Abstract Booklet

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Galactic cosmic rays (GCRs) are the principal source of ionisation in planetary atmospheres. Upon entering the atmosphere, collisions occur between GCRs and other atmospheric molecules to produce a variety of secondary particles. This results in a vertical profile of ion production rate, determined by atmospheric density and GCR flux. The region of maximum ion production is known as the Pfotzer-Regener Maximum. On Earth this occurs at 15-20 km, well above the tropospheric clouds. The thick sulphuric acid cloud deck on Venus, on the other hand, coincides with this maximum at about 60 km (1) where the temperature and pressure are more Earth-like, see figure 1. The presence of charge is known to influence cloud droplet microphysics on Earth, affecting the formation, growth, stability, and persistence of cloud droplets (2). It is therefore likely that the electrical effect of GCR ionisation also plays a crucial role in cloud behaviour on Venus.

One consequence of charging is a change in the critical minimum supersaturation at which droplets begin to form (2). The charging acts to stabilise droplets against evaporation, thereby allowing slightly larger drops to exist at lower saturation ratios. A major source of charge in planetary atmospheres is from cosmic ray ionisation, which has recently been demonstrated to influence clouds in the highly supersaturated atmosphere of Neptune (3). Condensation of gas directly onto atmospheric ions is a potential source of particles on Venus because supersaturation is common there, whereas this process would be impossible on Earth (4). Highly charged particles therefore allow condensation at lower temperatures than neutral particles, and this effect is modelled using Köhler theory (5); it could therefore be an important contributor in determining cloud droplet nucleation altitude.

The VENI (Venusian Electricity, Nephology, and Ionisation) project presented here examines the effects of charge on droplet lifetime and behaviour in a range of conditions. For this, individual droplets are initially levitated in an acoustic wave, processed visually using a high-speed camera, and monitored to determine evaporation timescales and related physical behaviour. A corona source is used to produce the ionisation rates typical of Venusian clouds, and to simulate transient space weather events such as solar flares. The droplet’s polarity and charge magnitude are measured by creating an electric field around the droplet and observing the deflection. The results of these experiments are expected to produce unique experimental data with relevance to the atmospheric electricity and cloud microphysics in planetary atmospheres, provide further information relating to whether or not a global electric circuit (GEC) may occur on Venus, and will be important in future mission design and hazard mitigation.

**Figure 1.** Modelled GCR ion production profile for Venus with characteristic T-P conditions within the clouds. Adapted from (1).

**References:**


Vertical profiles of isotopic ratios in H$_2$O and CO$_2$ in the Martian atmosphere as observed by ACS onboard the ExoMars Trace Gas Orbiter

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Introduction: Heavy isotope enrichment in C, O and H provide important constraints about the loss of the Martian atmosphere throughout its history. While the D/H ratio in H$_2$O shows a strong enrichment of the heavy isotope, being approximately a factor of six higher with respect to Earth-like values, the $^{18}$O/$^{16}$O ratios in both H$_2$O and CO$_2$ appear to be much more consistent with that observed on the Earth’s atmosphere.

In this work, we use solar occultation observations made with the mid-infrared channel of the Atmospheric Chemistry Suite (ACS MIR) onboard the ExoMars Trace Gas Orbiter to constrain, for the first time, simultaneous vertical profiles of the O isotopic ratios in H$_2$O and CO$_2$. In addition, the large coverage of ACS MIR solar occultations allows the analysis of seasonal and spatial variability of these ratios.

Measurements and methods: ACS consists of a set of three infrared spectrometers covering a wavelength range from 0.7 to 17 µm. In particular, the MIR channel, used in this study, is a cross-dispersion echelle spectrometer dedicated to solar occultation observations covering a total wavelength range between 2.3 and 4.2 µm. ACS MIR is equipped with a movable secondary grating that allows the selection of several diffraction orders within the full spectral range, allowing the measurement of high-resolution spectra ($\lambda/\Delta\lambda \sim 30000$-$50000$) in a wide instantaneous spectral range (0.15-$0.3$ µm) [1].

In this study, we analyse the data obtained using secondary grating position 5, which covers a spectral range from 2.53 to 2.67 µm. In this range, several absorption lines of the three main oxygen isotopologues in water vapour (H$_2^{16}$O, H$_2^{18}$O, H$_2^{17}$O) and the two main oxygen isotopologues in carbon dioxide ($^{12}$C$^{16}$O$_2$, $^{13}$C$^{16}$O$^{18}$O) are measured, allowing the simultaneous characterization of the oxygen isotopic ratios in both species [2].

The radiative transfer analysis of the measured spectra is performed using NEMESIS [3]. In each solar occultation, vertical profiles of pressure, temperature and volume mixing ratio of H$_2^{16}$O, H$_2^{18}$O, H$_2^{17}$O and $^8$O$^{12}$C$^{16}$O are retrieved.

Pressure and temperature profiles can be constrained under from $^{12}$C$^{16}$O$_2$ absorption lines, assuming the atmosphere is in hydrostatic equilibrium, and a known CO$_2$ volume mixing ratio profile, which we obtain from the Mars Climate Database [4]. Once the pressure and temperature profiles are retrieved, they are fixed, and the volume mixing ratio profiles for the other species are constrained from the depth of the corresponding absorption lines. Once all the profiles are retrieved, the vertical profiles of the isotope ratios are determined.

Results: Oxygen isotopic ratios in H$_2$O are retrieved from eight observations taken during the first three months of operations, yielding average values of $\delta^{18}$O(H$_2$O) = 200 ± 80 ‰ and $\delta^{17}$O(H$_2$O) = 230 ± 110 ‰ with respect to Earth-like values.

In the case of CO$_2$, $\delta^{18}$O(CO$_2$) in these eight observations is essentially consistent with Earth-like fractionation. Nevertheless, long-term monitoring of this isotopic ratio appears to show variations along the ratio of the bulk atmosphere, showing both depletion and enhancement with respect to Earth-like values.

References:


MULTISCALE AND MULTISPECTRAL MARS ANALOGUE OBSERVATIONS IN PREPARATION FOR EXOMARS 2020.

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Introduction:
The ExoMars 2020 rover ‘Rosalind Franklin’ will collect data from multiple imaging instruments at multiple spatial scales and spectral resolutions to assist the science teams in establishing the geology within the landing ellipse at Oxia Planum. Ground-based observations from PanCam \cite{1}, ISEM \cite{2}, and CLUPI \cite{3} will be augmented at a larger spatial scale with orbital imagery provided by NASA CRISM \cite{4}, and ExoMars CaSSIS \cite{5} instruments, and similarly at a smaller spatial scale with geochemical observations conducted by the rover’s onboard instruments such as the Raman Laser Spectrometer \cite{6}. In particular, the flat-lying terrain that typifies the landing site within Oxia Planum means target selection will be particularly driven by localised spectral variation observed remotely by the ExoMars rover. We present results from an analogue study conducted at the Námafjall geothermal field in Iceland (Fig.1-AB), which combines multiscale, multi-instrument observations of localised meter-scale hydrothermal alteration and oxidation of basaltic soils. ExoMars instrument emulators were used to simulate the orbital-to-geochemical data synthesis.

Methods:
The composition of the Námafjall geothermal field is generally basaltic, with visible hydrothermal alteration gradients extending radially from extinct fumarole centres due to changes in temperature, which are associated with distance. We imaged this gradient at multiple scales using (i) AISA Eagle and Hawk hyperspectral aerial imagery to emulate CRISM and CaSSIS orbital data, (ii) AUPE \cite{7} data to emulate PanCam data, (iii) ISEM and (iv) CLUPI emulator data. We collected hand samples for major element compositional validation using XRF.

True colour imagery and spectral summary parameters (Fig.1C-G) were used to identify spectral variability at orbital and rover scales as done previously \cite{7,8,9,10}. ISEM-E spectra were also used to cross-validate AUPE and Eagle/Hawk data (Fig.1H) Fumarole transects have been created and analysed (Fig.1I) at all scales (Eagle/Hawk, AUPE, ISEM-E, CLUPI-E, XRF) to form a complete picture of the meter to sub-meter scale alteration gradient, which is consistent with multi-stage, acid-sulfate weathering of a basaltic substrate under low-temperature (<150°C) hydrothermal conditions. Understanding the relationships between this multi-scale, multi-instrument data on Earth is key in the development of analysis techniques for ExoMars mission data.

References: \cite{1} Coates et al. (2017)Astrobio. 17(6-7), \cite{2} Korabiev et al. (2017) Astrobio. 17(6-7), \cite{3} Josset, et al. (2017) Astrobio. 17(6-7), \cite{4} Murchie et al. (2007) JGR:P 115(E5), \cite{5} Thomas et al. (2017). SSR 212(3-4), \cite{6} Rull et al. (2017) Astrobio. 17(6-7). \cite{7} Harris et al. (2015) Icarus 252, \cite{8} Pelkey et al. (2007) JGR:P 112(E8), \cite{9} Viviano-Beck et al. (2014) JGR 119(6). \cite{10} Allender et al. (2018) ISPRS 24, V10789.

