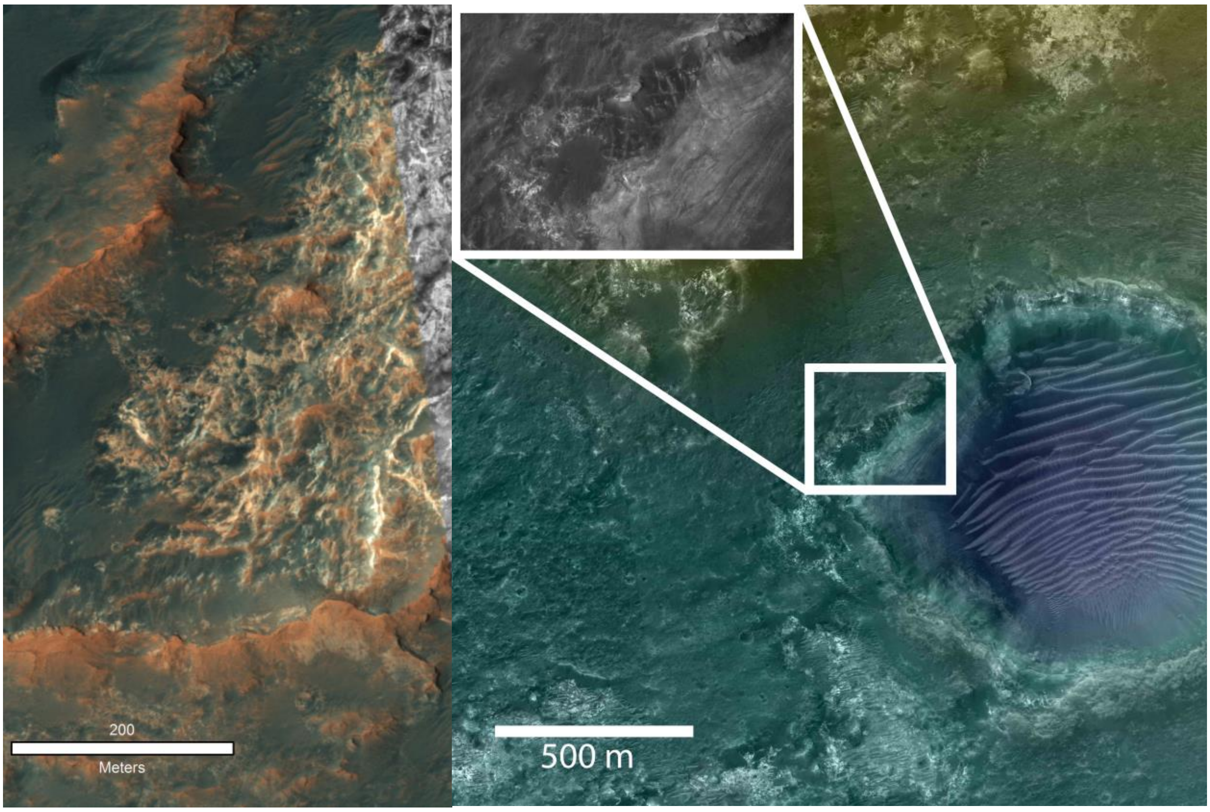


Figure 8. (a-left) HiRISE example of mineralized fractures/veins found in the clay-rich outcrops inside the 2σ AZ102 ellipse. (b-right) Example of fractures associated to the rim of a crater (inside the 1σ AZ129 ellipse) likely induced by the impact.

Habitable and biological potential of the landing site: phyllosilicate-bearing rocks as reactants for pre-biotic chemistry

On Mars, phyllosilicate-rich rocks are ideal targets in which to search for evidence of prebiotic chemistry and evidence of life. The extensive clay deposit at Mawrth Vallis in particular (Poulet et al., 2005; Loizeau et al., 2007; Bishop et al., 2008) implies a large, stable aqueous system. Fe-bearing phyllosilicates such as nontronite, Fe-rich montmorillonite, and glauconite/illite form preferentially in anoxic waters (Harder, 1988) such as those characteristic of conditions on early Earth (Kasting and Howard, 2006) and possibly early Mars. The changing redox conditions and the mildly acidic environment associated with hydrated silica and kaolinite outcrops (versus the Fe/Mg-smectite-

