Future *in situ* investigation of Noachian Fe/Mg phyllosilicates, fluvial and deltaic deposits as part of the ExoMars rover's science sampling strategy: implications for early Martian climates and aqueous environments

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**Introduction:**

The ExoMars Rosalind Franklin rover mission [1] will explore Oxia Planum, one of the oldest terrains on Mars, offering an unprecedented opportunity to investigate Fe/Mg phyllosilicate-rich units dating to the Noachian era (~4.1–3.7 Ga). These vast deposits comprising some of the most extensive clay-bearing terrains on the planet record environmental conditions that we can associate with potentially habitable settings [2].

The observations planned with the Rosalind Franklin rover will address questions about the past habitability, sedimentary, and geochemical history of the landing site and advance our understanding of early Mars' climate and hydrological evolution.

**Past climate conditions in Oxia Planum:**

The early Noachian was characterized by a denser atmosphere, enhanced surface weathering, and widespread fluvial activity [3]. Orbital data have revealed extensive Fe/Mg phyllosilicate units [2]—including smectite-bearing deposits such as nontronite that likely formed under neutral to mildly alkaline aqueous conditions [4]. These findings suggest prolonged interaction with liquid water and raise compelling questions about Mars' potential to sustain habitable environments.

However, many fine-scale textural and stratigraphic details, essential for reconstructing the environmental history of these deposits, cannot be studied from orbit. The ExoMars Rosalind Franklin rover will conduct the first *in situ* exploration of such ancient terrains.

**Science motivation:**

The landing site offers access to two distinct clay-bearing units: the Lower Bedrock Group (LBG) and the Upper Bedrock Group (UBG) [5]. Their material exhibits distinct spectral and colour differences, as identified in OMEGA and CRISM data [6]. The 'orange' terrains in Oxia correspond to the LBG. They show CRISM spectra indicative of Fe-bearing saponite or vermiculite, with possible siderite or Mg-serpentine. In contrast, the 'bluer' terrains, associated with the UBG, appear to contain an olivine component mixed with the previous minerals, suggesting weaker aqueous alteration [6].

These deposits are considered part of a broader sedimentary system that may have been connected to a large, long-lived body of standing water - possibly an early Martian ocean [7]. An alternative hypothesis is that the phyllosilicate-rich layers and sedimentary features may have formed in localized lacustrine or fluvial environments, such as ephemeral lakes, river-fed basins, or groundwater discharge zones [7]. In this latter case, clay formation would have occurred under transient wet conditions, driven by episodic climate fluctuations, volcanic or impact-induced hydrothermal activity, or by localized groundwater upwelling— without requiring a global or regional ocean [7]. Evaluating these competing scenarios is critical to understand the extent, duration, and habitability of aqueous environments on early Mars.

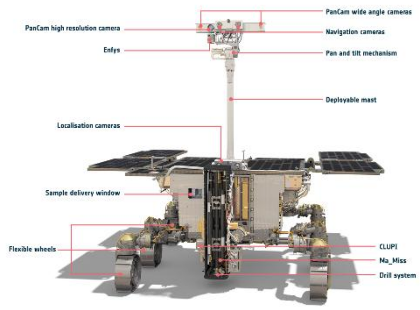


Fig.1 – The front view of ExoMars rover with some of the instruments: PanCam, Enfys, CLUPI, and Ma_MISS. Credits: ESA

**Methodology:**

A **Science Sampling Strategy ($S^3$)** is being developed for the Rosalind Franklin rover to ensure the acquisition of essential scientific observations during surface operations. This plan defines the measurements required from the instruments in the Pasteur Payload - WISDOM (Water Ice and Subsurface Deposit Observation on Mars) [8], PanCam (Panoramic Camera), ENFYS (Infrared spectrometer) [9], CLUPI (Close-UP Imager) [10], RLS (Raman Laser Spectrometer) [11], Ma_Miss (Mars Multispectral Imager for Subsurface Studies) [12], MicrOmega (Visible and Infrared Hyperspectral Microscopic Imager) [13] and MOMA (Mars Organic Molecule Analyzer) [14]— at each outcrop, rock unit, targeted sampling area, pre- and post-drilling.

Our science sampling strategy is structured around a tiered observational protocol, distinguishing between critical and complementary data products, to optimize science return under operational constraints.

- **Critical science observations** – These represent the observations needed to acquire the minimum information necessary for proceeding to the next step in the sampling workflow. They are essential for evaluating the scientific potential of a target and must enable, for example, sufficient characterization of its composition, texture, and context to justify continued investigation. These observations are mandatory and must be prioritized in operational planning, energy usage, and data downlink allocation.