Figure 1: (A-B): Námafjall study site location. (C) True colour Eagle/Hawk image (2m/pix). (D) Spectral parameter S438_671 from the suite in \cite{9,10} (2m/pix). Red areas are highly oxidised. (E&F) Zoomed images of fumarole trio from C&D. E shows spectral transect. (G) AUPE S438_671 parameter taken from location marked in D. (H) Multiscale comparison of trio spectra. (I) Eagle/Hawk spectra extracted from transect in E.
RELICT FORSTERITE IN UNEQUILIBRATED ENSTATITE CHONDrites


Introduction: Enstatite chondrites are notable for their reduced mineralogy [1] and chemical similarity to the inner Solar System; indeed, they are considered isotopic twins of Earth [2]. Solar and cosmogenic noble gas compositions also support heliocentric distances of EC parent bodies at 1-1.4 AU [e.g. 3]. While most authors have assumed that the ECs formed from material condensed at high C/O [e.g. 4], recent trace element work suggests that EC chondrule precursors may have formed in a more oxidising environment and were later reduced by exposure to a reducing Si- and S-rich gas [5]. This gas reduced olivine to Mg-rich pyroxene and formed sulphides, thus EC chondrules record an evolving nebular composition from oxidising to reducing conditions. We have made a detailed study of relict olivine in primitive enstatite meteorites in order to test this model.

Methods: Sections of Kota Kota (EH3; BM. 1905,105; P22810), MAC 88136 (EL3; 106) and Qingzhen (EH3; BM.1999.M27; P22813 & P22814) were studied. Element mapping by EDS (Zeiss EVO 15LS SEM) was used to locate olivine, followed by cathodoluminesence (CL) imaging and EPMA ( Cameca SX100 microprobe) for mineral compositions. Synchrotron XRF maps and Ti-XANES data were acquired at beamline I18, Diamond Light Source.

Findings: Relict forsterite grains were identified in all three meteorites, appearing as anhedral to subhedral cores in chondrules surrounded by enstatite. The grains exhibit different CL properties across the UEC in this study, broadly fitting into four groups: i) consistently red throughout; ii) red interiors rimmed by strong blue CL; iii) mixed CL appearing purple; iv) consistently blue throughout. Blue olivine differs from red olivine with lower Ca, Mn, and Cr, and higher Fe, Al and Ni concentrations. An example is included in Figure 1: chondrule C2 contains an almost intact forsterite grain and two others that are more progressively altered, all showing bright red CL. The grains are surrounded by enstatite with blue CL (Ca, Al, Ti, Cr, Mn-poor) and the whole central relic is surrounded by a later generation of chondrule growth – enstatite grains with red CL (Ca, Al, Ti, Cr, Mn-bearing). Consistent differences in Ti-XANES spectra are observed between the relict forsterite and surrounding enstatite.

Implications: The model of evolving nebular compositions is supported by our petrological observations, suggesting the chondrules were once more similar to those in carbonaceous and ordinary chondrites. If the enstatite chondrules did indeed original ly form under more oxidising conditions, they could plausibly be more closely related to the Earth and other terrestrial planets on the one hand, and to other chondrite groups on the other, than previously thought. Our work will advance to O and Cr isotopic analyses to constrain the formation region of the relic material, and dating via the Al-Mg system.

Fluctuations in Jupiter’s Quasi-Quadrennial Oscillation from Ground-based data

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Introduction:

Jupiter’s equatorial stratosphere display a down-ward-moving pattern of alternating winds and temperatures that repeats every 4-5 years, called the Quasi-Quadrennial Oscillation (QQO) [1-5]. This pattern is very similar to the Earth’s Quasi-Biennial Oscillation (QBO) [6], observed with an average period of 28 months, and to Saturn’s Quasi-Periodic Equatorial Oscillation (QPO) [7-8], with a periodicity of ~15 years, whose origins are believed to be linked to wave forcing from tropospheric convection. Long-term observations have shown that the QBO on Earth and the QPO on Saturn undergo abrupt disruptions by atmospheric events occurring at the tropopause far from the equator [9-11]. Here, we analyze Jupiter’s ground-based infrared data to reveal that Jupiter’s QQO displayed two significantly different periodicities between 1980 and 2011, confirming that the QQO can also be disrupted by strong atmospheric activity occurring at deeper levels.

Observations:

In this study, we use 7.6-7.9 µm images of Jupiter captured between 1980 and 2011 by four different instruments mounted at the NASA’s 3.5-m Infrared Telescope Facility (IRTF) on Maunakea, Hawai‘i. The 7.6-7.9 µm radiation, originated from the 10-20 mbar pressure level in Jupiter’s stratosphere, reveals the CH4 emission and allows estimates of stratospheric temperatures.

![Figure 1](Image)

Figure 1. Observed brightness temperatures (a) showing equatorial quasi-periodic warm and cool patterns. Variance of the temperature over the 31 years (b), confirming the QQO theory.

Figure 1 shows the zonally-averaged brightness temperature profile between ±30° latitude, where the QQO signal is clearly observed with temperatures at equatorial and off-equatorial latitudes oscillating in time between relatively cool and warm values. The variance of the temperatures for the entire observational data set shows that the QQO signal is most prominent between ±4° of the equator and at 12-14° north and south latitudes.

Analysis of the QQO periodicity:

Two different techniques are used to analyze the period of the QQO between 1980 and 2011: (i) Wavelet transform analysis shown in Figure 2; and (ii) a Non-Linear Least-Square Minimization and Curve-Fitting method. Both techniques show two significantly different periods of the QQO, with a ~5.5-year period between 1980 and 1990 and 3.9 years between 1994-2006, followed by a new change in the period after 2006. A constant 4-5-year period over 1980-2011 fails to reproduce the observed stratospheric temperature oscillations. The change in the periodicity of the QQO coincides in time with dramatic planetary scale disturbances observed at Jupiter's troposphere in 1990-1992 and 2006-2007 at equatorial and tropical latitudes, which completely altered Jupiter's banded structure appearance at the troposphere.

![Figure 2](Image)

Figure 2. Power spectrum of the stratospheric temperature variability over time for the equatorial latitudes between ±2°.

References:

ATMOSPHERIC IONISATION AND LIGHTNING AT THE ICE GIANT PLANETS

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Introduction:

Atmospheric electricity can take the form of spectacular discharges such as lightning, but there are also weaker processes continually active in all planetary atmospheres from ionisation, mainly from galactic cosmic rays (GCR). Lightning detection can provide insight into convection, whereas electrical processes away from storms may modulate cloud formation and chemistry, particularly if there is little insolation to drive other mechanisms. The ice giants appear to be unique in the Solar System in that they are far enough away from the Sun for GCR-related mechanisms to be significant in cloud formation, yet both also seem convective enough for lightning. This presentation will summarise recent searches for lightning, and the role of atmospheric ionization and electrical processes in cloud and aerosol formation at the ice giants.

Lightning:

Electrical discharges at both Uranus and Neptune were observed by Voyager 2 in the 1980s (Zarka et al. 2008). Uranus Electrostatic Discharges (UEDs) were similar to, but an order of magnitude weaker than, Saturn Electrical Discharges (SEDs), which were first detected by Voyager 1. SEDs were verified with subsequent simultaneous optical and electromagnetic detection by Cassini, and by the ground-based radio telescope UTR-2 (Konovalenko et al., 2013). Unexpectedly, given Neptune’s strong internal heat source, only four tentative sferics were detected by Voyager 2, and they were weaker than the UEDs. There has been no optical detection at either planet, which could have been because the discharges were taking place deep in the atmosphere (e.g. Aplin et al., 2019). Modelling found that Neptune lightning was most likely to occur in the ammonium hydrosulphide clouds between 10 and 50 bar, with the pressures considered too great in the lower water cloud layer for breakdown (Gibbard et al., 1999). Uranus is assumed to be similar.

Recently it has been suggested that terrestrial radio telescopes may be able to detect Uranian lightning, however Neptune lightning is expected to be too weak for terrestrial detection, requiring a space instrument for further investigation. Here we discuss the possibility of ground-based UED detection with the Ukrainian UTR-2 radio telescope and present some results from 2014, when storms were seen in the atmosphere of Uranus.

Atmospheric ionisation:

Recent reanalyses of ground-based telescope observations of the albedo of Neptune, in combination with Voyager 2 GCR data, have explained the well-known 11-year solar cycle modulation of the brightness fluctuations in terms of a combination of UV and GCR-modulated cloud formation (Aplin and Harrison, 2016). Spectral analyses of similar ground-based telescope observations of Uranus’ brightness show a clear 11-year periodicity, also linked to GCR ionisation (Aplin and Harrison, 2017). The mechanism involved is condensation of a supersaturated vapour onto ions formed by GCR, much like in a cloud chamber. We will present some new modelling of GCR ionisation rates, and ion and cloud charging properties at the ice giant planets.

References:

Aplin K.L., et al., Atmospheric electricity at the ice giants, Space Science Reviews, July 2019


PREDICTING POSSIBLE LIQUID WATER LOCATIONS BENEATH MARS’ SOUTH POLAR ICE CAP

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Introduction: A ~20 km wide area of bright subsurface radar reflections (here dubbed the HRA) interpreted as liquid water beneath the Martian south polar layered deposits (SPLD) in data from the MARSIS instrument [1], and two geologically recent potential eskers (landforms produced by subglacial melt) associated with viscous flow features in Martian mid-latitudes [2, 3], have suggested recent basal melting of Martian ice deposits may be feasible. Locally elevated geothermal heating is suggested as a possible cause [2-5]. Here, we present calculations of the expected theoretical locations of any subglacial water beneath Mars’ SPLD at high resolution for the area containing the HRA [5], and over the entire SPLD at lower resolution.

