Supplementary Material

**Remote and In-Situ Characterization of Mars Analogs: Coupling Scales to Improve the Search for Microbial Signatures on Mars**

# Supplementary Data

All supplementary data are within tables on FigShare - available permanently at 10.6084/m9.figshare.17838392 (temporary link: https://figshare.com/s/07e4e39a7dcebc63e170).

# Supplementary Figures and Tables

## Supplementary Figures

Diagram

Description automatically generated

**Supplementary Figure 1.** Summary of preserved geolipid biomarkers detected in various mineral classes at each Mars analog site. Filled symbols indicate the class of lipid biomarker was detected in the mineral class; hollow symbols indicate the lipid biomarker was not detected; plus (+) symbols indicate minerals with no published lipid biomarker investigations, i.e. the mineral class is a major lithology, but has not yet been explored for lipid biomarkers; no symbol indicates the mineral class is not a major component of the lithology. This plot only conveys the detected presence of lipid biomarkers and does not contain information on the abundance or quality of the recovered biomarkers. “Sat. hydrocarbons” include aliphatic and monocyclic saturated hydrocarbons. “Other” includes isoprenoidal lipids not included in other categories.  See **Table S3** for details.

## Supplementary Tables

**Supplementary Table 1**: Spatial resolution and wavelength coverage for select imagers on Mars.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Mission** | **Instrument** | **Type** | **Spatial Resolution** | **Wavelength Coverage** | **Reference** |
| Perseverance (Jezero) | Supercam (VISIR) | VISIR Spectroscopy | <mm to <m | 0.385-0.465 μm, 0.536-0.853 μm, 1.3-2.6 μm | Fouchet et al., 2021; mars.nasa.gov, SuperCam |
|  | Supercam (CRMI) | Color Remote Micro Imager | 60 µm at 1.5 m distance | – | Gasnault et al., 2015; mars.nasa.gov, SuperCam |
|  | Mastcam-Z | Panoramic Imager | 1 mm near; 3-4 cm at 100 m | 400-1000 nm | mars.nasa.gov, Mastcam-Z |
| Curiosity (Gale) | MastCam-34 | Panoramic Imager | 450 micron near (2 m); 22 cm at 1 km | 440-1035 nm (exact bands vary) | mars.nasa.gov, Mastcam |
|  | MastCam-100 | Panoramic Imager | 150 micron at 2 m; 7.4 cm at 1 km | 440-1035 nm (exact bands vary) | mars.nasa.gov, Mastcam |
|  | ChemCam | Remote Micro Imager | 1 mm at 10 m | – | mars.nasa.gov, ChemCam |
|  | MAHLI | Hand Lens Imager | 13.9 μm | 380-680 nm | mars.nasa.gov, MAHLI |
| MRO (Global) | HiRISE | High Res Remote Imager | Smallest resolvable features ~1 m | 400-1000 nm | mars.nasa.gov, HiRISE |
|  | CTX | Remote Imager | 6 m at 300 km | 500-800 nm | mars.nasa.gov, CTX |
|  | MARCI | Remote Imager | 1 to 10 km | Visible/ UV filters | mars.nasa.gov, MARCI |
|  | CRISM | VISIR Spectroscopy | 18.4 meter/pixel at 300 km altitude | 362 - 3920 nm | mars.nasa.gov, CRISM |
| Odyssey (Global) | THEMIS - VIS | VIS Remote Imager | 18 m | 425 nm to 860 nm | mars.nasa.gov, THEMIS |
|  | THEMIS - IR | IR Remote Imager | 100 m | 6.78 μm to 14.88 μm | mars.nasa.gov, THEMIS |