bearing rocks) suggest active chemistry on early Mars (Bishop et al., 2008). A change in iron in the phyllosilicate units is also observed such that an Fe^{2+}-bearing unit is frequently observed between the Fe^{3+}- and Mg-rich phyllosilicates below and the Al/Si-rich materials above (Bishop et al., 2012). Abrupt changes in chemistry like this are often indicative of biogeochemical activity on Earth. Phyllosilicates can catalyze chemical reactions due to their surface acidity and by bringing together molecules on their surfaces (Pinnavaia, 1983). One of them, montmorillonite, has been found to catalyze a number of organic reactions, including the formation of oligomers of ribonucleic acid that contain monomer units from 2 to 30–50 (Nikalje et al., 2000; Ferris, 2006). Theng (1974) reviewed the adsorptive and catalytic interactions of organic molecules on clay surfaces. The particular features of clay chemistry that govern these reactions include the local acidity of clay surfaces, shape specificity of reaction sites, motion restriction on water molecules, and the binding properties of specific cations (Pinnavaia and Mortland, 1986).

What happened in the intermediate strata between Fe/Mg smectite and Al-smectites is also interesting with regard to potential habitability conditions. One model under consideration here is that the nontronite unit formed a hard, resistant and non-porous surface. If this occurred then the sediments deposited on top of the nontronite could have been altered in one or more long-term and wide-spread aqueous events that produced extensive leaching and alteration near the surface and formed kaolinite/halloysite and other Al- and Si-rich clays. The Fe^{2+} and K leached out of the ash/sediments could have been trapped at the impermeable nontronite border and redeposited to form ferrous mica. Another possibility is that under long-term exposure to aqueous conditions smectites can convert to Fe^{2+}-phyllosilicates such as glauconite or stevensite if microbial activity or organic compounds provide a reducing environment, if wet/dry cycling occurs, or in the presence of abundant iron or high salinity (Chamley, 1989 and Nagy, 1995).

Habitable and biological potential of the landing site: Clay interactions with microbes

In order to sustain life an environment must provide essential nutrients, biologically accessible energy and liquid water (Nealson, 1997). Studies of terrestrial marine basalts with chemical compositions consistent with Mars (McSween et al., 2009) have shown that these rocks contain sufficient requirements (e.g. nutrients, water, radiation protection) to sustain life (Fisk et al., 1998). Other studies have shown that microbes may even be facilitating palagonitization of basalt into clays and other altered phases (e.g. Alt and Mata, 2000, Konhauser et al., 2002 and Benzerara et al., 2005). Microbial weathering of Fe-rich phyllosilicates has also been observed (Sanz-Montero et al., 2009).

Experiments with soil bacteria and viruses have shown that they can survive in a variety of soil and clay environments including temperature and moisture extremes replicating Martian conditions (Hawrylewicz et al., 1962, Foster et al., 1978 and Moll and Vestal, 1992). Elevated growth rates of microbes were noted for a neutral montmorillonite system relative to an acidic one (pH 3.6–4.0) with synthetic Fe^{3+}-exchanged montmorillonite (Moll and Vestal, 1992). Organic molecules and metal hydroxides present in smectite interlayer regions and adsorbed on grain surfaces may have provided nutrients for these microbes.

Habitable and biological potential of the landing site: Preservation

Preservation of biosignatures is favored in rapid burial conditions in fine-grained, clay-rich systems or by chemical precipitation of clay minerals and silica in void space (Farmer and Des Marais, 1999). At present, it is unclear whether the thick (~300 m) stratigraphic package of layered rocks in this region represents rapid deposition. However, the thick section of rocks implies either an extremely long-lived aqueous system or rapid deposition over a shorter period. On Earth, long-term preservation is most successful in host rocks composed of stable minerals that are resistant to

weathering and provide an impermeable barrier for the biosignatures. Mineral precipitates such as phyllosilicates and silica provide an excellent matrix for fossilization of microbial biosignatures (Farmer and Des Marais, 1999). Possible biosignatures include cell-shaped objects, remnants of biomolecules or microorganisms in fluid inclusions, the presence of polycyclic aromatic hydrocarbons, and biogenic mineral structures or compositions (Des Marais and Walter, 1999; Farmer and Des Marais, 1999; Cady et al., 2003; Westall, 2008).