Method: Water flow beneath terrestrial ice sheets is governed by the subglacial hydraulic potential, $\phi$, which can be calculated from surface and bed topography [6]:

$$\phi = (\rho_w - k \rho_i) g Z + k \rho_i g S.$$  \hspace{1cm} (1)

Here, $g$ is gravity (3.711 $m \, s^{-2}$); $\rho_w$ is the density of the subglacial liquid, (1000 kg m$^{-3}$ for pure water to 1980 kg m$^{-3}$ for saturated perchlorate brine); $Z$ and $S$ are the bed and surface elevation (m); $\rho_i$ is the ice density (910 kg m$^{-3}$) and $0 < k < 1$ is a dimensionless factor which represents the influence of ice overburden pressure on the local subglacial water pressure. We use surface topography from the Mars Orbiter Laser Altimeter, and SPLD bed elevations derived from MARSIS data to calculate the subglacial hydraulic potential surface beneath the SPLD. We use a flow accumulation algorithm on the potential surface which identifies (and preserves flow continuity through) closed depressions on the surface [7] which form the locations where subglacial liquid would be expected to collect. In [5] we compare the observed location of the HRA with predicted depression locations, performing a suite of experiments to test the robustness of the inferred basin locations. Here, we extend this and calculate the flow routing and inferred basin locations across the entire SPLD at a resolution of 64 pixels per degree (~920 m per pixel), using our standard values from [5].

Results: Figure 1 shows that the HRA does not coincide with a predicted basin in the potential surface [5]. This finding is robust to variations due to instrument uncertainty, the assumed ice and water density, the value of $k$ and DEM resolution. We interpret this finding to mean that if the HRA is liquid, it is most likely an isolated patch constrained by the surrounding frozen-based ice, rather than a true, topographically-controlled subglacial lake.

![Figure 1](image1.png)

Figure 1. Calculated flow accumulation values at 200 m resolution. X and Y axis units are km from the centre of the area. Basins appear as areas of high, uniform values. Colour scale units are the log$_{10}$ of the upstream area flowing into each cell in km$^2$. Red contour shows the HRA [1]. Red box in Fig. 2 shows the location.

![Figure 2](image2.png)

Figure 2. Calculated flow accumulation values for the entire SPLD at 64 pixels per degree, with area colour scale units as Fig. 1. Red box shows the area in Figure 1.

MODELLING ESKER FORMATION ON MARS

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Introduction: Eskers are sinuous sedimentary ridges that are widespread across formerly glaciated landscapes on Earth [e.g. 1]. They form when sediment in subglacial tunnels is deposited by meltwater, and are exposed when ice retreats. Some sinuous ridges on Mars have been identified as eskers. Whilst some such systems are thought to have formed early in Mars’ history beneath more extensive ice sheets [e.g. 2], smaller, younger systems (Fig. 1) associated with extant glaciers in Mars’ mid latitudes have been identified [3, 4].

Figure 1. High Resolution Imaging Science Experiment image ESP_044804_2130 of the glacier-linked esker in Phlegra Montes identified by Gallagher and Balme (2015).

Elevated geothermal heating and formation during periods with more extensive glaciation have been suggested as possible prerequisites for esker deposition [3, 4]; modeling [5, 6] also supports geothermal heating as a possible cause of the area of assumed liquid water beneath Mars’ south polar ice cap [7].

Two recent models of esker formation on Earth use the same basic physics, but consider different time and spatial scales. Hewitt and Creyts (2019) [8] focus on longer/larger scales, assume ubiquitous basal melt, supplemented by summer melting, and develop general constraints on the spacing and scaling of eskers beneath retreating ice sheets. In contrast, Beaud et al. (2018) [9] focus on smaller scale, inter-seasonal patterns of sediment deposition of an individual esker in response to a range of varying and variable water inputs. Given it seems likely that geothermally-driven subglacial melt on Mars will be spatially and temporally limited, and that detailed morphological measurements of a putative Martian esker are available [3], here we adapt the model of [9] and use it initially to investigate the impact of Martian conditions on subglacial tunnel systems, aiming then to investigate the effect of discharge and topography as controls on Martian esker deposition.

Methods: We adapt [9] with $g$ and other constants altered to Martian values. We conduct a series of model experiments varying the assumed liquid density ($\rho_L$) from 1000 kg m$^{-3}$ to 1980 kg m$^{-3}$ (the density of saturated perchlorate brine) and ice hardness ($A$) from $2.4 \times 10^{-22}$ Pa$^{-1}$ to $5 \times 10^{-22}$ Pa$^{-1}$ (a temperature range of 0°C to -50°C) in order to explore effect of Martian parameter values on the operation of subglacial tunnel systems. We aim to extend this modeling in a series of experiments of increasing complexity to investigate the water discharge needed to deposit eskers of the size observed in association with current mid-latitude glaciers [3, 4]; the impact of variable water discharge on esker formation by simulating a possible catastrophic release of meltwater from an assumed geothermal event using a Mars-adapted model of water release from Antarctic subglacial lakes [10]; and using observed bedtopography of a mid-latitude esker [3] to assess the possible impact of topography on deposition patterns and esker morphology.

Results and discussion: A key aspect of model behavior is the decrease in sediment carrying capacity towards the ice margin due to increased conduit size as ice thins [8, 9]. Initial results with no sediment/tunnel feedback suggest that Martian parameters emphasise this effect, making deposition more likely over a greater length of the conduit. Lower gravity has the largest impact; flow shear stress increases with higher liquid density, but reduces markedly for harder ice due to decreased tunnel closure lowering water pressure and hence velocity.

Simulations of the hypothesised moon forming event reproduce the physical properties of the Earth-Moon system, but do not constrain the fraction of the Moon which came from the impactor. Similarities of the Earth and Moon in refractory element and isotopic ratios of a number of elements suggest however that silicate Moon is dominantly comprised of pre-impact silicate Earth. A zeroth order model would therefore equate the silicate Moon with Earth’s peridotitic mantle. Arguments against such a simplistic approach are firstly the low concentrations of volatile elements in lunar basalts and secondly the apparent enrichment of silicate Moon in Fe and Ti relative to terrestrial peridotite.

In order to determine how close compositionally the source regions of lunar basalts are to terrestrial peridotite we have experimentally investigated the fractional crystallization of a magma ocean comprised of fertile, volatile-depleted pyrolite at the reducing conditions and pressures appropriate to the early Moon. The approach was to start with the putative lunar peridotite composition and perform a series of stepwise crystallisation experiments. Starting at 2 GPa and 1625°C, the pressure and temperature were decreased systematically at each step to yield a crystal fraction of approximately 9% in each of 11 steps. The composition of the remaining melt fraction in each experiment was measured by electron microprobe and used as the starting composition for the next step in the series.

Our results show that during fractional crystallisation of a peridotitic magma ocean the residual melt composition evolves to refractory element concentrations similar to those observed in lunar mare basalt. Mixing of this residual melt with more olivine-rich material can account for much of the lunar surface material; it is therefore broadly possible, after extensive fractional crystallization to form the Mare Basalts from a fertile terrestrial peridotite.

Here the modelled and experimentally found liquid line of descent diverge early on in the line of descent. This can be assigned to the over stabilisation of pyroxene in the MELTS thermodynamic modelling program. I have used the phMELTS version at 1.5GPa and starting above the liquidus. Crosses are bulk rock data from the Apollo missions. Mixing between the early and late stages of crystallisation can explain much of the diversity of lunar surface lithologies.
OPPORTUNITIES FOR INVOLVEMENT IN THE EXOMARS PROGRAMME

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Introduction:
The European Space Agency (ESA) ExoMars Programme consists of two elements [1]: the Trace Gas Orbiter (TGO), launched in 2016 and currently performing science operations from Mars orbit, and the ExoMars Rosalind Franklin Rover (ERFR), scheduled to launch in July 2020 and to land on the martian surface in March 2021. Both elements are focused on the search for extant or ancient life on Mars; TGO can measure small traces of potentially biologically significant gases such as Methane in Mars’ atmosphere, and ERFR has an onboard laboratory and a deep drill system that will allows samples from ~ 2 m beneath the surface to be extracted and examined for the presence of possible biosignatures.

Figure 1. ExoMars Trace Gas Orbiter (top) and Rosalind Franklin Rover (bottom)

UK role in ExoMars
UK science and industry has played a key role in the ExoMars programme, including designing and assembling the ERFR. The UK also has significant representation in the leadership of both ExoMars programme elements, including PI (Principal Investigator), Co-PI (Co-Principal Investigator) and CoI (Co-investigator) roles on instruments on TGO and ERFR. Examples of UK leadership include the TGO NOMAD [2] instrument (Co-PI Manish Patel, Open University), ERFR PanCam Instrument [3] (PI, Andrew Coates, Mullard Space Science Laboratory, UCL) and ERFR Raman Spectrometer instrument [4] (Co-PI Ian Hutchinson, University of Leicester). In addition, many UK scientists are involved in ESA steering groups that provide advice and direction on how the missions run. Examples include the ExoMars Rover Science Operations Working Group (RSOWG) and Data Archiving Working Group (DAWG).

Here, we provide an update on the progress of the ExoMars programme, and describe how members of the community can become involved in the science and operations of TGO and ERFR. Potential users of TGO and ERFR data can find them at the ESA Planetary Science Archive (http://psa.esa.int), but input from the Instrument science teams provides important additional context.

References:
ARAM DORSUM: AN EXTENSIVE NOACHIAN-AGE FLUVIAL DEPOSITIONAL SYSTEM IN ARABIA TERRA, MARS

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Introduction: Fluvial processes created extensive river-systems on ancient Mars, as demonstrated by observations of relict erosional valley systems, preserved in negative relief (e.g., [1]), and by aggradation alluvial systems, often preserved in positive relief as upstanding ridges due to differential erosion (e.g., [2]). Here, we describe the geomorphology and stratigraphy of Aram Dorsum (Figure 1), a particularly well-preserved ridge-system in western Arabia Terra. Aram Dorsum is a flat-topped ridge ~85 km long, ~1 km wide, with a surface ~40 m above the adjacent flat-lying terrain.

