ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (xxxx) xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Investigating the Oxia Planum subsurface with the ExoMars rover and drill

Francesca Altieri[a,*], Alessandro Frigeri[a], Michèle Lavagna[b], Alice Le Gall[c]
Sergey Yuryevich Nikiforov[d], Carol Stoker[e], Valérie Ciarletti[c], Maria Cristina De Sanctis[a]
Jean-Luc Josset[f], Igor Mitrofanov[d], Elliot Sefton-Nash[g], Jorge L. Vago[g]

[a] *INAF/IAPS, Rome, Italy*
[b] *Politecnico di Milano, Milan, Italy*
[c] *LATMOS/IPSL, UVSQ Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt, France*
[d] *Space Research Institute of the Russian Academy of Sciences (IKI), Moscow, Russia*
[e] *NASA Ames Research Center Moffett Field, CA 94035, USA*
[f] *Space Exploration Institute, Neuchatel, Switzerland*
[g] *European Space Agency, Noordwijk, the Netherlands*

Received 1 July 2022; received in revised form 11 January 2023; accepted 20 January 2023

Abstract

To search for possible signs of life on Mars (past and present), it is necessary to investigate the subsurface. The thin martian atmosphere allows UV and ionizing radiation to damage potential chemical biosignatures at or below the surface. This effect, however, decreases with depth. Thus, organic molecules and potential biomarkers can be better preserved in the subsurface. The ExoMars Rosalind Franklin rover is equipped with a drill able to collect samples from a maximum depth of 2 m for the first time on Mars. In this study we describe how we will use the drill telemetry information in combination with the rover subsurface instruments' data to better assess the stratification, compositional variations and connection with surface morphology. Understanding the subsurface sample environment is crucial to inform the investigations to be conducted on samples within the rover's Analytical Laboratory Drawer (ALD). Moreover, the synergic use of drill telemetry and the rover subsurface instruments' outcomes will inform planning of drilling activities and improve the selection of drilling sites.

Keywords: Mars; Space mission; Subsurface; Composition; Stratigraphy

1. Introduction

Recent Mars orbiting and landed missions have advanced our understanding of the history and evolution of the planet. Several lines of evidence support the hypothesis that, in its very ancient history, Mars had a surface environment that was at least locally habitable (Mahaffy et al., 2015; Grotzinger et al., 2014). Answering the question of whether life could have ever developed on Mars is one of the main scientific goals of Martian exploration.

The martian atmosphere is very tenuous (roughly equivalent to Earth's at 30 km altitude). As a consequence, damaging ultraviolet (UV) light and ionizing radiation can reach the surface more or less unimpeded. Moreover, UV photochemistry produces aggressive oxidant species whose reactivity can vary depending on the local environmental conditions, *e.g.* heat and water availability (Quinn et al.,

* Corresponding author.
E-mail address: francesca.altieri@inaf.it (F. Altieri).

https://doi.org/10.1016/j.asr.2023.01.044

Please cite this article as: F. Altieri, A. Frigeri, M. Lavagna et al., Investigating the Oxia Planum subsurface with the ExoMars rover and drill, Advances in Space Research, https://doi.org/10.1016/j.asr.2023.01.044

2013; Lasne et al., 2016). Because the radiation dose decreases with depth (the overburden acts as a shield), organic molecules, including potential biosignatures, have a much better chance of surviving for very long periods if protected in the cold martian subsurface at sufficient depth (*e.g.* Vago, 2017; Kminek, 2006). When searching for possible indicators of past or present life on Mars, it is imperative to investigate the subsurface.

The scientific goals of the ExoMars Rosalind Franklin rover are to search for signs of life (past and present) and to determine how water and geochemistry vary with depth in the shallow subsurface (Vago et al., 2017). To do this, the rover is equipped with a drill with a maximum depth of 2 m and with a dedicated suite of instruments (Pasteur Payload, Vago et al., 2017 and references therein): PanCam (Panoramic Camera, a panoramic camera with two wide-angle cameras, WACs, and a high-resolution camera, HRC), CLUPI (Close - UP Imager), ISEM (Infrared Spectrometer for ExoMars, an infrared Spectrometer on the rover mast), WISDOM (Water Ice and Subsurface Deposit Observation On Mars, a ground-penetrating radar), ADRON-RM (Autonomous Detector of Radiation of Neutrons Onboard Rover at Mars, a neutron detector for determining subsurface hydration), Ma_MISS (Mars Multispectral Imager for Subsurface Studies, a miniaturized spectrometer integrated within the drill), MicrOmega (Micro Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activite, a Vis-IR imaging spectrometer for mineralogy studies), RLS (a Raman Laser Spectrometer), and MOMA (a Mars Organic Molecule Analyzer, with two operational modes: for Gas Chromatograph-Mass Spectrometry (GC–MS), and Laser Desorption -Mass Spectrometry, (LD-MS)).

The mission's landing site is in Oxia Planum, an ancient region of Mars at the transition between the Arabia Terra and Chryse Planitia Regions. Oxia Planum shows a strong potential for past habitability and for the preservation of physical and chemical biosignatures. It contains extensive Noachian clay-bearing units and layered outcrops (clear evidence of water/rocks interactions) (Carter et al., 2016; Quantin-Nataf et al., 2021; Mandon et al., 2021; Brossier et al., 2022) that will be accessible to the ExoMars rover. The clay-bearing deposits have been dated via crater chronology at ∼ 4.0 Ga, meaning they will be the oldest terrains investigated so far by a rover on Mars.