**Supplementary Table 2**. Number of Web of Science publications between 1993 and 2021 that match the search term “Mars” and terms for each terrestrial analog site. Publication counts are shown for broad, disciplinary categories based on more detailed category assignments generated by Web of Science.  Search terms for each site are as follows:: ATC = “Atacama salars” or “saltflats”; HIC = “Haughton Impact Crater” or “structure”; LON = “Lonar lake” or “crater”; MDV = “McMurdo Dry Valleys”; RIO = “Rio Tinto” or “Riotinto” or “Tinto River”. Search conducted October 2021.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Disciplinary Category** | **ATC** | **HIC** | **LON** | **MDV** | **RIO** | **Total** |
| *Atmospheric* |  | *2* |  | *1* |  | *3* |
| Meteorology Atmospheric Sciences |  | 2 |  | 1 |  | 3 |
| *Biology* | *6* | *17* | *1* | *19* | *65* | *108* |
| Biochemistry Molecular Biology |  |  |  | 1 |  | 1 |
| Biodiversity Conservation |  |  |  | 1 |  | 1 |
| Biology | 4 | 16 | 1 | 7 | 46 | 74 |
| Biophysics |  | 1 |  |  |  | 1 |
| Biotechnology Applied Microbiology |  |  |  |  | 2 | 2 |
| Cell Biology |  |  |  |  | 1 | 1 |
| Ecology | 1 |  |  | 2 | 4 | 7 |
| Marine Freshwater Biology |  |  |  | 3 | 1 | 4 |
| Microbiology | 1 |  |  | 3 | 9 | 13 |
| Microscopy |  |  |  | 1 |  | 1 |
| Plant Sciences |  |  |  | 1 | 1 | 2 |
| Zoology |  |  |  |  | 1 | 1 |
| *Chemistry* |  | *1* |  | *1* | *3* | *5* |
| Chemistry Analytical |  | 1 |  |  | 1 | 2 |
| Chemistry Multidisciplinary |  |  |  | 1 | 1 | 2 |
| Chemistry Physical |  |  |  |  | 1 | 1 |
| *Engineering* |  | *7* |  | *3* | *6* | *16* |
| Construction Building Technology |  | 1 |  |  |  | 1 |
| Engineering Aerospace |  | 4 |  | 2 | 2 | 8 |
| Engineering Civil |  | 1 |  |  | 1 | 2 |
| Engineering Electrical Electronic |  | 1 |  |  |  | 1 |
| Engineering Environmental |  |  |  |  | 1 | 1 |
| Engineering Industrial |  |  |  |  | 1 | 1 |
| Engineering Manufacturing |  |  |  |  | 1 | 1 |
| Engineering Multidisciplinary |  |  |  | 1 |  | 1 |
| *Environmental Sciences* | *4* | *1* | *1* | *6* | *8* | *20* |
| Environmental Sciences | 4 | 1 | 1 | 6 | 8 | 20 |
| *Geosciences* | *14* | *47* | *16* | *47* | *85* | *209* |
| Geochemistry Geophysics |  | 19 | 11 | 15 | 24 | 69 |
| Geography Physical | 3 |  |  | 7 |  | 10 |
| Geology |  | 2 | 1 | 2 | 3 | 8 |
| Geosciences Multidisciplinary | 11 | 23 | 3 | 21 | 49 | 107 |
| Mineralogy |  |  |  | 1 | 8 | 9 |
| Paleontology |  | 2 |  | 1 | 1 | 4 |
| Remote Sensing |  | 1 | 1 |  |  | 2 |
| *Physics & Astronomy* | *5* | *27* | *5* | *26* | *71* | *134* |
| Astronomy Astrophysics | 5 | 27 | 5 | 25 | 68 | 130 |
| Physics Applied |  |  |  |  | 2 | 2 |
| Physics Condensed Matter |  |  |  |  | 1 | 1 |
| Physics Multidisciplinary |  |  |  | 1 |  | 1 |
| *Other* | *1* | *3* | *1* | *12* | *29* | *46* |
| Imaging Science Photographic Technology |  | 1 |  |  |  | 1 |
| Instruments Instrumentation |  |  |  | 3 | 1 | 4 |
| Limnology |  |  |  | 1 |  | 1 |
| Materials Science Multidisciplinary |  | 1 |  |  | 3 | 4 |
| Medicine General Internal |  |  |  | 1 |  | 1 |
| Metallurgy Metallurgical Engineering |  |  |  |  | 3 | 3 |
| Mining Mineral Processing |  |  |  | 1 | 3 | 4 |
| Multidisciplinary Sciences | 1 |  | 1 | 3 | 6 | 11 |
| Mycology |  |  |  |  | 1 | 1 |
| Optics |  | 1 |  | 2 | 1 | 4 |
| Public Environmental Occupational Health |  |  |  |  | 1 | 1 |
| Robotics |  |  |  |  | 1 | 1 |
| Spectroscopy |  |  |  | 1 | 9 | 10 |
| ***Grand Total*** | ***30*** | ***105*** | ***24*** | ***115*** | ***267*** | ***541*** |