Key Observations and Interpretations: Aram Dorsum is composed of a main ridge and several smaller, subsidiary ridges converging into it in a branching network pattern. Surrounding the main and subsidiary ridges are low-relief plains that extend a few kilometers either side. In addition, there are many examples of layering in the flanks of the ridges, and some channel segments are buried by other channel segments, or by smooth marginal materials. These observations show that Aram Dorsum formed as an ag gradational alluvial system and was once a large river set in extensive flood plains. Similar ‘inverted fluvial channels’ are common elsewhere on Mars and on Earth (e.g., Figure 2, [3]–[5]). The contributory ridges represent smaller alluvial systems, and their setting and network pattern suggest a distributed source of water.

The alluvial succession here is up to 60 m thick, suggesting a formation time of \(10^5\) to \(10^7\) years by analogy to Earth (e.g., [6]). Correlating our observations with previous regional-scale mapping [7] shows that Aram Dorsum was formed in the mid-Noachian. Our observations are consistent with Aram Dorsum having formed by long-lived, quiescent flows of water, sourced both regionally and locally.

Conclusion: Our observations suggests that Aram Dorsum was once an extensive river system, active in the mid-late Noachian. The morphological evidence points to frequent or seasonal precipitation as the source of water. The location and inferred depositional setting of Aram Dorsum are inconsistent with a distant point-source of water, such as a rarely-melting ice-sheet in the southern highlands (e.g., [8]).

References:
The reconstruction of ancient compound aeolian bedforms in Gale crater, Mars

Introduction: The Stimson formation, Gale crater, Mars is an aeolian sandstone which accumulated on a deflationary unconformity stratigraphically above the lacustrine Murray formation. Between Sols 987 and 1454, Mars Science Laboratory rover Curiosity traversed this outcrop documenting the nature and distribution of facies within the Stimson to determine the origin, stratigraphic context, and palaeoclimatic significance.

Figure 1: Stimson outcrops

Northern Outcrops: The northern most outcrops, within the Emerson plateau area (Figure 1) are characterised predominantly by simple metre-scale cross sets, up to 1 m thick (Figure 2). These are bounded by decametre-length sub-horizontal bounding surfaces, which are interpreted to be interdune surfaces. No fine-grained interdune deposits were recorded in this region. Internally, these cross sets are composed by millimetre-thick uniform lamina- tions, interpreted as wind ripple strata. No evidence for grainflow strata was observed, but textural analysis of grains using the Mars Hand Lens Imager suggests transport by aeolian processes. Measurement of foreset dip-azimuths across the Emerson Plateau record a dominant sediment direction toward the north east.

Southern Outcrops: The southern outcrops, in the Murray Buttes area (Figure 1) are characterised by compound cross sets (Cosets), with measured thicknesses up to 4 m (Figure 2). Cosets are bounded by sub-horizontal bounding surfaces, which can be traced laterally across the width of the outcrop. Within these cosets, inclined bounding surfaces, interpreted to be superposition surfaces, divide individual cross sets which have thicknesses up to 1 m thick. Although close inspection of cross laminations could not be conducted within the Murray buttes, they have the same visual expression and apparent uniform thickness as those observed in the Emerson Plateau. Again, no evidence of fine-grained interdune deposits, or damp aeolian processes were recorded. Inter- dune surfaces are interpreted to have formed by passage of a scour pit preceding a migrating draa scale bedform (also described as a complex or compound dune), with superposition surfaces being scoured during the transit of superimposed dunes down the draa’s lee slope. The superposition surfaces record the orientation of the draa’s lee slope, and can be used to determine sediment transport direction for the draas, while the cross lamination dip-azimuth can be used to determine sediment transport direction in the superimposed bedforms. In the Murray Buttes, Draas migrated toward the north-north-west, while superimposed bedforms migrated north east.

Environmental reconstruction: Palaeoenvironmental reconstruction based on these observations records a transect across a dry aeolian system. The outcrop at Emerson Plateau represents a more distal section of the erg, characterised by simple dunes approximately 10 m high, with wave lengths of ~160 m. The outcrops at the Murray Buttes represent the preserved expression of a more central part of the Stimson Erg, where draas with heights up to 60 m, and spacings up to 900 m were present. Superimposed the draas indicating a complex wind regime.
THREE-DIMENSIONAL RECONSTRUCTION AND QUANTIFICATION OF FLUVIAL-DELTAIC SEDIMENTARY DEPOSITS IN GALE CRATER, MARS, FROM ROVER-DERIVED DIGITAL OUTCROP MODELS

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Introduction: Modern and ancient fluvial-deltaic systems on Earth contain highly diverse ecosystems in all terrestrial climates. Fluvial and lacustrine deposits have been discovered on Mars by the NASA Mars Science Laboratory rover Curiosity [1, 2, 3, 4], and may be present in Oxia Planum [5, 6], where the ESA ExoMars rover Rosalind Franklin [7] is set to land in 2021. The primary aim of this mission is to find evidence for ancient life, therefore fluvial-deltaic sandstones, mudstones and siltstones are high priority targets for sampling and drilling. The geometries of sedimentary structures and distribution of sedimentary facies within these fluvial systems provide information which can be used to reconstruct the geometries and flow parameters of these ancient systems. This provides us with quantitative means with which to make inferences on the ancient climate of Mars, and aids decision making with regards to planetary rover contact science.

3D analysis methodology: In this research we used the 3D visualization software tool PRo3D [8] to visualize the outcrops as scaled 3D textured models. Mastcam data taken from different rover locations was processed into 3D surfaces and spatially matched to Navcam stereo-panoramas to create digital outcrop models (DOMs). Sedimentary facies, key bounding surfaces and sedimentary structures were mapped out on the DOM and the dip and strike of lithological boundaries, key bounding surfaces, and cross-laminations were measured directly from the DOMs. Apparent widths and thicknesses of the layers and cross-lamination sets were measured. The true dimensions were estimated based on geometrical constraints provided by palaeocurrent directions. Regularly spaced, sedimentary logs were collected and matched to illustrate the detailed internal structures of the outcrops analysed.

Fluvial-deltaic outcrops in Gale crater: We used 17 Mastcam stereo-panoramas from the Shaler outcrop, Yellowknife Bay, imaged on Sols 120-121 and 309-324 and 14 Mastcam stereo-panoramas taken between Sols 753 – 901 during the Pahrump Hills campaign to create DOMs of outcrops which show clear fluvial characteristics. The observations from these are summarized below.

Shaler. A DOM was constructed which contained a 25 m x 9 m area of outcrop which trended NE-SW. Four types of sedimentary structures were identified; low-angle cross strata dipping to the SE, ~50 cm thick; convex up, sub-parallel undulating laminations forming structures with 20-40 cm amplitude and 2 m wavelength; single sets of trough cross-laminations and compound, stacked cosets of trough cross-laminations, with thicknesses on average 9 cm, and yielding a common palaeoflow direction to the NE and SW. Coarsening to the SW is observed, together with an increase of bounding surface dip from 10-12 in the NE increasing to <25 in the SW part of the outcrop. This steepening also corresponds with dominant single sets of cross-laminations in the NE, and composite cosets in the SW. These data allow us to reconstruct the internal architecture of the bar-form [3] which forms the Shaler outcrop.

Pahrump Hills. A DOM was constructed showing the Chinle, Whale Rock and Newspaper Rock outcrops in their regional context in the Pahrump Hills area, interpreted [4] to be 0.5m - 2 m thick lenses of fluvial sandstones within the lake deposits represented by the surrounding Murray mudstones. These are formed primarily of compound sets of 5-10 cm thick primarily SE dipping trough cross-laminations, as well as low angle cross-laminations in the Chinle outcrop which are 3 – 10 cm thick and exhibit a largely southward palaeoflow direction.

Summary: Here we present the first detailed quantitative 3D analysis of fluvial sedimentary architectures on Mars, using rover image data. We compare these results to data collected in the Old Red Sandstone fluvial outcrops of Pembrokeshire, SW Wales, imaged with the Aberystwyth University PanCam emulator, as well as make inferences based on our understanding of environmental reconstruction and flow parameters in terrestrial systems to understand these fluvial deposits.

THERMAL INFRARED SPECTRAL SIGNATURE OF AQUEOUSLY AND THERMALLY METAMORPHOSED CM AND CY CHONDRITES

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Introduction: JAXA’s Hayabusa2 will return samples from the C-type asteroid Ryugu in 2020 [1] and NASA’s OSIRIS-REx will return samples from the B-type asteroid Bennu in 2023 [2]. Preliminary observations suggest a complex alteration history on both bodies: Hayabusa2 found evidence for dehydration on the surface of Ryugu [3], and observations by OSIRIS-REx identified similarities between highly aqueously altered CM and CI chondrites and Bennu [4]. In order to interpret the results from these missions we need to analyse appropriate meteorite analogues. To that end we have collected thermal infrared (TIR) emissivity spectra for a suite of aqueously and thermally altered CM, CY and CM-an chondrites under appropriate simulated asteroid environment conditions (SAE) [e.g. 5].

Samples: We investigated three unheated CM chondrites: Alan Hills (ALH) 83100 (CM1/2), ALH 83102 (CM1/2) and Lonewolf Nunataks (LON) 94101 (CM2). We also analysed the heated chondrites (heating stages after [6]) Elephant Moraine (EET) 92069 (CM2, Stage II, 300 – 500 °C) [7], Wisconsin Range (WIS) 91600 (CM-an, Stage II) [8], Yamato (Y-) 793321 (CM2, Stage II) [9], Pecora Escarpment (PCA) 02010 and PCA 02012 (both CM2s, Stage IV, >750 °C) [10], and the CY chondrites Yamato (Y-) 980115 (Stage III, 500 – 750 °C), Y-86720, Y-86789, and Belgica (B-) 7904 (all Stage IV) [11].