The rover drill (Figs. 1 and 2) is tasked with acquiring and delivering interesting samples to the Analytical Laboratory Drawer (ALD) instruments (RLS, MicrOmega and MOMA). To reach its maximum extension, the drill operates using several rods that are successively connected to reach depths up to 2 m. Vertical drilling speed depends greatly on the characteristics of the material being penetrated, and intuitively, progress is slower in harder materials. The mission has assumed a daily progress of about 50 cm. This means that drilling deep can take several sols. Therefore, drilling and the subsequent analysis of the sample can be considered a relatively "expensive" operation in terms of time and resources. For this reason, it is very important that the drilling sites be interesting and useful for achieving the mission objectives.

The location of where to drill and extract samples from will be carefully chosen based on the results obtained by several rover instruments (cameras, ground penetrating radar, etc.). While the drill is not designed to make scientific measurements, its telemetry (i.e. engineering data, sometimes also called housekeeping data) contains precious information that will help us to understand the subsurface terrain properties.

In this work we describe how we intend to combine the drill telemetry data with those from the rover instruments investigating the subsurface (ADRON-RM, CLUPI, Ma_MISS and WISDOM) to support the mission's subsurface scientific objectives.

2. ExoMars rover drill

The ExoMars rover is equipped with a rotary drill (without percussion capability) able to acquire samples at depths ranging between 0 and 2 m from multiple holes. The drill tool's diameter is 2.0 cm. The drill's sample chamber has a shutter mechanism for closing the front; this allows collecting small cores, fragments, or loose regolith. The extracted samples are typically 3 cm long by 1 cm in diameter. As a system, the drill includes the following main elements (Fig. 2):

1) The drill tool (70 cm long) is equipped with a sample acquisition device (including a shutter, movable piston, position, and temperature sensors) and the Ma_MISS instrument front elements (sapphire window, IR lamp, reflector, and optical fiber see also *Sec* 4). Ma_MISS measurements are made through the 8x4 mm sapphire window situated ∼ 22 cm above the drill tip (see also Fig. 2).
2) A set of three extension rods (50 cm each) to access the required penetration depth. They also contain optical and electrical contacts for the transmission of Ma_MISS signals to the spectrometer in the upper part of the drill box.
3) The rotation–translation group, comprising sliding carriage motors, guides, and sensors.
4) A backup drill tool, without a spectrometer.

When traveling, the drill box lies horizontally across the rover's front face, while it assumes a vertical stance for drilling; it is raised and rotated for delivering a sample to the analytical laboratory's inlet port (see Fig. 4 in Vago et al., 2017). The drill box's maneuverability is also used for orienting CLUPI observations (*Sec*. 4).

3. The scientific application of the ExoMars rover drill

The drill's performance will depend on the physical properties of the materials being investigated. Resistance

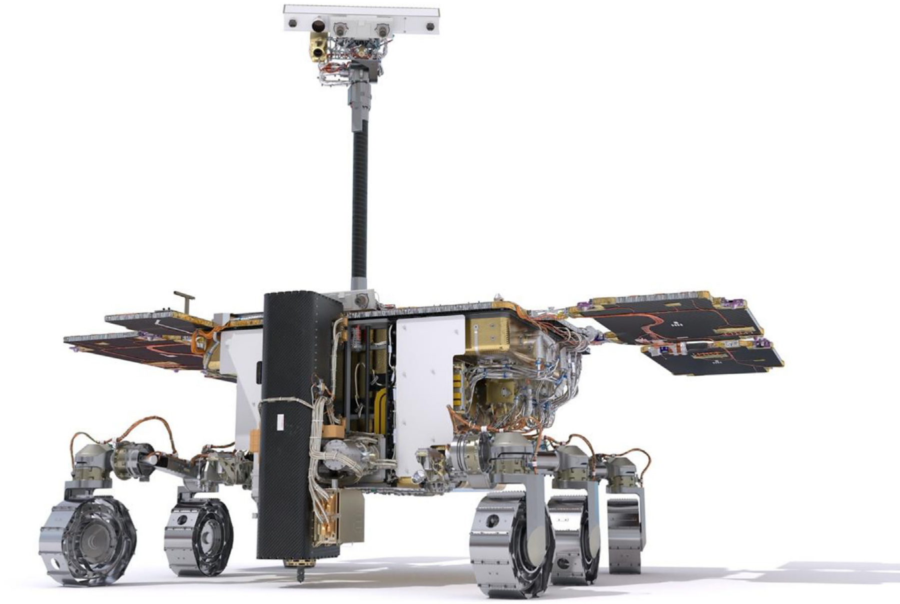

Fig. 1. View of ExoMars Rosalind Franklin rover with subsurface drill. Credits. ESA/Mlabspace. For a sketch of the rover showing the location of the drill and the nine Pasteur payload instruments refer to Fig. 5 in Vago et al., 2017.