- **Non-critical science observations** – These are valuable but not strictly required for progression in the sampling workflow. They enhance scientific understanding, improve interpretation, and provide additional contextual depth. Such observations may include extended mineralogical or textural datasets, additional high-resolution images, repeated measurements, or broader environmental context. While not mandatory, they contribute significantly to the overall scientific return when time, energy, and data resources allow.
- **Opportunistic science** – Unplanned or adaptive scientific investigations that take advantage of spare resources or respond to unexpected findings encountered during rover operations. For example, observations may be triggered by the detection of unusual features or materials during a traverse. While not part of the core operational sequence, opportunistic science adds flexibility and scientific richness to the mission without significantly altering the primary mission timeline or objectives.

This tiered approach is designed to maximize science return under operational constraints (*e.g.*, limited data volume, time, and rover mobility). It ensures that key information is prioritized for collection while maintaining flexibility to investigate secondary targets of opportunity.

**Geological features to be mapped within the Fe/Mg phyllosilicate rich deposits:**

A range of geological features are expected to be preserved in the clays, each offering insights into the sedimentary and climatic history of early Mars. They will be investigated at multiple observational scales using the rover's payload.

- At **the outcrop scale,** PanCam and CLUPI will be used to characterize mineral grain sizes and texture, including bedding structures, stratification, and fine-scale laminations, which are diagnostic of past depositional environments. Polygonal fractures and desiccation cracks, visible in exposed surfaces will be investigated, as they may indicate surface drying events or freeze-thaw cycles and will be documented using high-resolution imaging.
  Morphological features such as honeycomb textures, erosional pits, and bright patches outcrops will further inform interpretations of weathering and diagenetic processes.
- **Subsurface** information will be provided by the WISDOM ground penetrating radar, which will detect buried layering, structural discontinuities, and facies transitions. This data will help to reconstruct the vertical architecture of the sedimentary sequence and identify lateral environmental changes not visible from the surface alone.
- **In targeted areas** selected for detailed analysis, CLUPI will resolve fine grain-scale textures, while characterizing the spatial distribution of primary and secondary minerals. Features such as alteration halos, coatings, veins, and authigenic mineral phases —indicative of aqueous alteration and post-depositional fluid activity— will be key targets for pre-drilling observations.
- **Following drilling,** powdered subsurface samples will be analyzed by RLS and MicrOmega to determine mineralogical assemblages, cementation features, and signs of diagenesis. Critically, MOMA will assess the presence of organic molecules within the fine-grained, clay-rich matrix, which offers the greatest potential for biosignature preservation.

Through this multi-tiered observational strategy, the ExoMars Rosalind Franklin mission is equipped to investigate the full spectrum of sedimentary, diagenetic, and potentially biological features embedded within the Fe/Mg phyllosilicate terrain, providing essential context for reconstructing early Martian climates and habitability.

**Next steps:**

The next phase of this work will focus on integrating the identified geological features and corresponding science observations into a structured framework that will distinguish between **critical** and **non-critical** science. This classification will guide operational planning by ensuring that high-priority observations - those required to confirm scientific relevance and justify continued investigation— will be acquired first and consistently across sites. Non-critical observations, while not essential for advancing the sampling sequence, will be incorporated when mission resources allow, to enrich scientific interpretation and contextual understanding.

Building on this framework, detailed operational scenarios will be developed to distribute specific instrument activities across different sols (Martian operational days), corresponding to each phase of the surface workflow—from initial approach and characterization, through pre-drilling assessment, to post-drilling analysis. These scenarios will be optimized to maximize science return within the constraints of the mission, including limited data volume, available energy, instrument usage limits, and rover mobility. This strategy will enable efficient decision-making and ensure that all essential data are acquired to meet the ExoMars mission's scientific objectives: reconstructing early Martian environments and evaluating the planet's past habitability.

**Expected outcomes and implications:**

Through the *in situ* investigation of Fe/Mg phyllosilicates and the implementation of a structured science sampling plan, we aim to:

- Constrain the depositional environment of Noachian phyllosilicates (*e.g.*, lacustrine, fluvial, or marine origins).
- Determine the role of water–rock interaction and diagenesis in shaping these ancient terrains.
- Evaluate whether these deposits record a single climatic regime or multiple episodic events driven by obliquity variations or atmospheric transitions.

Ultimately, this work will contribute to improve models of early Mars' climate evolution and assess the duration and stability of potentially habitable environments. Such observations will be essential for testing competing hypotheses about the planet's early climatic and geological conditions —whether Mars once sustained long-term, stable wet environments capable of supporting a global ocean, or instead experienced shorter-lived, localized aqueous episodes governed by internal and external planetary processes.

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