Experimental: Samples were ground to a powder with particle size of <35 µm. TIR emissivity measurements were collected in the Planetary Analogue Surface Chamber for Asteroid and Lunar Environments (PASCALE) at Oxford University. The near-surface environment of Bennu was simulated by removing atmospheric gases (<10⁻⁴ mbar), cooling the chamber interior to <-150 °C and heating samples from above and below until the maximum brightness temperature of the sample was ~75 °C. This induces a thermal gradient in the upper hundreds of microns of the sample, which is what we would expect on the surface of Bennu near local midday [12]. Spectra were collected using a Bruker VERTEX 70v Fourier Transform IR (FTIR) spectrometer from 1800 – 200 cm⁻¹ (5.5 – 50 µm) using a wide range beam splitter at a resolution of 4 cm⁻¹.

Results & conclusions: The TIR spectral signature in CM chondrites is controlled by the primary, Mg-rich olivine content, which in turn is determined by the degree of aqueous alteration. Samples which have experienced less aqueous alteration show overtone and vibrational bands associated with forsteritic olivine throughout the whole spectral range. Due to the absence of this primary olivine phase in the CY chondrites, their spectra seem to reflect secondary, poorly crystalline Fe-rich olivine. It is therefore difficult to determine whether thermal metamorphism has occurred from TIR spectral signature alone, unless high degrees of aqueous alteration occurred. Additionally, spectral features due to magnetite are identifiable when abundances are ~10 vol%, and as these features have been detected in the Bennu spectrum, this implies comparable abundances on its surface.

TIMESCALES OF MAGMA TRANSFER IN APOLLO 15 MARE BASALTS OBTAINED THROUGH FE-MG DIFFUSION MODELLING IN OLIVINE AND PYROXENE CRYSTALS

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Introduction:

The chemical characteristics of crystals in igneous rocks provide a record of the magmatic environments and processes they experienced[1]. Here we use compositional zoning within crystals (Fig. 1) to extract information about the timescales of lunar magmatic processes.

Chemical zonation in crystals is produced in response to changing magmatic variables, such as the surrounding melt composition, as the crystal grows[1]. Atoms may diffuse across initially sharp compositional boundaries within a crystal as the mineral re-equilibrates with its surrounding magmatic environment. Diffusion is a time-dependent process with known diffusion rates for certain elements within different minerals[1]. Therefore, we can fit diffusion models to chemical profiles in zoned crystals to determine how long the crystal resided in a particular magmatic environment.

Diffusion modelling has been successfully used on samples with a terrestrial magmatic origin, allowing for a better understanding of magmatic plumbing systems and processes prior to eruption [2,3,4]. Here we present diffusion timescales for Apollo 15 mare basalts to gain insight into lunar magmatic processes.

Erupted ~3.35 to 3.25 billion years ago, the Apollo 15 mare basalts have been chemical classified as either quartz-normative or olivine-normative based on differences in bulk rock SiO2, FeO and TiO2 wt% [5,6]. The petrogenetic relationship between the two suites has proven to be controversial. The most recent hypothesis, based on major and minor trace element abundances, is that the quartz-normative suite underwent a multi-stage crystallisation history whilst the olivine-normative suite predominantly crystallised in lava flows on the lunar surface [7]. We aim to use quantitative petrological techniques to understand how differences in magmatic histories, as recorded in crystal zoning patterns, may have resulted in the chemical differences between the two Apollo 15 mare basalts suites.

Methods:

A total of 48 olivine and 13 pyroxene crystals from nine thin sections were identified as suitable candidates for Fe-Mg diffusion modelling based on their zonation patterns. Electron probe microanalysis (EPMA) was used to measure major elements in line profiles across the zoned olivines and pyroxenes. Iron diffusivity in olivine is strongly anisotropic; so we used electron backscatter diffraction (EBSD) to determine the crystallographic orientation. Fe-Mg diffusivity is also dependent on temperature and oxygen fugacity. Appropriate values for these variables in the Apollo 15 magmatic system will be established using existing literature and software (e.g. MELTS and SPICES).

Summary:

Preliminary results suggest crystal residence times of 1.68-3.84 years, with a ~1 year time difference between the average timescales for quartz- and olivine-normative samples.

This study will provide a greater understanding of the processes during magma storage and eruption of the Apollo 15 mare basalts. Our results may have implications for our understanding of the architecture of lunar magmatic systems, and the rates of magma transfer lunar magmatic processes across the Moon as a whole.

Figure 1: A backscattered electron image of an olivine crystal in thin section sample 15485.31. The crystal shows diffusion zoning from a Mg-rich core to an Fe-rich rim. The location of the EPMA profile is shown in red.

References:

**Saturn’s Seasonal Atmosphere: Cassini CIRS contrasts to VLT and IRTF observations**

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**Abstract**

Observations from the Texas Echelon Cross Echelle Spectrograph (TEXES) on NASA’s IRTF and the VISIR instrument on the VLT are used to characterize the Saturn’s seasonal changes. Radiative transfer modelling (using NEMESIS [8]) provides the northern hemisphere temperature progression of the atmosphere over 10 years, both during and beyond the Cassini mission. Comparisons between imaging observations taken one Saturn year apart (1989-2018) show the extent of the interannual variability of Saturn’s northern hemisphere climate for the first time.

**1. Introduction**

With the culmination of Cassini’s unprecedented 13-year exploration of the Saturn system in September 2017, and with no future missions currently scheduled to visit the ringed world, the requirement to build upon Cassini’s discoveries now falls upon Earth-based observatories. Mid-infrared observations have been used to characterise features such as the extreme temperatures within an enormous storm system in 2011 [1,6], the cyclic variations in temperatures and winds associated with the ‘Quasi-Periodic Oscillation’ (QPO) in the equatorial stratosphere [2] and the onset of a seasonal warm polar vortex over the northern summer pole [3]. Saturn’s axial tilt of 27° subjects its atmosphere to seasonal shifts in insolation [4], the effects of which are most significant at the gas giant’s poles. The north pole emerged from northern spring equinox in 2009 (planetocentric solar longitude $L_s=0^\circ$), and northern summer solstice in May 2017 ($L_s=90^\circ$), providing Earth-based observers with their best visibility of the north polar region since 1987, with its warm central cyclone and long-lived hexagonal wave [5,6].

Studying these interconnected phenomena within Saturn’s atmosphere (particularly those that evolve with time in a cyclic fashion) requires regular temporal sampling throughout Saturn’s long 29.5-year orbit. We present here a showcase of research from the wealth of archived observations from both TEXES and VISIR obtained over the past decade.

**1.1 Temperature progression**

Methane ($\text{CH}_4$) is used to determine stratospheric temperatures due to its even distribution across the planet, as well as its well understood emissive behavior. Figure 1 shows the visible changes in the stratospheric and tropospheric conditions as seen by VISIR over 3 years; these images are representative of a range of filters between 7-20 μm, which can be stacked and inverted to derive the 3D temperature distribution in the upper troposphere and stratosphere. Using this technique, we probe changes in the atmospheric 3D temperature distribution across the planet disc in VISIR observations taken from April 2008 ($L_s=343^\circ$) to July 2018 ($L_s=102^\circ$); thereby discerning the spatial variability as well as temporal.

VISIR observations concurrent with the Cassini/CIRS observations will be used to cross-check the time-series from Cassini, which can be extended beyond the end-of-mission with the newer VISIR observations. These profiles will provide a new measure of long-term temperature variability in the context of an established model.

**1.2 Interannual Variability**

Spectroscopic maps of the northern summer hemisphere from TEXES instrument on the IRTF collected in September 2018 have provided a unique opportunity, as they were acquired exactly one Saturn year apart from the 1989 observations of Gezari et al, (1989) [7], which were the first ever 2D images of Saturn in the mid-IR. Examining the differences in brightness temperatures and composition will indicate the extent of any interannual variation for Saturn’s northern hemisphere. This study will also provide unique
insight into the timescale of the QPO which will be contrasted with a previously suggested biennial cycle [2]. The seasonal temperature progression measured in Section 1.1 also enables us to place this interannual variability in a wider context and provides further opportunity for insightful comparison with the comparatively shorter-term temperature variability.

Figure 1 (opposite): VISIR observations from P95-102 sensing the troposphere (right) and stratosphere (left). Polar warming is evident in the stratosphere; but is considerably smaller than that seen during southern summer and in the historical record of the 1980s. The warm polar hexagon is seen at the north pole, the first such observation from the ground. Work to remove residual striping is ongoing and has been successfully applied to the 2017 images. 2015-16 images have been published by Fletcher et al., 2017 [2].

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Quantifying Dune and Ripple Migration in Valles Marineris, Mars: A Source-to-Sink Aeolian system.

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Introduction: Aeolian processes are the dominant surface process on present-day Mars. In this study, we have identified an active source-to-sink aeolian system in Coprates Chasma, Valles Marineris. The source region is continually being eroded supplying sediment to an eastward migrating sand sheet and dune field. We have measured the migration of the dune field and using these values, been able to calculate an approximate age of the dune field.

Study Site: We have studied the ripple and dune movement of a 111 km$^2$ dune field in southern Coprates Chasma, in the south east of Valles Marineris (Figure 1). The dune field is part of an aeolian system which transitions from a potential source region, which is a layered deposit, to a sand sheet to the dune field. The dune field is made up of barchan and barchanoid dunes that range in height from 3-182 m (arithmetic mean ~ 50 m), making the Coprates dunes some of the largest on Mars.