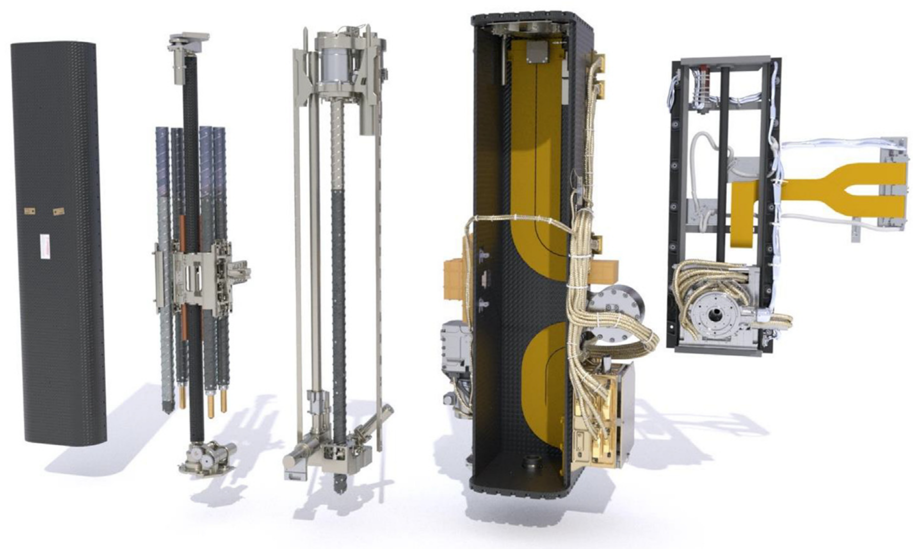

Fig. 2. From left to right. the drill box cover; the carrousel with three extension rods, plus a spare drill tool; the drill mandrel with its vertical traveling stage, depicted holding the main drill tool; the drill box with associated electronics (the CLUPI instrument can be seen on the lower left); and the drill attachment mechanism. Credits. ESA/Mlabspace.

to fracture is generally different from rock, to rock/soil, to soil according to their nature and composition. The physical properties of rocks/soils (*e.g.* hardness and fracture toughness) can be very different, depending on several factors, *e.g.,* mineral composition; porosity, shape, size-distribution and packing arrangement of mineral grains, the presence of natural cements in sedimentary rocks; the temperature and pressure of formation; and the volatile content. These characteristics collectively define a particular mechanical rock/terrain behavior.

Rosalind Franklin's drill needs to penetrate the rocks/terrains and, by removing the cuttings, create a borehole. The rate of penetration, rotational speed, as well as weight on bit and torque (WOB and T, see Fig. 3) required to make vertical progress are recorded as drill telemetry. These telemetry recordings will inform us about the mechanical behavior of rocks and terrains drilled at Oxia Planum, which, in turn, will provide insights into the litho-stratigraphic sequence at the landing site.

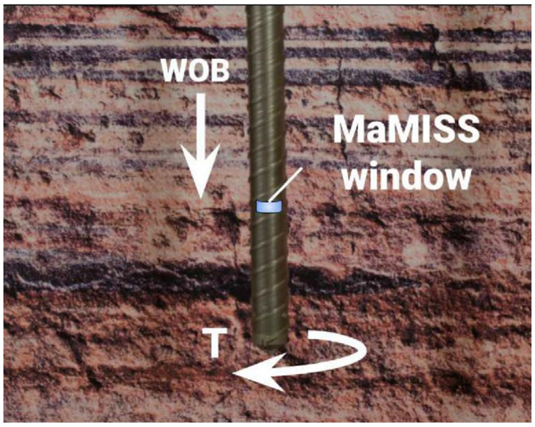

Fig. 3. Cross-section view of drilling into a sedimentary rock. The position of the Ma_MISS window is ~ 22 cm above the drill tip. The weight on bit (WOB) and torque (T) are among the most interesting parameters collected in the drill telemetry, providing information on the mechanical properties of rock layers. Modified from https://bit.ly/3bxe0M9 and Frigeri et al., (2021).

The mechanical behavior of some martian rocks has been studied by NASA's Mars Science Laboratory (MSL) at Gale crater, where sediments from fluvio-lacustrine environments are exposed. Their strength has been derived from surface imaging and spectroscopy (Kronyak et al., 2019), by investigating the mechanical damage of Curiosity wheels (Arvidson et al., 2017), and by using the Powder Acquisition Drill System (PADS). Engineering data collected by PADS has been used to retrieve the uniaxial compressive strengths of rocks at Gale Crater by means of the comparison with the performances of an identically assembled drill system used on terrestrial samples of comparable sedimentary class (Peters et al., 2018). Engineering data from the Mars Exploration Rovers (MERs) Rock Abrasion Tool (RAT) on Opportunity has been also used to infer Martian rock physical properties at Meridiani Planum. Results show that the investigated rocks have bulk properties similar to a range of terrestrial rocks from chalk to limestone (Myrick et. al., 2004). The ExoMars drill's response will extend these kinds of observations to the subsurface.

In 2011 preliminary tests were performed by the Italian drill manufacturer Leonardo with the Rosalind Franklin drill Engineering Model (EM) (Magnani et al., 2011). The set of materials used during the tests included samples of geyserite, claystone with high calcium content (HCC), claystone with low calcium content (LCC), gypsum, sandstone with high quartz content (HQC), sandstone with low quartz content (LQC) and loose sand. Our analysis of further tests performed on those samples in 2017 suggests that the information we can derive from drill telemetry can discriminate fairly well between different types of rocks (mudstones / sandstone / claystone). As an example Fig. 4 (from Frigeri et al. 2020; see also Frigeri et al., 2021) shows the use of drill telemetry from EM drilling of the samples described before. The graph indicates that although the dif-