We cannot exclude that in some places phyllosilicate materials were locally mobilized and redeposited. However, the perseverance of smectite clay minerals in this region for billions of years implies that, subsequent to the minerals' formation, their interaction with water has been extremely limited (in terms of cumulative effects of water/rock ratio, heat, and time) (Tosca and Knoll, 2009). Unlike on Earth, where sediments inevitably become diagenetically altered at the scales of hundreds of millions of years, the lack of diagenetic maturity at Mawrth Vallis implies that the original chemical, mineralogical, and textural properties of the rocks are likely to reflect ancient conditions during the time period in which they formed. This is immensely important in terms of preservation potential; the rocks in the Mawrth Vallis region likely have preserved evidence of surface processes, organic or inorganic, that occurred during the ancient epoch recorded in the rocks. Compared to other martian phyllosilicate deposits, the Mawrth Vallis rocks offer some advantages in terms of accessibility to preserved material. Some martian phyllosilicate deposits are found within geomorphic settings that are clearly linked to aqueous processes. For example, phyllosilicates within well-preserved delta deposits (Ehlmann et al., 2008; Grant et al., 2008) or putative lacustrine environments (Milliken et al., 2010a) are enticing astrobiological targets. However, these settings may not represent sustained aqueous activity over geologically significant timescales. Furthermore, access to the largest volume of the deposit is limited. In the case of a preserved delta, a surface rover can only access the edges of the deposit. For the Mawrth Vallis area, we have a more complete mineralogical picture of the aqueous history because of the stratigraphy; multiple aqueous mineral assemblages are observed throughout the exposed stratigraphic section. On Earth, paleoenvironments are understood not through studies of preserved paleogeomorphology but through the analysis of good exposures of eroded and tectonically dismembered stratigraphic sections. The clays were capped by a regionally-extensive mafic dark mesa-forming unit that helps in preserving the clays and morphologic features. Because the terrain around Mawrth Vallis is eroded, Exomars will have access to many well-preserved exposures that represent environments recorded throughout the volume of the deposit. One of the numerous examples is shown on Fig. 9.

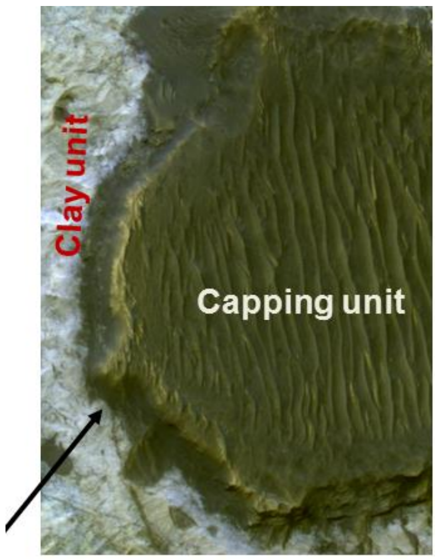


Figure 9. The material that was buried below the dark cap unit (arrow) and only recently exhumed is of great interest in terms of preservation index.

Probability of reaching high priority targets

We combine the figure of probability (Figures 2 and 3) with the four major high priority targets described previously (Fe/Mg-rich outcrops, Al/Si-OH-rich outcrops, veins, fluvial activities) to calculate the probability of being able to reach them after landing. As recommended we assume a drive of 1 km, 3 km, and 5 km. Five ellipses were considered, but note that their centre was not optimized to increase the probabilities. We separate the probability for the two major types of clays. Not surprisingly their derived probability is similar as both major clay units are mostly co-located.

Table 3. Probabilities to reach the four major targets assuming a drive of 1, 3 and 5 km. Colour code: 0 to 0.3: red; 0.3 to 0.6: orange, 0.6 to 1: green. The probability for both types of clays are based on CRISM identification except for one case (albedo HRSC-based probability). The probability for the veins are clearly underestimated as these features are identified only with HiRISE colour strips that provide a very limited partial spatial coverage of the region.