Methods and Data: We measured the dune and ripple displacement using images from the High Resolution imaging Science Experiment (HiRISE; 0.25 m/pixel) [1] and Context Camera (CTX; 5-6 m/pixel) [2] with a combination of software including Co-registration of Optically Sensed Images and Correlation, (COSI-Corr) [3] a change detection software, over a seven year time period. Ripple migration was measured with sub-pixel correlation of HiRISE images with COSI-Corr. Dune crest displacement was measured manually with CTX images in ArcGIS.

The thermal inertia (Ti; the degree of slowness with which the temperature of a material approaches that of its surroundings) of the dune field, sand transport pathway, potential source region and the floor of the valley was measured with THEMIS [4] (Thermal Emission Imaging System) data.

Results and Conclusions: We measured the dune crest and ripple displacement over a seven year time-period. The geometric mean dune crest displacement rate was calculated to be 0.38 my$^{-1}$ and ripple displacement rate was 0.81 my$^{-1}$ and crest fluxes range from 0.96 m$^3$my$^{-1}$ to 32.5 m$^3$my$^{-1}$. The topography of the valley; the large valley walls of 4 km height are likely to cause katabatic and aplanetic slope winds, facilitating dune and ripple movement. The channeling of the winds through the valley can be seen by the movement of the dune field eastwards down the valley. The thermal inertia results support the idea of material being transported down the valley because there are similar thermal inertia values for the potential source region, sand transport pathway and the dune field. There were sharp differences in the thermal inertia values of the bajadas on the floor of the valley in comparison to the sand transport pathway. Suggesting that the bajadas are composed of a different material than the basaltic sand, which makes up the dune field, although there are other factors to consider.

In this study, we successfully showed the migration of the Coprates Chasma dune field and identified a potential source region. Assuming a constant displacement rate from the potential source region, an approximate age of the dune field of 78 ma was calculated. The age of the dune field is relatively young, showing it is the most recent feature within the valley and the dune front will continue to migrate eastwards down the valley.

THE EFFECT OF METAMORPHIC HEATING ON THE ORGANIC MATTER AND AMORPHOUS SILICATES IN CO CHONDRITES

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Introduction: Carbonaceous chondrites preserve the original building blocks of the solar system and are important tracers for the formation and evolution of asteroids. The matrix of CO3 carbonaceous chondrites contains up to ~3.5 wt% carbon mainly in a wide variety of organic materials including soluble molecules and kerogen-like insoluble organic matter (IOM) [1-3]. The loss of spatial information in previous studies limits our understanding of the relationship between the mineralogy and organic materials in carbonaceous chondrites.

Raman spectroscopy analysis of CO3 chondrites reports no link between the OM maturity and the mineralogy [4]. However, transmission electron microscopy (TEM) studies of CR3.0 chondrites suggest the OM has a close spatial relationship with specific mineral phases such as phyllosilicates, as well as being distributed along grain boundaries [5]. A relationship between organic matter and GEMS has also been observed in interplanetary dust particles (IDPs) [6, 7].

Here, we have characterised the spatial relationships between the functional chemistry of carbonaceous carbon material and the mineralogy in the matrix of CO3 chondrites within the petrologic range 3.0 to 3.8. The combination of TEM and scanning transmission X-ray microscopy (STXM) provides the high spatial resolution (10’s nm) and the spectral and mineralogical analysis necessary for in-situ analysis of fine-grained and heterogeneous chondrite matrix.

Methodology: Matrix areas within the CO3 chondrites were initially characterised using an FEI Quanta 650 scanning electron microscope (SEM). Focused ion beam (FIB) sections were extracted from these areas and attached to Cu TEM grids. TEM analyses were carried out using a FEI T20 instrument operated at 200 kV. Carbon, nitrogen, oxygen and iron X-ray absorption near edge structure (XANES) spectra were obtained from the FIB sections using STXM on beamline I08 at Diamond Light Source, UK.

Results: The matrix of primitive CO3 chondrites consists of an amorphous groundmass within which is embedded ~0.1 μm silicate, sulphide, metal and phyllosilicate grains. TEM imaging also revealed a systematic change in the porosity of the matrix as a function of metamorphic grade. Re-crystallization and equilibration caused by metamorphic heating progressively increased the porosity and average grain size of the minerals up to CO3.8. Amorphous Fe-bearing silicates in the CO3.0 chondrites are almost fully oxidized with a Fe^{3+}/ΣFe ratio close to 1.0. On heating the Fe in silicates becomes rapidly reduced with Kainsaz (CO3.2) containing only ~10% Fe^{3+} and Moss (CO3.6) being almost entirely Fe^{2+}.

Spatial variations in the functional chemistry of the organic matter in the most primitive CO3 chondrites were imaged. This variation was most evident in the intensity of the aromatic, ketone and carboxyl spectral features. As a function of metamorphic heating the aromatic group persists while the ketone and carboxyl groups disappear such that in Moss (CO3.6) only aromatic carbon was observed. Graphite was not definitively identified in any of the samples.

Discussion: Metamorphic heating on the parent body of the primitive CO3 chondrites crystallised the amorphous Fe-bearing silicates, systematically modified the modal mineralogy [8], increased the porosity of the matrix and homogenised the molecular speciation within the organic matter. The hydrated amorphous silicates dehydrate within a narrow temperature interval of about 100ºC and there is a concomitant reduction of the Fe^{3+} to Fe^{2+} as the amorphous Fe-bearing silicates transform into crystalline minerals. This reduction of the Fe is facilitated by the changing redox conditions likely due to the removal of oxidizing H₂O and the initial presence of reducing agents such as H and C.

The spatial variation and complexity of the OM functional chemistry reduces with metamorphic heating. The homogenisation of the OM in the higher petrologic grade CO chondrites is potentially facilitated by the release of water from the amorphous Fe-bearing silicates and the increased permeability resulting from the recrystallisation of the primitive fine-grained mineralogy.

Plutonic Igneous Float Rocks at Ireson Hill, Gale Crater, Mars

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Introduction: Igneous float rocks discovered by surface missions on Mars have given unique insights into the igneous processes that have operated throughout the planet’s history. We examine a group of float rocks that were identified by the Mars Science Laboratory mission’s Curiosity rover at the Ireson Hill site, circa. Sol 1600. Images from the MastCam, Mars Hand Lens Imager (MAHLI) and ChemCam Remote Micro-Imager cameras provide textural and morphological evidence that these float rocks are igneous in nature, with one particular rock, “Pogy”, showing clearly igneous texture. Geochemical data provided by the APXS and ChemCam instruments allow us to compare the compositions of these rocks to similar examples from Gale crater, as well as elsewhere on Mars. Our work has focused on Pogy as it has the strongest evidence for its igneous origin.

Texture: High resolution images of Pogy (fig. 1) reveal a crystalline texture with two visually distinct phases. A lighter toned phase makes up approximately 60% of Pogy’s texture, and the darker toned phase approximately 20%. The remainder being interstitial material without distinct grains. Both phases are anhedral, with grain sizes typically ranging from 1-1.5 mm. We interpret this to mean that Pogy is plutonic in origin. The texture of the three other float rocks at Ireson Hill cannot be determined from available imagery.

Composition: Results are presented for three igneous float rocks. Pogy’s APXS geochemical composition (fig. 2) shows high similarity in SiO₂, Na₂O, K₂O, CaO, Al₂O₃ & TiO₂ to the Adirondack-class basalt compositions predominant at the Gusev crater MER mission site, with some difference seen in MgO and FeO(T), resulting in a reduced Mg#. Previous work has hypothesized that the more evolved basaltic and trachy-basaltic compositions observed in Gale crater may have evolved from a parental magma with composition similar to that of the Gusev basalts[1], but direct observations of such a composition are absent at Gale crater [2].

![Figure 1: A) MAHLI image showing Pogy’s crystalline texture. B) MastCam image of Pogy. Scale bar = 4cm.](image1.png)

Figure 1: A) MAHLI image showing Pogy’s crystalline texture. B) MastCam image of Pogy. Scale bar = 4cm.

![Figure 2: Total Alkali vs Silica composition plot. Contours show bulk ChemCam data (up to Sol 1482). Cross shows ChemCam precision (solid) and accuracy (dashed) Adirondack class APXS compositions (squares) from [3]. Pogy composition (diamond) from APXS, other Ireson Hill data (crosses) from ChemCam.](image2.png)

Figure 2: Total Alkali vs Silica composition plot. Contours show bulk ChemCam data (up to Sol 1482). Cross shows ChemCam precision (solid) and accuracy (dashed) Adirondack class APXS compositions (squares) from [3]. Pogy composition (diamond) from APXS, other Ireson Hill data (crosses) from ChemCam.

In our analysis of Pogy’s composition, we employ CIPW normative mineral calculations which indicate that Pogy is silica-saturated, although this mineralogy does not clearly relate to images of Pogy’s texture.

We use MELTS [4] to investigate possible magmatic evolution pathways for Pogy. Pogy-like compositions can be generated by fractionation of magmatic compositions previously derived as parental to Adirondack-class basalts [5], with approximately 13% of the original mass removed through olivine crystal fractionation. The exact conditions of magmatic evolution differ somewhat from the Gusev basalt pathways in order to account for the lower Mg# of Pogy’s composition compared to the Adirondack composition.

Our results suggest that this rock is sourced from a similar mantle source to the Gusev basalts, which may be related to evolved compositions in Gale crater through varying degrees of fractionation.

The Lunar Trailblazer mission: Understanding the Moon’s water


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Introduction: Lunar Trailblazer is a pioneering NASA SIMPlex mission to investigate the presence and form of water on the Moon, selected for Phase A/B development with Preliminary Design Review in September 2020 and launch as an ESPA Grande class ride-along as early as late-2022. This presentation will describe the science mission design and associated techniques to characterize the Moon’s water.