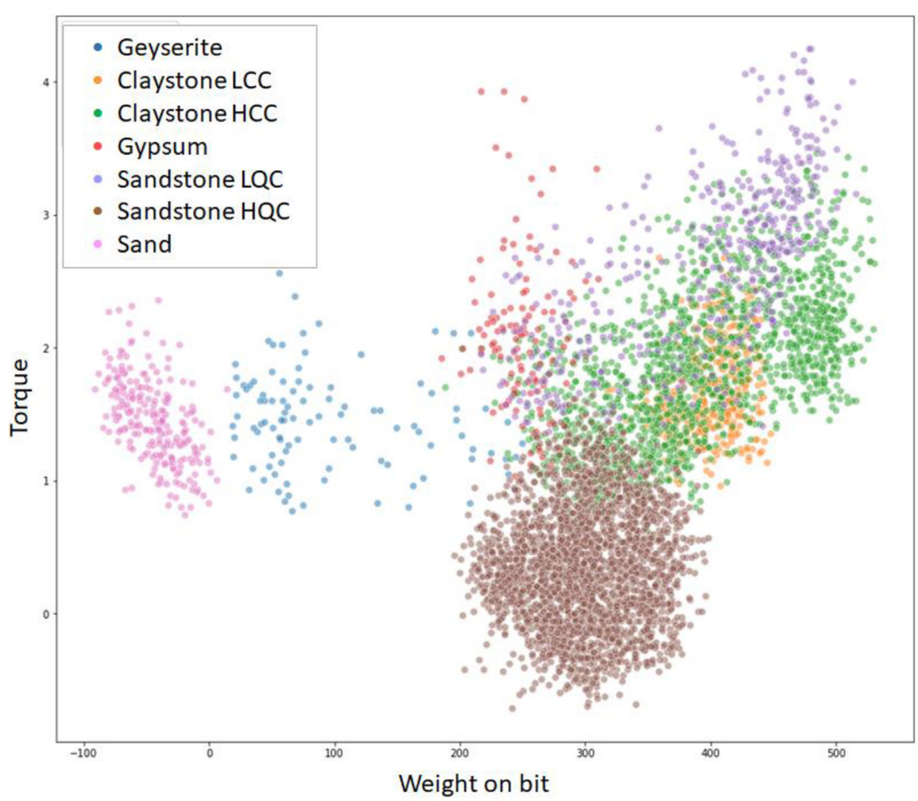

Fig. 4. Torque (Nm) versus weight on bit (N) for selected samples used for the tests performed on the drill EM.

ferent mechanical behavior of different rocks is evident, integrating these observations with context measurements is critical. However for a proper validation, more tests on the rover ground test model (GTM) drill are needed. The GTM rover, Amalia, is located at the Rover Operation Control Center (ROCC, Torino).

The temperature sensor on the drill tip will also be of interest, as well as additional telemetry from ALD equipment (*e.g.* from the sample rock crusher's electrical current behavior) and from the rover wheels (*e.g.* depth of wheel marks, wheel trenching). The latter can contribute further to the characterization of the top rock/soil centimeters from where a sample is extracted. Surface modification induced during wheel passages have been investigated by MER and MSL teams to characterize Martian regolith mechanical properties, as well as evaluate the extent to which rocks were imprinted into soil or broken (*e.g.* Sullivan et al., 2011;Arvidson et al., 2014).

4. ExoMars rover instruments devoted to the investigation of the subsurface and synergies with drill telemetry

4.1. ADRON-RM

ADRON-RM is a compact, passive detector of neutrons (Mitrofanov et al., 2017). It is accommodated inside the ExoMars rover body, on the rear balcony, at a height of about 0.8 m above the surface. As the rover moves, ADRON-RM will measure the spatial variability of the neutron flux emitted from the martian subsurface in the thermal and epithermal energy ranges ($<$0.4 eV up to $\sim$ 1 keV.). The neutron flux data will then be converted into an estimation of water-equivalent hydrogen (WEH) content and abundance of neutron absorption elements, in particular of chlorine and iron, in the subsurface.

The main objectives of the ADRON-RM scientific investigation are to establish within a depth of 60 cm: (1) the distribution of bulk hydrogen content (in the form of free or bound water); (2) assess the bulk composition of major soil neutron absorption elements (Cl, Fe, S, Ti, etc.); (3) monitor the neutron component of the natural radiation background and estimate the neutron radiation dose at the martian surface from galactic cosmic rays (GCRs) and solar particle events (SPE); and (4) depending on the mission duration, investigate seasonal changes of the neutron environment due to variations of atmospheric and subsurface properties. Among the ADRON's scientific goals, the assessment of the distribution of bulk hydrogen content will be crucial for the purpose of this project as better illustrated in *Sec*. 5 (see also Fig. 6). Mechanical properties of rocks and soils are also dependent on the water content.

4.2. CLUPI

CLUPI (Josset et al., 2017) is a camera system to acquire high resolution, color, close-up images of outcrops, rocks, soils, drill fines, and drill samples, providing visual information similar to what geologists would obtain by visual inspection and using a hand lens. These images will complement those images taken by the PanCam instrument ((Coates et al., 2017)). The instrument is accommodated on the drill box and, by moving both the rover and the drill box, it can be oriented and raised to observe in a variety of viewing modes. CLUPI has three different Field Of View (FOV) configurations, which are used in six modes of operation. These are: (1) Geological survey (FOV 1) looking to the front, for the characterization of physical properties (*e.g.* hardness, induration, friability morphological features, veins, texture, grain sizes) of rocks and dusty terrains in the vicinity of the rover, as well as of rover track marks to examine soil consistency, and depth of the superficial oxidized layer. (2) Close-up outcrop observation (FOV 2) for looking to the side; using the rover's motion, CLUPI can be panned across a rock surface to image its structure in 2D and 3D by means of *ad hoc* overlapping image motion processing techniques. (3) Drilling area observation (FOV 2 with different configurations) for imaging the drilling area both with a narrow and wide coverage to investigate fine details and the broad context; (4) Drilling operation observation (FOV 3) for monitoring the drilling process and observing the mound of fines that it generates. In particular, color and textural variations can help us to infer whether, while drilling, different types of material or deposits have been encountered and to obtain information on mechanical properties of the soil, such as grain size, shape, and cohesion; (5) Observation of the core sample (FOV 3) collected by the drill at very high resolution, once it has been deposited on the rover's front tray and prior to its delivery to the ALD for further processing and studies; and (6) Investigation of the drill hole (FOV 2) for observing the state of the surface after drilling, the amount of dislodged fines, and their color plus the physical properties of the drill hole itself.