Ellipse AZ	102.000	108.750	115.500	122.250	129.000
Ellipse Centre Longitude	-18.309192	-18.309192	-18.309192	-18.309192	-18.309192
Ellipse Centre Latitude	22.214021	22.214021	22.214021	22.214021	22.214021
P(Clay-1km) HRSC-based	0.906834	0.905768	0.900504	0.889991	0.893108
P(FeMgClay-1km)	0.541695	0.515600	0.503200	0.507832	0.544047
P(FeMgClay-3km)	0.919257	0.918669	0.919487	0.926130	0.938991
P(FeMgClay-5km)	0.977736	0.978214	0.981917	0.987144	0.989376
P(AlSi-phases-1km)	0.501412	0.471241	0.459562	0.475071	0.515263
P(AlSi-phases-3km)	0.895002	0.892141	0.897342	0.910696	0.928053
P(AlSi-phases-5km)	0.965588	0.961139	0.966240	0.975520	0.984060
P(Veins-1km)	0.126173	0.127313	0.126957	0.123672	0.123229
P(Veins-3km)	0.420372	0.409612	0.397513	0.380819	0.373988
P(Veins-5km)	0.618711	0.608979	0.599803	0.589005	0.580903
P(Valleys_1km)	0.149889	0.162547	0.193315	0.232470	0.243981
P(Valleys_3km)	0.329514	0.371912	0.457193	0.551233	0.591013
P(Valleys_5km)	0.525352	0.600542	0.717380	0.817315	0.862663

Several hazards were reported by the project (mostly TARs, slopes) and could impact the derived probability and the accessibility of the high priority targets. However, the probability regarding to the clays are based on the CRISM detection. As in situ investigations increase the likelihood to detect clays (as demonstrated by the Curiosity mission), it means that the probability values correspond to lower limit. Another aspect is the numerous small windows of the clay-bearing outcrops inside the capping unit, which are visible on HR images (see one example on Figure 10). The reported probability calculation is here performed assuming the capping unit as a blind zone with no clays. But if Exomars lands on the capping unit, there is a great chance to be able to investigate clay-bearing outcrops within small distances (<1 km). We therefore decided to estimate the probability by using clay detection from the HRSC albedo as light-toned deposits can be considered as clays in the MV region (see Table 3). In this case, the probability increases a lot (from about 0.55 based on CRISM identification to >0.9 for 1 km traverse, see line "*P(Clay-1km) HRSC-based*" in Table 3) as expected.

The valleys are very large structures so that we consider the hazards shall have a minor impact on the derived probabilities. However, we cannot exclude that some parts (especially rims) of these features could be hard to reach. The veins/fractures are visible and were mapped with HiRISE

images only. As the HiRISE coverage of the region is partial only, the number of fractures and threfor the derived probability values are thus clearly underestimated. We actually estimate that the real probability should be similar to the values derived for clay-bearing outcrops as the veins are frequently associated with these outcrops. There are in general easily accessible, while sand dunes could be problematic to reach some of them and/or their center.

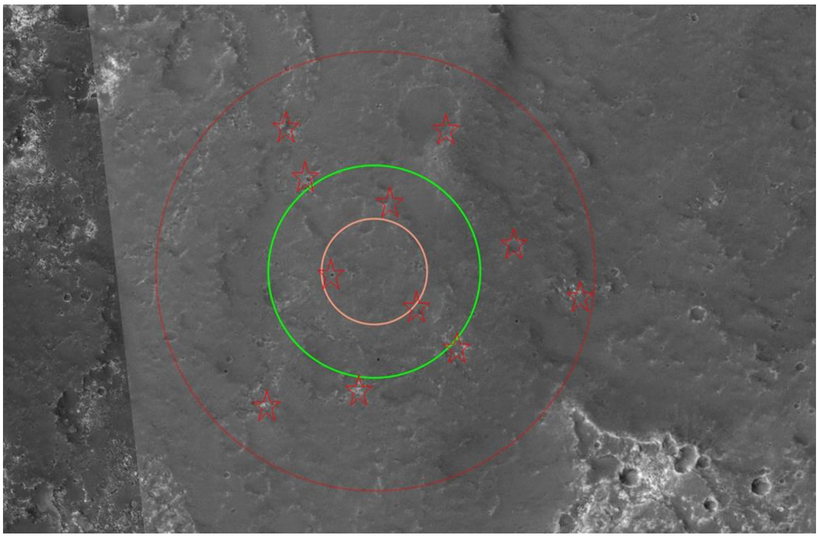


Figure 10. Farthest point from clay-bearing unit inside 3σ ellipses. No phyllosilicate is detected by CRISM and OMEGA but the presence of light-toned outcrops and small craters are identified with CTX and HiRISE images (spots identified by red stars). The circles have diameter of 1, 2 and 4 km.