**Supplementary Table 3**. Summary of mineral classes at each terrestrial analog site that contain preserved lipid biomarkers and approximate age of preserved lipids. In some cases the age of preserved lipids could not be determined.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Analog** | **Location** | **Mineral Class** | **Approx. age of preserved lipids** | **Reference** |
| ATC | Yungay soil pit | Clay minerals, halite | 0.04 - 2 Ma | Wilhelm et al., 2017 |
|  | Subsurface | Evaporites | Paleozoic, Mesozoic, Tertiary, Holocene | Barbieri et al., 2011 |
|  | Subsurface | Evaporites | Quaternary (0.1 - 9 Ma) | Sánchez-García et al., 2018 |
|  | Lagoons | Gypsum evaporates, carbonate microbialites | Not determined | Farías et al., 2014 |
|  | Surface sediments from Monturaqui, Salar Grande, Yungay | Gypsum, halite, volcanics | Few hundreds of years | Ziolkowski et al., 2013 |
|  | Hypersaline subsurface deposit | Halite- and perchlorate-rich deposit | 2-5 Ma | Fernández‐Remolar et al., 2013 |
|  | Subsurface core | Halite- and perchlorate-rich deposit | Not determined | Parro et al., 2011 |
|  | Surface sediments | Iron-bearing minerals, silicates, carbonates, sulfates, clays and oxides | Not determined | Cabrol et al., 2007 |
|  | Surface sediments | Limestones | Triassic - Jurassic (199 - 209 Ma) | Sánchez-García et al., 2021 |
|  | Dry alluvial fan | Surface and subsurface sands and silts | Quaternary/Holocene (present - 2.58 Ma), Oligocene (23 - 30 Ma) | Nauny et al., 2019 |
| HIC | Clasts in impact melt breccias | Carbonate | 39 Ma | Lindgren et al., 2009 |
|  | Surface mineral crusts | Carbonate | Not determined | Parnell et al., 2006 |
|  | Bedrock, recent sediments and ice | Carbonates (dolomitic limestone) | Palaeozoic bedrock,  Miocene sediments, Quaternary ice | Parnell et al., 2004 |
|  | Lacustrine deposits | Dolomite | Early Miocene | Eglinton et al., 2006 |
|  | Endostromatolites | Dolomite | Ordovician-Silurian | Lacelle et al., 2009 |
|  | Bedrock and sediment | Dolomite | Lower Paleozoic | Parnell et al., 2005 |
|  | Surface deposits | Gypsum | Quaternary (<1.6 Ma), Eocece (39 Ma) | Bowden and Parnell 2007 |
| LON | Lake sediment core | Calcareous clay | 0.6 - 11.2 cal. ka | Sarkar et al., 2015 |
|  | Lake sediments | Carbonate minerals | Quaternary | Anoop et al., 2015 |
|  | Lake sediment core | Clay | 0.6 - 11.2 cal. ka | Prasad et al., 2014 |
|  | Lake surface sediments | Clay minerals | Not reported | Sarkar et al., 2014 |
| MDV | Lake sediments | Carbonates (calcite) | Not reported | Doran et al,. 1994 |
|  | Soils | Silicate (quartz) | Pleistocene | Matsumoto et al., 1990 |
|  | Soils | Silicate (quartz) | Pleistocene | McKelvey and Webb 1962 |
| RIO | Fluvial sediments | Evaporites | 500 - 2500 years | Parro et al., 2011 |
|  | Subsurface | Iron-bearing | 2.1 - 10 Ma | Fernández-Remolar et al., 2008 |
|  | Subsurface | Oxides (iron) | Oligocene | Fernández-Remolar et al,. 2021a |
|  | Subsurface | Oxides (iron) | 2 - 25 Ma | Fernández-Remolar et al,. 2021b |
|  | Subsurface | Oxides (iron), silicate (quartz) | > 6 Ma | Fernández-Remolar et al., 2021c |
|  | Rio Tinto riverbed | Sulfate-rich sediments | Not determined | Sánchez-García et al., 2020 |