As an example, in Fig. 5, we show two images of drill powders generated from holes made by the Curiosity rover respectively at Yellowknife Bay and Confidence Hills. Differences in the colors of the excavated fines are mainly linked with the oxidation state of the materials. CLUPI

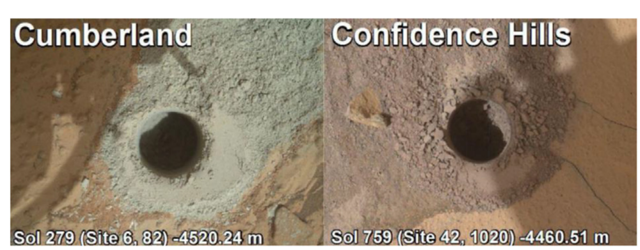

Fig. 5. Two examples of images of drill holes performed by NASA's Curiosity Rover respectively on Yellowknife Bay (Cumberland location, left image) and Confidence Hills (right image) in Gale Crater on Mars. The diameter of the holes is 1.6 cm. Images have been taken by the rover's Mars Hand Lens Imager (MAHLI) camera. From https://photojournal.jpl.nasa.gov/catalog/PIA21254. Credits NASA/JPL-Caltech/MSSS/UA.

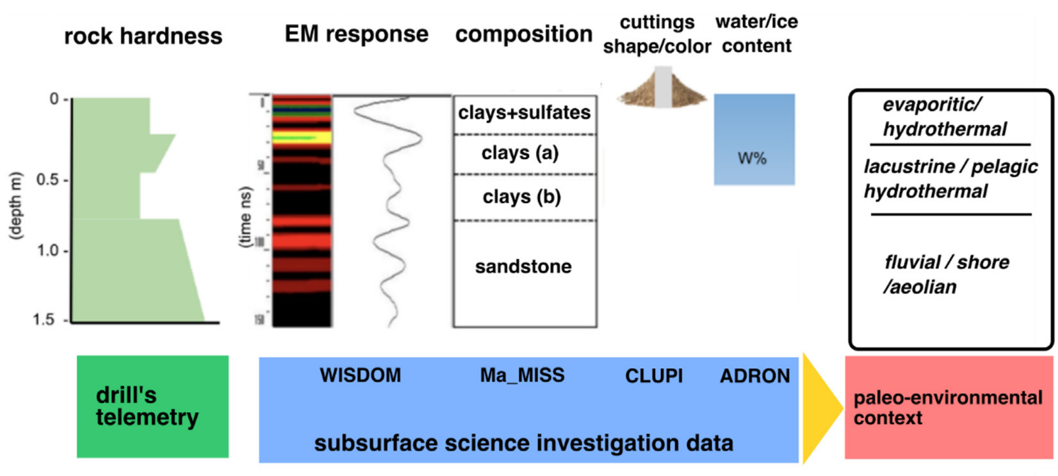

Fig. 6. Rosalind Franklin subsurface science investigation integrated with drill's telemetry.

images of the cuttings and dust being transported to the surface will allow us to correlate color variations with mechanical variations recorded by the drill and with the findings from other subsurface instruments.

4.3. Ma_MISS

Ma_MISS (De Sanctis et al., 2017; 2022) is the visible and near infrared (VIS-NIR 0.4–2.3 μm) micro spectrometer hosted in the drill system. This instrument can produce hyperspectral images of the borehole walls excavated by the rover drill. An image is assembled, point by point, by making use of the drill's rotation and vertical translation movements. The Ma_MISS optical head is accommodated in the drill tip (Fig. 3). Light, emitted through a sapphire window, is employed to investigate the borehole wall. Optical links are integrated in the drill tip and in the extension rods to send the reflected VIS-NIR light upwards. The Ma_MISS spectrometer is accommodated on a side wall of the drill box, near the top. The Ma_MISS spectral range, resolution, and imaging capabilities have been carefully chosen to identify mineral VIS-NIR diagnostic features. By exploiting the movements of the drill, i.e. rotation and translation, Ma_MISS can be used to investigate Mars' subsurface composition. Spectra acquired with Ma_MISS have very fine spatial resolution (120 μm). They can reveal different minerals within a given rock that would not be recognizable at coarser resolution. The main objectives of Ma_MISS are to: (1) Determine the composition of subsurface materials; (2) Map the distribution of H_2O-bearing and OH-bearing minerals, including H2O-ice; (3) Characterize important optical and physical properties (*e.g.* grain size); (4) Produce a stratigraphic column to provide information on subsurface geology. Ma_MISS will play a key role in associating composition to the different layers that are inferred by the drill's telemetry, and to features identified from the other subsurface investigations (WISDOM and ADRON-RM).

4.4. WISDOM

WISDOM (Ciarletti et al., 2017) is a ground penetrating radar designed to characterize the composition and structure of the shallow subsurface down to depths ranging from 3 to 10 m (with a vertical resolution of ~ 3 cm, Oudart et al., 2021), depending on the dielectric properties of the regolith. This depth range, commensurate with the drill capability, is critical to understanding the geologic, stratigraphy, distribution, and state of any subsurface water. This information will help us to find optimal drilling sites in our quest for possible signs of life. More specifically, the WISDOM radar's scientific objectives are: (1) To understand the 3D geology and geologic evolution of the landing site, including lithology, stratigraphy, and structure; the scale and magnitude of spatial heterogeneity; and the electromagnetic, physical, and compositional properties of the subsurface. 2) To investigate the local distribution and state of subsurface water, including the potential presence of ice-rich frozen ground, segregated bodies of ground ice, and the persistent or transient occurrence of liquid water/brine. And (3), to identify the most promising targets for subsurface sampling, as well as potential hazards, such as the presence of buried rocks, which could damage the drill and jeopardize the successful retrieval of samples.