The detection via remote sensing of possible surficial water in both sunlit and shadowed regions of the Moon was one of the most unexpected discoveries of the 2000s. Observations by near infrared imaging spectrometers, in particular M3 on Chandrayaan-1 [1] and confirmed by lunar flybys (e.g. VIMS on Cassini [2] and the Deep Impact spacecraft [3]) have shown possible water/hydroxyl at around 3 µm, with hints of spatial variation. At the lunar poles, observations of permanently shadowed regions with temperatures <100 K [4], other datasets from NASA’s Lunar Reconnaissance Orbiter, and measurements made by the LCROSS impactor [5] indicate polar water ice.

However, although measurements by M3 were capable of detecting water, the instrument was not optimized to characterize it fully, e.g. form, abundance, and temporal variation. The Lunar Trailblazer mission is designed to resolve these questions.

The Lunar Trailblazer Mission: Lunar Trailblazer targets understanding of the Moon’s water: its form (ice, H2O, or OH), abundance, and distribution as well as the Moon’s potential time-varying lunar water cycle. A Ball Aerospace-integrated smallsat will carry the JPL High-resolution Volatiles and Minerals Moon Mapper (HVM3) shortwave infrared imaging spectrometer and the UK-contributed, University of Oxford/STFC RAL Space-built thermal infrared multispectral imager, which simultaneously measure composition, temperature, and thermophysical properties. From ~100-km polar orbit, Lunar Trailblazer will detect and map water on the lunar surface at key targets with 4 science objectives: (1) determine its form (OH, H2O or ice), abundance, and local distribution as a function of latitude, soil maturity, and lithology; (2) assess possible time-variation in lunar water on sunlit surfaces; (3) use terrain-scattered light to determine the form and abundance of exposed water in permanently shadowed regions; and (4) understand how local gradients in albedo and surface temperature affect ice and OH/H2O concentration, including potential identification of new, small cold traps.

This mission provides unprecedented sensitivity for direct detection of lunar water at key targets. HVM3 builds upon the demonstrated ability of M3 to detect lunar water even in permanently shadowed regions (Li et al., 2018) with enhanced spatial and spectral resolution, SNR, and spectral range. LTM brings enhanced spatial and spectral resolution relative to Diviner. Understanding the lunar water cycle and determining the abundance, local distribution and form of water will support exploration and utilization of the Moon and its resources. Identification and characterization of water and its forms is critical knowledge as lunar exploration moves forward. Reconnaissance of potential landing zones will also be possible.

Science Payload: Lunar Trailblazer carries two remote sensing instruments:

HVM3 (JPL, Figure 1, left) is a push-broom visible and near-infrared spectrometer derived from the M3 mapping spectrometer flown on Chandrayaan-1. HVM3 extends the spectral range to capture the full 3.0 µm by covering 0.6 to 3.6 µm at 10 nm spectral and <70 m/pixel spatial resolution.

Figure 1. HVM3 hyperspectral near-IR imager (left), LTM, multispectral thermal infrared mapper (right)

Lunar Thermal Mapper, LTM (Oxford/RAL Space, Figure 1, right) is a push broom multi-spectral thermal mapper with eleven compositional and four temperature mapping channels. LTM has a spatial resolution of 25 m/pixel with a swath width of 11 km, capturing the temperature of the surface in the central section of the HVM3 field of view.

THE MINERALOGICAL RECORD OF GROUNDWATER-SEDIMENT REACTIONS IN GALE CRATER

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Introduction: The Curiosity Rover has traversed over 21.3 km in Gale Crater since its landing in 2012. Predictions made prior to landing based on NIR characterisation of the landing site [1] have turned out to be accurate with clay-bearing, hematite-rich horizons and sulphate mineralization present within the Gale sedimentary sequence e.g. [2]. The Gale sediments are dominated by an Early Hesperian fluvio-lacustrine system [3]. Through a combination of CheMin XRD mineralogy, ChemCam and APXS compositional analyses, and MastCam, MAHLI imagery, a record of groundwater-sediment reactions has been revealed associated with the secondary mineral assemblages.

We have conducted a series of thermochemical models since 2012 which use the unique mineralogical and compositional data in order to understand the T, redox, pH, and water/rock ratios associated with the secondary mineralogy, and through those constrain the conditions of habitability in Gale [4-6].

Here we review the knowledge about mineralogy and water-rock reactions at Gale Crater from our own and others’ work.

Methods: CHIM-XPT and CHILLER were used for thermochemical modeling [7]. The inputs for CHIM-XPT are the fluid chemistry, the reactant/host rock chemistry, and the system temperature and pressure. Water/rock ratio (W/R) is the ratio of incoming fluid to reacted host rock chemistry. Modelled mineral assemblages at a variety of T, W/R, redox etc are then compared to the mineral assemblages and alteration compositions. For details see [4,5,8].

Diagenesis and Partial Overprint of Source Compositions: At Yellowknife Bay YKB in the Bradbury stratigraphic group, the importance of relatively low temperature diagenesis through groundwater-sediment interaction became clear to the MSL team. This was manifested by Mg-rich (clay) ridges, nodules and sulphate veins within the fine grained sediments e.g. [4, 9]. The CheMin-derived mineralogy of YKB mudstone showed a saponite-magnetite bearing assemblage [10]. Our modelling suggested the YKB secondary mineral assemblage formed by the reaction of a CO2-poor and moderately oxidizing, dilute aqueous solution with the sedimentary rocks at 10-50 °C and W/R of 100–1000, with pH mainly near neutral [4,5]. There was an absence of mineral assemblages e.g. zeolites, chloride, ilite that would be associated with more elevated temperatures. However, in detail the record of water-rock reaction has different stages including late, abundant sulphate veins which may record dissolution of evaporite layers [5]. Remarkably, there is an Amazonian K-Ar age dating evidence from SAM for much more recent, limited jarosite mineralization in Gale [11].

The Murray-VRR Formation. The Murray Formation and Vera Rubin Ridge (previously called Hematite Ridge) which overly the Bradbury unit also include diagenetically altered mudstones [2]. Our modelling [6,8] suggests a key difference from YKB lies in a higher W/R and with evidence for somewhat elevated temperatures.

Preservation of Relict Source Rock Compositions. The record of water-rock reaction at YKB and into the overlying Murray Formation did not entirely mask the nature of detrital source materials that fed into the Gale fluvio-lacustrine system. Using ChemCam and APXS data respectively, it was demonstrated by [12,13] that the source materials likely included tholeiitic basalt, a high silica igneous and alkaline basalts.

Conclusions: The fluvio-lacustrine sediments of Gale Crater have preserved secondary mineral assemblages in the Bradbury Group and Murray-Vera Rubin Ridge formation which our models suggest were largely controlled by variations in W/R ratio and to some extent temperature during groundwater related diagenesis. Careful analysis of the Gale data also allows, at least for some stratigraphic units, the record of water-rock reaction and source compositions input to be distinguished. Our ongoing work as we analyse this unique mineralogical record will highlight any changes in these fluid conditions and source material through the Gale stratigraphy.

INVESTIGATING THE RELATIONSHIP BETWEEN OZONE AND WATER-ICE CLOUDS USING RETRIEVED DATA FROM THE EXOMARS TRACE GAS ORBITER

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This project will use retrievals of ozone and ice-water clouds in the martian atmosphere from the ultraviolet (UV) spectrometer, UVIS, aboard the ExoMars Trace Gas Orbiter (TGO). Ozone abundance will be mapped and compared to the water-ice opacity and their interaction will be used to assess the atmospheric chemistry between ozone, water-ice and hydroxyl radicals. Hydroxyl photochemistry may be indicated by a non-negative or fluctuating correlation between ozone and water-ice, which will contribute to understanding the stability of carbon dioxide and chemistry of the martian atmosphere.

Introduction

Ozone (O\textsubscript{3}) is a trace gas found in the martian atmosphere e.g. [1], which can be used for tracking general circulation of the atmosphere [2] and trace chemicals, as well as acting as a proxy for water vapour [3]. The photochemical break down of water vapour produces hydroxyl radicals, which are trace gases known to participate in the destruction of ozone [4, 5]. As a result, the relationship between water vapour and ozone follows an anti-correlation. Water-ice may also follow this theory [6].

The photochemical reactions between ozone, water-ice clouds and hydroxyl radicals are poorly understood in the martian atmosphere due to the short lifetime and rapid reaction rates of hydroxyl radicals [7, 8]. These reactions are essential for the destruction of ozone, as well as indirectly contributing to the water cycle and stability of carbon dioxide (measured by the CO\textsubscript{2}–CO ratio) in the martian atmosphere [5, 9, 10].

The detection of ozone in the presence of water-ice clouds suggests that the preexisting relationship between water-ice and ozone is not always anti-correlated[7]. Global climate models (GCMs) are in disagreement of the chemical processes occurring within water-ice clouds [4, 6, 11]. For example, the heterogeneous photochemistry described in the LMD (Laboratoire de Météorologie Dynamique) GCM did not significantly improve the model [6].

This leads to the following questions: what is the relationship between water-ice clouds and ozone, and can the chemical reactions of hydroxyl radicals occurring within water-ice clouds be determined through this relationship?

Methodology

This project aims to address these topics using nadir and occultation retrievals from the ExoMars Trace Gas Orbiter of ozone and water-ice clouds. Nadir and Occultation for MArs Discovery (NOMAD) is an instrument aboard the TGO, which contains a UV and visible spectrometer, UVIS [12, 13]. The spectrometer takes observations in two modes; nadir (total column) and occultation (vertical profile). The observations are used in an inverse process called a retrieval. DISORT is the radiative transfer model used in the retrieval, which calculates spectra with \textit{a priori} of albedo, water-ice, dust and ozone. Within the iterative process, the radiative transfer model simulates spectra which are statistically compared against the observed spectra using a chi-squared test. If the test fails, the \textit{a priori} are adjusted and the iteration repeats until the fit between the simulated and observed spectra is determined to be reasonable.