**Supplementary Table 4**: Spatial extents of macroscopic biological features at analog sites with references.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Analog** | **Feature** | **Location** | **Size range** | **References** |
| ATC | Cyanobacterial mat | Laguna Puilar in Salar de Atacama | mm to cm | [Dorador et al., 2018](https://www.zotero.org/google-docs/?0gkCd4) |
|  | Biofilm on sediments | Laguna Puilar in Salar de Atacama | mm to cm | [Dorador et al., 2018](https://www.zotero.org/google-docs/?H9EdJF) |
|  | Cyanobacterial mat | Laguna Tebenque | mm to cm | [Cockell et al., 2002](https://www.zotero.org/google-docs/?jV7wei) |
| HIC | Endolithic cyanobacteria | Gneiss outcrops in eastern crater wall | mm to cm | Lacelle et al., 2009 |
|  | Endostromatolites | Southern rim of the crater in the Allen Bay Formation | mm to cm | Lacelle et al., 2008, Clarke et al., 2019 |
|  | Biofilm aggregates | Meltwater streams in northwest rim of the crater | cm to m to km | Chacon-Baca et al., 2021 |
| LON | Cyanobacterial mat | Lake surface, lake margins, lake benthos | mm to m | [Surakasi et al., 2010;](https://www.zotero.org/google-docs/?WvG62k)  [Sarkar et al., 2014](https://www.zotero.org/google-docs/?c8z66y) |
| MDV | Cyanobacterial mat | Lake margin, lake benthos, ice, ephemeral streams | mm to m | [Taton et al., 2006;](https://www.zotero.org/google-docs/?wO3W1S)  [Laybourn-Parry and Wadham, 2014;](https://www.zotero.org/google-docs/?WYIw7f)  [Hawes et al., 2019;](https://www.zotero.org/google-docs/?rgtBJI) [Sohm et al., 2020](https://www.zotero.org/google-docs/?broken=ogLH64) |
| RIO | Fe-rich microbial mats | Terraced iron formations in Tintillo River | cm to m to km | [Fernández-Remolar and Knoll, 2008](https://www.zotero.org/google-docs/?XM4XfP) |

**Supplementary Table 5**: Table of characteristic mineral absorption bands as detected by VNIR imagers for specific minerals at each analog site.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Analog** | **Mineral Class** | **Mineral** | **Feature band wavelength (µm)** | **Reference** |
| ATC | Carbonates | Carbonates | 3.4 to 3.5, 3.9 to 4.0 | [Flahaut et al., 2017](https://www.zotero.org/google-docs/?broken=HQk7gQ) |
|  | Clay Minerals | Carbonates and clay | 2.1 to 2.5 |  |
|  |  | Smectite Clay | 1.40 to 1.41, 1.90 to 1.92 |  |
|  |  | Al-Phyllosilicates | 2.19 to 2.21 |  |
|  |  | Nontronite | 2.28 to 2.29 |  |
|  |  | Saponite | 2.30 to 2.31 |  |
|  |  | Chlorites | 2.33 to 2.37 |  |
|  | Other Silicates | Serpentine | 2.31 to 2.33 |  |
| HIC | Carbonates | Calcite | 2.34 and 2.50 | [Greenberger et al., 2020](https://www.zotero.org/google-docs/?broken=SeeZwc) |
|  |  | Dolomite | 2.32 and 2.50 |  |
|  | Clay Minerals | Illite | 2.20 and 2.35 |  |
|  |  | Illite-like | 2.24 and 2.33 |  |
|  | Sulfates | Gypsum | 1.45, 1.76, and 2.21 |  |
|  | Hydrated Silica | Hydrated Silicas | 2.0 to 2.5 |  |
|  | Clay Minerals | Phyllosilicates | ~ 2 |  |
| LON | Clay Minerals | Fe/Mg smectite clays | 2.3 | [Ehlmann et al., 2008](https://www.zotero.org/google-docs/?broken=YKcBXq) |
|  |  | Al smectite | 2.2 |  |
|  | Volcanic | Weathered glasses | 2.2 |  |
|  |  | Pyroxenes | 1.0 and 2.0 |  |
|  |  | Palagonite | 2.2 |  |
| MDV | Carbonates | Calcite | 3.36, 3.48 | [Bishop et al., 2014](https://www.zotero.org/google-docs/?broken=SoRDGF) |
|  | Volcanic | Pyroxenes | 0.94 and 1.94 |  |
|  | Clay Minerals | Chlorites | 2.25 and 2.34 |  |
|  | Other Silicates | Aluminosilicates | 2.19 to 2.34 |  |
|  | Hydrated Silica | Actinolite | 2.33 and 2.38 |  |
| RIO | Oxides | Hematite | 1.9 | [Roach et al., 2006; Sobron et al., 2014](https://www.zotero.org/google-docs/?broken=pDLtqQ) |
|  |  | Goethite | 0.59, 0.60, 0.76, and 1.4 |  |
|  | Sulfates | Gypsum | 1.44, 1.45, 1.49, 1.54, 1.75, 1.76, 1.94, 1.95, 2.20, and 2.26 |  |
|  |  | Jarosite | 0.43, 0.89, 1.46, 1.85, and 2.26 |  |