WISDOM measurements (in the form of radargrams) will be compared to those of other subsurface instruments and the drill. Radar reflection/scattering will likely be correlated to changes in mechanical behavior or composition. In particular, layers with different signal attenuation may point to changes in composition (*e.g.* a higher attenuation is expected in fine grained rocks, such as clay/mudstones). WISDOM data will also allow information collected during a vertical survey to be extrapolated horizontally, by correlating WISDOM readings (taken at 50-cm vertical intervals between 0- and 2-m depth) to both Ma_MISS and drill telemetry.

5. Geological models and evolution of processes

The ExoMars drill stands as a hardware element that is in addition to the nine instruments in the rover's 'Pasteur' payload. Its telemetry response offers a unique opportunity to record the mechanical behavior of martian rocks and can complement and enhance measurements and observations by the instruments.

Drilling operations on Mars will provide an opportunity to record:

1. The number of different rocks being drilled;
2. The thickness and depth of rocks/layers with different mechanical behavior;
3. The hardness/compaction of the rocks.

These three elements can help to establish the stratigraphic sequence at the drill site. Since drilling will be the first operation to directly access the subsurface, this knowledge will be important for strategic and tactical planning performed at ROCC, by the science and control teams of the rover mission.

By keeping track of changes in composition, layering, and on mechanical behavior with depth, we can construct a litho-mechanical stratigraphic sequence of the drill site, resulting from a succession of geologic processes which occurred in the terrains being drilled (Fig. 6). The drill's telemetry will inform us about variations in rock hardness with depth during drilling. These data will be useful for WISDOM, which images the structure of the shallow subsurface in terms of variations of scattering intensity and/or electrical permittivity. If the subsurface is stratified, WISDOM can reveal the layers' thickness provided they are at least 4 cm thick (Oudart et al 2021). In case of a heterogeneous subsurface, a method was recently developed to estimate the typical size of isolated buried cobbles, pebbles and boulders from the differences of scattering they generate in the frequency sub-bands of the instrument (Brighi et al., 2022). If instead, the subsurface only includes a few reflectors, the analysis of the diffraction curve of individual reflectors will provide an estimate of the subsurface permittivity (Oudart et al., 2022). The permittivity is a frequency dependent parameter that is influenced by composition and porosity. It can therefore be linked to composition and mechanical properties, such as hardness (ElShafie & Heggy 2013). Consequently, a correlation analysis of mechanical properties deduced from comparing drilling and permittivity values from WISDOM will contribute to understanding the structure and properties of the subsurface. This knowledge will be extremely useful for planning successive drilling operations using WISDOM data. Ma_MISS associates mineral composition information (De Sanctis et al., 2022) to the drill's mechanical response and to WISDOM's permittivity radargrams. CLUPI observes the color and shape of grains being accumulated on top of the borehole as a function of depth during drilling. ADRON-RM informs us about total water content. All these data help to reconstruct what the paleoenvironments were where the rocks being drilled formed. This, in turn, will help us to focus our search for possible signs of life on the most suitable subsurface targets at our landing site.

The information gleaned from this suite of instruments in combination with drill's telemetry can also be used to detect and characterize underground water ice. Shallow buried ice is not expected at Oxia Planum. However, recent results from the FREND neutron detector on board the ExoMars Trace Gas Orbiter (TGO) have pointed to the presence of permafrost oases near the martian equator (Malakhov et al., 2020) and in particular in Candor Chaos in the central area of Valles Marineris (Mitrofanov et al., 2022).

6. Supporting the ExoMars rover mission's scientific goals

In the framework of the ExoMars rover's main science goals, obtaining knowledge about the geologic context under the topographic surface of Oxia Planum is critical to identifying and focusing on layers and structures potentially associated with the presence of past or current life on the Red Planet. Rosalind Franklin will be the first rover able to investigate the martian shallow subsurface, where ancient rocks/terrains have not been degraded by the action of radiation, winds, and oxidants, where potential biosignatures have an opportunity to be preserved. The multi-instrument analysis, including the drill, that we describe here has several applications within the ExoMars project and operations:

- It provides contextual information to support the analysis of subsurface samples by ALD instrumentation (MicrOmega, RLS, MOMA). Since the samples extracted from the subsurface will be crushed to maximize the surface available to investigate for the possible presence of chemical biosignatures, the information from the drill telemetry and from the subsurface instruments will help us determine the samples' natural conditions (*in situ*), prior to extracting them for further studies;
- It allows us to improve our knowledge of the subsurface,drill hole by drill hole, helping to refine the requirements for deciding where best to collect future samples;
- The outcome from this synergic strategy complements the surface geological/compositional analysis of the site performed by PanCam and ISEM.

However, concerning point 1 it should be noted that the sample will be crushed to be passed to the ALD instruments. This operation will take place at a temperature higher than what the sample will have seen in the subsurface. During processing it is not impossible that the sample may experience same alterations. In this respect, Ma_MISS observations will be crucial as it is the only instrument on the rover that can study the sample material in its native condition. That is, in the borehole, at the very cold subsurface temperatures (typically, below 50-cm depth, around –60 °C, the average between night and day excursions). Although Ma_MISS is positioned some 20 cm above the position from which the sample will be obtained, if considered important, and if the hardness, time, and energy will allow it, we can planning to penetrate 20 cm into the formation of interest to ensure that the same mineral matrix where the sample will be collected can be investigated by Ma_MISS. If we were to follow this approach, then Ma_MISS spectra can be spatially associated with samples retrieved from a maximum depth of 180 cm. In all cases, the compositional analysis established from Ma_MISS results can be compared with what MicrOmega (the IR spectrometer in the ALD) will measure after rock crushing. This will allow studying possible alterations induced by the crushing process.