2. TERRAIN AND HAZARDS

Elevation

Figure 11 illustrates the position of the three ellipses (see Table 1) over MOLA elevation map. As already mentioned, ellipses are slightly above the -2 km for high azimuths and to the extreme ends of the ellipse pattern. P. Fawdon et al. report an average percentage area of 5.7% above -2 km. If altitude limit <-2 km is a mandatory limitation, then the highest azimuth ellipses need to be shifted to the north-west to safer terrains (white ellipse on Figure 11).

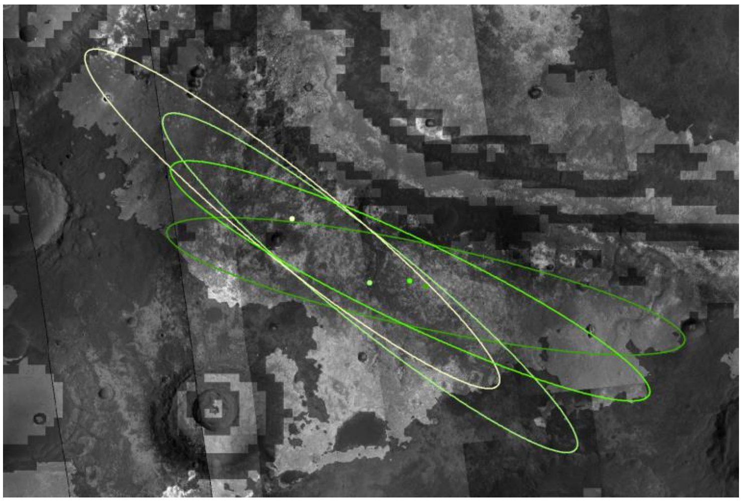


Figure 11. Ellipses as defined in Table 1 over MOLA elevation. Elevation above -2 km are shaded black. White ellipse is an alternate maximum azimuth ellipse position if the elevation is a mandatory constraint.

Slopes

We invited the LSWG members to read the report “SLOPE_REPORT_2017_03_09_v1”by Fawdon et al. regarding to this aspect as we did not have the time and resources to perform such analyses.

Crater density and distribution

We identify crater with diameter D > 100 m over a significant area of the landing site region from CTX mosaic (Fig. 12). The crater density exhibits minor variations with local increasing values in the eastern part. This could be due to secondary craters coming from larger impacts. We also confirm several previous studies that there is a higher density for the capping unit than for the clay-bearing outcrops due to quick erosion of the soft clay-rich unit.

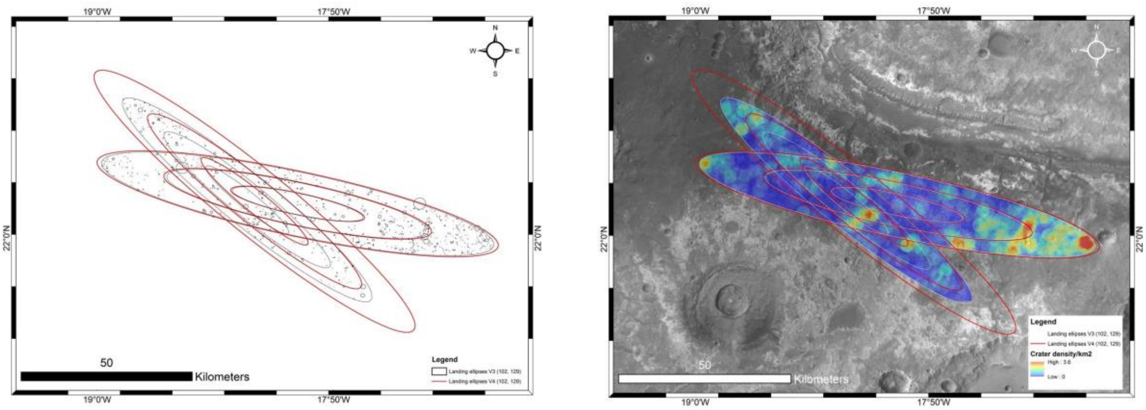
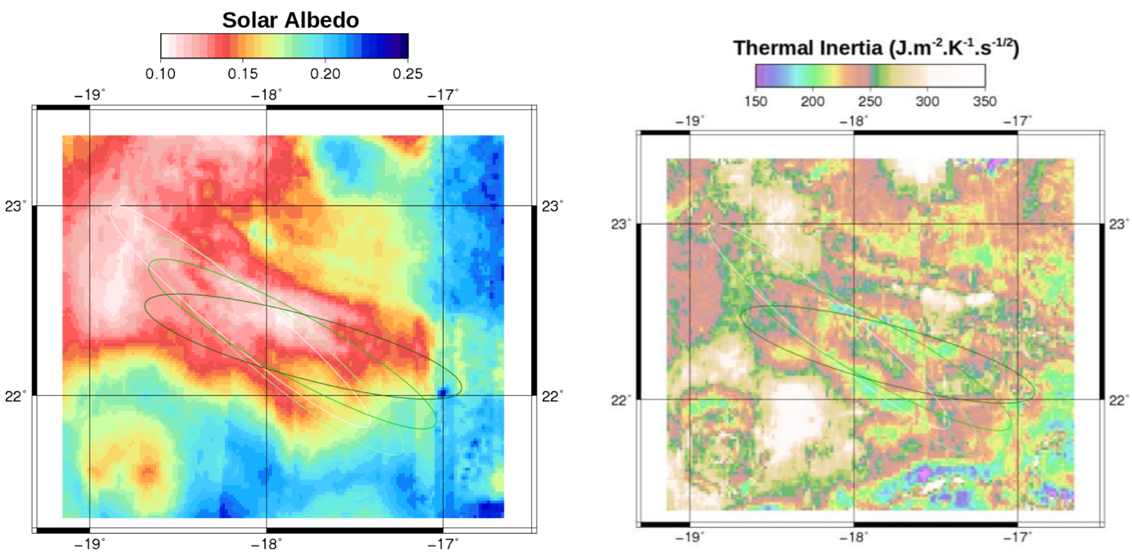