7. Contributing in understanding Oxia Planum formation

From remote sensing analysis of the location and extension of the clay-bearing and layered units in Oxia Planum, two main hypotheses have been formulated for the unit's formation (Quantin-Nataf et al., 2021; Carter et al., 2016):

- Subaqueous: (Most likely pyroclastic) fine sediments that settled in a palustrine, lacustrine, or marine environment altering to clays. From remote sensing data it is not possible to infer if the clays were formed during sedimentation or transported from another source region, although the lateral extension of the clay province would seem to favor the hypothesis of a large, standing body of water.
- Subaerial/surficial: Pedogenic (top-down snow or rain alteration) or groundwater (bottom-up alteration) of otherwise dry volcanic or aeolian deposits.

Orbital data interpretation has suggested that hydrothermal alteration is unlikely given the large elevation range, thickness and layering of the deposits (Carter et al., 2016). However, given the very old nature of the rocks, from a time when substantial internal heat should have still been available to drive a lot of volcanism, and hence hydrothermal circulation, the network of dense fractures found all over the landing site represent an important target to investigate the effect of fluid circulation in a wide range of temperatures.

The CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) instrument on board NASA's Mars Reconnaissance Orbiter (MRO) has provided evidence at Oxia Planum of a spectral feature (2.5 μm band) in association with absorptions diagnostic of Fe/Mg clay minerals (Mandon et al., 2021; Altieri et al., 2021, Brossier et al., 2022). This band is consistent with the occurrence of another type of clay (*e.g.* serpentine, chlorite, or smectite) or carbonates, increasing the site's astrobiological relevance. However, the possible presence of carbonates remains controversial and *in situ* analysis is therefore needed. By extending the orbital and surface analysis of Oxia Planum into the subsurface with the strategy proposed in this work, we will gain a new, more mature understanding of how the region formed.

8. Summary and final remarks

The ExoMars drill has the task to drill exploratory boreholes at Oxia Planum (the ExoMars rover landing site) and collect samples to be delivered to the rover's Analytical Laboratory Drawer (ALD). The data of the ExoMars rover instruments devoted to the characterization of the subsurface (ADRON-RM, CLUPI, Ma_MISS and WISDOM) when considered together with the drill telemetry can greatly enhance the mission's scientific return. By monitoring drilling parameters, such as the torque and the weight on bit, which are influenced by physical properties of subsurface materials, we can establish subsurface stratification, composition, hardness of the rocks, and state of compaction of the sediments.

The combined use of subsurface instrument and drill telemetry results will improve the Rosalind Franklin rover's capabilities for locating and characterizing subsurface geological horizons potentially hosting past (or present) biosignatures. A full understanding of the sample environment is mandatory to (1) complement the investigations that will be conducted by the ALD instrumentation (MicrOmega, RLS, MOMA); (2) to refine criteria for deciding where to collect other samples; and (3) to improve knowledge of the site's geological context by extending the surface observations of PanCam and ISEM.

The ExoMars Rosalind Franklin rover provides us, for the first time, with the unique opportunity to investigate the martian shallow subsurface. We must use all the tools at our disposal in this mission. The results of ExoMars may have a great impact on what types of samples we may want to bring to Earth on future Mars Sample Return missions. They may also prove crucial for informing the future human exploration of the red planet.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the ExoMars project, and the states, agencies , industries participating in the ExoMars program and the two Anonymous Reviewers for their constructive review.

References

Altieri, F., et al. (2021). Spectral classes investigation on Oxia Planum, the ExoMars 2022 landing site, by means of CRISM/MRO data, 52nd Lunar and Planetary Science Conference, held virtually, 15-19 March, 2021. LPI Contribution No. 2548.

Arvidson, R. et al., 2014. Terrain physical properties derived from orbital data and the first 360 sols of Mars Science Laboratory Curiosity rover observations in Gale Crater. J. Geophys. Res. Planets 119, 1322–1344. https://doi.org/10.1002/2013JE004605.

Arvidson, R. et al., 2017. Relating geologic units and mobility system kinematics contributing to curiosity wheel damage at Gale Crater, Mars. J. Terramech. 73 (2017), 73–93.

Brighi, É., et al. (2022). Identifying heterogeneity sizes in the subsurface with WISDOM, the GPR of the ExoMars mission, Europlanet Science Congress 2022, Granada, Spain, 18–23 Sep 2022, EPSC2022-55, https://doi.org/10.5194/epsc2022-55.

Brossier, J. et al., 2022. Constraining the spectral behavior of the clay-bearing outcrops in Oxia Planum, the landing site for ExoMars "Rosalind Franklin" rover. Icarus, 115114. https://doi.org/10.1016/j.icarus.2022.115114.

Carter, J., et al. (2016). Oxia Planum: A Clay-Laden Landing Site Proposed for the ExoMars Rover Mission: Aqueous Mineralogy and Alteration Scenarios. LPI XLVII, Abstract #2064.

Ciarletti, V. et al., 2017. The WISDOM radar: unveiling the subsurface beneath the exomars rover and identifying the best locations for drilling. Astrobiology 17 (6–7), 565–584. https://doi.org/10.1089/ast.2016.1532.

De Sanctis, M.C. et al., 2017. Ma_MISS on ExoMars: mineralogical characterization of the martian subsurface. Astrobiology 17 (6–7), 612–620. https://doi.org/10.1089/ast.2016.1541.

De Sanctis, M.C., et al. (2022). Exploring the shallow subsurface of Mars with the Ma_MISS spectrometer on the ExoMars Rover Rosalind Franklin, Planetary Science Journal, 3, 6, id.142, 15 pp, doi: 10.3847/PSJ/ac694f

ElShafie A., Heggy E.(2013). Dielectric and hardness measurements of planetary analog rocks in support of in-situ subsurface sampling, PSS, Volume 86, 15 September 2013, Pages 150-154 , doi : 10.1016/j.pss.2013.02.003.

Frigeri, A., et al. (2020) Combining ExoMars' Ma_MISS and Drill data. 14th Europlanet Science Congress 2020, held virtually, 21 September 2020 - 9 October, 2020. Abstract id. EPSC2020-882.

Frigeri, A., et al. 2021. Integrating Drill Telemetry in Ma_MISS Science Onboard the ExoMars 2022 Rover. 52nd Lunar and Planetary Science Conference, LPI Contribution No. 2548, id.1462.

Grotzinger, J.P. et al., 2014. A Habitable Fluvio-Lacustrine Environment at Yellowknife Bay, Gale Crater, Mars. Science 343, 6169. https://doi.org/10.1126/science.1242777.

Josset, J.-L. et al., 2017. The close-up imager onboard the ESA ExoMars rover: objectives, description, operations, and science validation activities. Astrobiology 17 (6–7), 595–611. https://doi.org/10.1089/ast.2016.1546.

Kronyak, R. et al., 2019. Mineral Filled fractures as indicators of multigenerational fluid flow in the Pahrump Hills member of the Murray formation, Gale crater, Mars. Earth Space Sci. 6 (2), 238–265.

Lasne, J. et al., 2016. Oxidants at the surface of mars: a review in light of recent exploration results. Astrobiology 16, 977–996.

Magnani, P., et al. (2011). Testing the ExoMars EM Drill Tool in Mars Analogous Materials. In: Proceedings of ASTRA. Noordwijk, The Netherlands: ESA, 2011.

Mahaffy, P.R. et al., 2015. The imprint of atmospheric evolution in the D/H of Hesperian clay minerals on Mars. Science 347 (6220), 412–414. https://doi.org/10.1126/science.1260291.

Malakhov, A.V., et al. (2020). Ice Permafrost "Oases ý Close to Martian Equator: Planet Neutron Mapping Based on Data of FREND Instrument Onboard TGO Orbiter of Russian-European ExoMars Mission, Astronomy Letters, 2020, Vol. 46, No. 6, pp. 407–421.

Mandon, L. et al., 2021. Morphological and spectral diversity of the clay-bering unit at the ExoMars landing site Oxia Planum. Astrobiology 21 (4), 464–480.

Mitrofanov, I.G. et al., 2017. The ADRON-RM instrument onboard the ExoMars rover. Astrobiology 17 (6–7), 585–594. https://doi.org/10.1089/ast.2016.1566.

Mitrofanov, I. et al., 2022. The evidence for unusually high hydrogen abundances in the central part of Valles Marineris on Mars. Icarus 374. https://doi.org/10.1016/j.icarus.2021.114805 114805.

Myrick, T. M., et. al. (2004). The RAT as a Mars Rock Physical Properties Tool,Space 2004 Conferene and Exhibit 28-30 San Diego, California https://doi.org/10.2514/6.2004-6096

Oudart, N. et al., 2021. Range resolution enhancement of WISDOM/ExoMars radar soundings by the Bandwidth Extrapolation technique: validation and application to field campaign measurements. Planet. Space Sci. 197. https://doi.org/10.1016/j.pss.2021.105173 105173.

Oudart, N. et al., 2022. Retrieval of the ground dielectric constant by planetary GPR accomodated on a rover : application to WISDOM/ExoMars radargrams, 2022. Planet. Space Sci. 224. https://doi.org/10.1016/j.pss.2022.105606 105606.

Peters, G.H. et al., 2018. Uniaxial compressive strengths of rocks drilled at Gale Crater, Mars. Geophys. Res. Lett. 45 (1), 108–116. https://doi.org/10.1002/2017GL075965.

Quantin-Nataf, C. et al., 2021. Oxia Planum - the landing site for the 2022 ExoMars "Rosalind Franklin" Rover Mission: geological context and pre-landing interpretation. Astrobiology 21, 3.

Quinn, R.C. et al., 2013. Perchlorate radiolysis on Mars and the origin of martian soil reactivity. Astrobiology 13, 515–520.

Sullivan, R. et al., 2011. Cohesions, friction angles, and other physical properties of Martian regolith from Mars Exploration Rover wheel trenches and wheel scuffs. J. Geophys. Res. 116, E02006. https://doi.org/10.1029/2010JE003625.

Vago, J.L. et al., 2017. Habitability on early Mars and the search for biosignatures with the ExoMars rover. Astrobiology 17 (6–7), 471–510. https://doi.org/10.1089/ast.2016.1533.

Coates, R. Jaumann, A.D. Griffiths, C.E. Leff, N. Schmitz, J.-L. Josset, G. Paar, M. Gunn, E. Hauber, C.R. Cousins, R.E. Cross, P. Grindrod, J. C. Bridges, M. Balme, S. Gupta, I.A. Crawford, P. Irwin, R. Stabbins, D. Tirsch, J.L. Vago, T. Theodorou, M. Caballo-Perucha, G.R. Osinski, and the PanCam Team,The PanCam Instrument for the ExoMars RoverA.J. Astrobiology 2017 17:6-7, 511-541, https://doi.org/10.1089/ast.2016.1548

Kminek G. Bada JL (2006). The effect of ionizing radiation on the preservation of amino acids on Mars. Earth Planet. Sci. Letters. 245, 1-5.