Figure 12. (left) Locations of the craters with diameter D > 100 m in the landing site region roughly delimited by ellipses AZ102 and AZ129. (right) Crater density.

Albedo, Thermal inertia, Dust

We performed these analyses using new solar albedo and thermal inertia maps (Audouard et al. 2017) (Figure 13). None pixel at 60 ppd is lower than 0.1. The lower value found for the set of four ellipses is 0.104. The lower value for the thermal inertia is 175 (SI). This is in good agreement with the LSSWG results reported in the summary table of Bridges et al. (2007).



Rock Abundance

For this aspect, we rely on the work performed by the LSSWG.

				F_k (D) fit (%)		
Site	Total area (km²)	Number of features	Number of rocks (1.5≤D<2.25 m)	D ≥ 0 m	D ≥ 0.18 m	D ≥ 0.35 m
Aram	7.00	12951	1923	17.6	10.9	6.9
Oxia	5.00	2122	590	13.8	8.2	5.0
Mawrth	2.50	2713	242	12.2	7.1	4.2

Figure 1: [from Bridges et al. 2017] Cumulative areal percentage occupied by shadow-casting features manually counted in selected areas inside 3-sigma ellipses at ExoMars Rover candidate landing sites. Diameter is constrained 1.5 ≤ D ≤ 2.25 m, where the signal from float rocks is highest (Golombek et al., 2012).

It is likely that the percentages reported in this table partly include sloping terrains. Manual inspection of the HR images indicates the quasi-absence of float rocks in the clay-bearing deposits and only very few in the capping unit.

The thermal inertia is not influenced by the rocks so that the large values (>200 SI) found for the site is a good indicator of the thermo-physical properties of the soils, namely outcrops for clay-bearing and consolidated pyroclastic mafic material for the capping unit.

The LSSWG has led studies on loose deposits (TARs and flatbeds) and on rock abundance at the three candidate landing sites. The major results of the studies are summarised in Bridges et al. 2017 LPSC #2378, *Selection and Characterisation of the ExoMars 2020 Rover Landing Sites*. A summary table can be found hereafter, as well as a further note about loose soils based on a parallel study at U. Lyon. Please tell us if you agree or disagree with any point in these results, in particular with the distribution and density of TARs, sub-TAR scale bedforms, dust coverage, loose soil, or other aeolian features, highlighting any areas likely to pose problems for rover mobility.

We did not have the time and resources to perform such analyses so we rely on these studies. Our only concern regards to the fact that these numbers are based on very limited mapping coverage, so that the percentage is possibly biased.

Table 1. ExoMars Landing Site Characteristics

	Oxia Planum	Aram Dorsum	Mawrth Vallis
Lat, Long	18.14 N, 335.76 E	7.869 N, 348.8 E	22.16 N, 342.05 E
Azimuth Range	100-125°	93-116°	102-129°
Semi-Major Axis	60 km	50 km	60 km
Elevation	100% <-2 km -3.6 km to -2.66 km	≥ 93% <-2 km -2.57 km to -1.88 km	≥ 89% <-2 km -3.02 km to -1.46 km
Slopes	**% Compliant**	**% Compliant**	**% Compliant**
2-10 km	> 99	>99	>98
330 m	98	99	98
7 m	94	95	88
2 m	95	95	92
Thermal Inertia	100% ≥150 J m^{-2} s$^{-0.5}$ K^{-1}	99% ≥150 J m^{-2} s$^{-0.5}$ K^{-1}	99.5% ≥150 J m^{-2} s$^{-0.5}$ K^{-1}
Albedo	100% 0.1 - 0.26	100% 0.1 - 0.26	100% 0.1 - 0.26
TAR Coverage	4.1 %	1.4 %	20.3 %
Rock Abundance (d≥18, 35 cm)	8.2, 5%	10.9, 6.9%	7.1, 4.2%

Loose soil estimates for discussion (see D. Loizeau presentation on LSSWG website, and LPSC abstract Loizeau et al. 2017 LPSC #1927):

These are based on preliminary HiRISE mapping at ~0.1% coverage of the ellipses, so the percentage coverage are possibly biased. Thickness estimates are very difficult and only made via the observation of filled or partially filled structures. We have differentiated thin dust/sand deposits, perhaps as thin as millimetres, and up to several cm, from thick dust/sand deposits (TARs, dunes and flatbeds) that are likely to be at least a few tens of cm in thickness.

According to this study:

1. *The surface of Mawrth Vallis is largely covered with thin and thick dust or sand deposits. A significant part is also occupied by bedrock. The remnants of the dark capping unit seem to produce the sand that feeds the sand bedforms.*

We agree with this study.

Conclusion on ExoMarwth

The table below summarizes the major properties of the landing site based on criteria proposed during the previous workshop. Generally speaking, Mars space exploration has demonstrated that Martian geology and environment evolved dramatically during the first few hundred million years. This is recorded in the mineralogical diversity placed in geomorphological context. Visiting Mawrth Vallis will enable exploring this critical Noachian time period. Marwth Vallis is packed with thick outcrops of phyllosilicates, a variety of other aqueous materials, mineralized veins/fractures and fluvial features. These very diverse mineralogical and geological characteristics shows multiple aqueous geochemical environments and processes (deposition, alteration, erosion, mineralization) through time and small regional variations due to localized processes (e.g. ponds, evaporates, mineralized veins). It is remarkable that Mars has uniquely recorded these sites with excellent preservation index. Investigating these rocks will be essential for determining if habitable sites were actually inhabited. Overarching goals of Exomars include characterizing potential habitable sites and searching for potential bio-relics. Visiting Mawrth Vallis will then enable investigating these likely habitable sites. Landing at Mawrth Vallis will also guarantee finding a full range of minerals and exciting geological features that will enable tracing the evolution of Mars' ancient environment and climate.

Property	Mawrth Vallis
Age span (Ga)	Early-Middle to early Hesperian
General nature of aqueous sediments	Sedimentary material requiring sustained water that capture multiple aqueous environment. End of stratigraphy likely ended by pedogenic process. Fluvial activities. Extremely diverse mineralogy (clays, sulfates, ferrous phases)
Duration of aqueous events	Various events over 400 Ma
What are the most interesting targets (their age in Ga)?	4.0+ Ga
How much of the ellipse is occupied by interesting targets?	>90% at 1 km drive
Are interesting targets small and far apart? Or distributed all over?	Distributed all over, land-on

Rock and mineral variety over short distances	**Very high for clay units**
What is not high priority targets, is it interesting?	**Provenance of cap rock unit but still interesting for past igneous processes of the planet**
Ponded water areas	**Yes, sulfate deposits and fluvial activities.**
Signatures of possible low-T hydrothermal systems	**Yes, numerous mineralized fractures/veins. Also induced-impact fractures in crater rims**
Biosignature preservation: Fine grain size	**Yes, soft, easy to drill. Many windows.**
Biosignature preservation: Rapid burial	**Yes due to sedimentary process and by capping unit deposition**
Biosignature preservation: Recent exhumation	**Yes. Most recent at foot of capping unit**

References

We included several references in the text but we did not have time to list them as for a peer-reviewed paper. We would be happy to provide any information if necessary before the workshop.