The data provided by UVIS will be more complete spatially and temporally than other datasets by previous instruments, reducing uncertainty and potentially increasing the reliability of the results. Analysis will include temporal and spatial binning of data to help visualize any patterns in these dimensions. Correlation tests will be conducted to determine the significance of the relationship on short term and seasonal dimensions along a range of zonally averaged latitudes.

Hypothesis

Water-ice clouds may act as a sink for hydroxyl radicals, implying that there should not be an anti-correlation between ozone and water-ice.

Ozone abundance is greatest in the winter at the polar regions, which also coincides with the appearance of the polar hood clouds [14, 15]. The use of nadir observations will enable the comparison between total column of ozone abundance at high latitudes (>60°S) in a range of varying water-ice cloud opacities, as well as the equatorial region (30°S – 30°N) during aphelion. Water-ice clouds may remove hydroxyl radicals [7, 11] and thus the suggested anticorrelation between ozone and water-ice will not hold.

Summary

Interactions between hydroxyl radicals and the surface of water-ice clouds are poorly understood. This project will address these interactions by assessing the relationship between ozone and water-ice clouds on different temporal and spatial resolutions using retrieved data from the UVIS instrument aboard the TGO. Nadir and occultations will be used in short-term and seasonal timeframes in the polar regions and during aphelion in the equatorial region.
DESTROYING ICY OCEAN WORLDS

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Introduction:
Icy ocean worlds in the outer solar system are now a major source of interest for those interested in astrobiology [1]. However, they also hold other interests. One issue is how such bodies will respond to hypervelocity impacts. These high-speed impacts are major evolutionary drivers in the solar system. Most impact studies however look at rocky bodies, typical of the inner solar system, e.g. [2,3]. As well as causing cratering, e.g. [4], such impacts can, if violent enough disrupt the target body. Here we report on a series of laboratory experiments to simulate impact processes on a variety of hypothetical icy worlds. The issues that arise mostly concern the influence of target layering on the impact process.

Programme of work:
We have already published extensively concerning impact processes on homogeneous ice targets, e.g. [5-7]. We have also recently published work on the effect of different materials being present beneath a surface ice layer [8]. Now we are presenting data on how such layered icy bodies are disrupted. We started some years ago with homogeneous icy bodies being disrupted, in both laboratory experiments [9] and analytical models [10]. Next, we have just published experimental data for disruption of an icy body with a water interior [11], where we show that there is no change in the catastrophic disruption threshold compared to that for the solid ice body of equal size. All the experiments used the Univ. of Kent two-stage light gas gun [12] to fire mm-sized projectiles at ice targets of approximately 18 cm diameter. The impact speed was varied (up to 5 or 6 km s⁻¹), until disruption occurs.

New work:
In 2020, we will present new experimental data for disruption of two other types of ice worlds. The first is for a solid ice shell with a hollow interior, a sort of icy Dyson sphere.
We will then show what happens to a target with an icy surface, an intermediate internal (water) ocean and a solid core.

These two examples complete the set of basic configurations of ice worlds (see Fig. 1). We will show how the catastrophic disruption energy varies between these examples.

Fig. 1. a) Solid ice target. b) Water foiled ice target. c) Ice surface, intermediate water ocean, solid core target. d) Hollow ice target. Models of all are made in the laboratory and subject to impact experiments.

Bibliography
HYPERVELOCITY IMPACT FACILITY – UNIVERSITY OF KENT

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Introduction:

The Kent hypervelocity impact laboratory [1,2] has been operational for over 25 years. Processes involving hypervelocity impacts are a major area of scientific enquiry. Kent has published of order 100 refereed journal papers on the subject, and continues to publish new work each year. The topics covered in such research include:

- Basic response of materials to shock compression [3].
- Survival of projectile materials after impact [4,5,6]
- Astrobiology (generation of complex organic materials via impacts, as well as survival of spores, microorganisms and even fossils against impact damage) [7,8,9].
- Development of new technologies to determine the dust in space [10].
- Capture of intact materials after impact to determine their composition and origin [11].
- Catastrophic disruption of targets [12].

Other topics such as impact damage to space vehicles/structures are also studied. As well as providing a facility for Kent staff and students, the gun is available to external users, and it is our intention to continue and extend this access (see below).

Current capacity:

The laboratory currently houses a two-stage light gas gun [1,2]. This can fire horizontally at speeds from 0.35 to 8.5 km s\(^{-1}\), or vertically at speed up to 2 km s\(^{-1}\). Projectiles are carried in nylon sabots, which are discarded in flight, and can range from micron-sized dust to mm-sized spheres. We can also fire ice at the targets. The target chamber is a cube, 1.3 m on each size, and is evacuated to low pressure during a shot. The targets can be cooled or heated during an impact; they can also be instrumented and read out in real time. Various high-speed cameras are available to image the impacts (but currently not ultra-high speed). A 360º tour of the Kent gun lab is on-line https://www.youtube.com/watch?v=3pTMzoj6Hgo&app=desktop

National and international access:

The Kent impact lab has a long history of external collaborations and intends that this should continue. We have collaborators who visit, or we supply samples for projects. Some of the work is purely collaborative, and some of it is supported by the user providing funds. We have also just secured funding via the ERC funded Europlanet programme to be a Trans-National facility; so from 2020-2024 we will be able to provide funding for international visitors to visit (if they are also part of this programme) http://www.europlanet-2020-ri.eu/

Anyone interested in using the facility should contact Mark Burchell (m.j.burchell@kent.ac.uk).

Bibliography

INTERNAL STRUCTURE OF A MID-LATITUDE GLACIER ON MARS

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Introduction: We present observations of internal flow structures within a viscous flow feature (VFF; 51.24°W, 42.53°S) interpreted as a debris-covered glacier in Nereidum Montes, Mars (Fig 1A). The structures (Fig 1B) are exposed in the wall of a gully alcove that is incised parallel to VFF flow-direction. They are located near to the glacier terminus and appear to connect the glacier bed to arcuate flow-transverse foliations on its surface (Fig 1A). Such flow-related foliations are common on the surfaces of martian VFF [e.g., 1], but their relation to VFF-internal structures and ice flow is poorly understood. We combine 3D analyses of the internal structures with 3D numerical modelling to explore their implications for glacial flow and stress regime.

Methods: We use a 1 m/pixel digital elevation model (DEM) derived from 25 cm/pixel High Resolution Imaging Science Experiment (HiRISE) stereo-pair images, along with a false-colour (merged IRB) HiRISE image. We measure the dip and strike of the VFF-internal structures using ArcGIS 10.7 software. We also input the DEM (and an inferred glacier bed topography derived from it) into ice flow simulations using the Ice Sheet System Model [2], assuming present-day mean annual surface temperature (210K).

Results and Discussion: The VFF-internal structures associated with surface foliations dip up-glacier at ~20° from the bed. This is inconsistent with bed-parallel layering from ice accumulation without a component of flow deformation. The up-glacier-dipping structures and associated surface foliations are spectrally ‘redder’ than adjacent portions of the VFF, which appear ‘bluer’ (Fig 1B). This could be due to differences in debris concentration and/or surficial dust trapping between the internal structures and the bulk VFF [e.g. 3]. Preliminary modelling suggests that the up-glacier-dipping internal structures occur at the onset of a compressional regime as ice flow slowed towards the VFF terminus.

Conclusions and Implications: We propose that the up-glacier-dipping internal structures represent englacial shear zones (thrusts or folds), as is often observed in flow compression zones in glaciers on Earth [e.g., 4]. The structures could represent pathways of transport of material from the VFF bed to its surface.

Martian glaciers are of astrobiological interest [5], but current limitations in drilling technology prevent direct exploration of their interiors and beds. New evidence that surficial debris near to VFF termini could contain a component of englacial and/or subglacial materials suggests it may be possible to sample those materials without access to the subsurface. This could reduce the potential cost and complexity of future missions that aim to explore englacial and subglacial environments on Mars.

THE SEARCH FOR ORGANIC SIGNATURES WITHIN DYNAMIC FEATURES ON THE MARTIAN SURFACE

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Introduction:
Mars has increasingly been shown to exhibit dynamic processes on the surface, despite having previously been thought to be inactive [1]. The South Polar Residual Cap (SPRC) exhibits significant change over time, being covered with quasi-circular CO2 ice sublimation features known as ‘Swiss Cheese Terrain’ (SCT) [2]. Another type of dynamic feature that has been observed with the advent of high-resolution cameras (<5m) is Recurring Slope Lineae (RSL), which may be the result of briny water causing lengthening and darkening streaks on the Martian surface [3]. These features are of interest as they may expose new material that has been previously shielded from the high levels of ultraviolet radiation on the Martian surface, and allow for the detection of organic molecules; more specifically, Polycyclic Aromatic Hydrocarbons (PAHs), which are considered to be a ‘building block’ for life, and have yet to be detected on Mars [4].

Here we identify suitable regions for potential exposure of new material on the SPRC and within RSLs, and utilise data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on board NASA’s Mars Reconnaissance Orbiter (MRO) satellite [5] to examine infrared spectra of regions of interest to establish their composition and evolution, compare the results to laboratory analogues, and assess whether there might be any spectral signatures indicative of PAHs.

Methods: Full Targeted Resolution (FRT) CRISM products were used to maximise spatial resolution (~20m/pixel) of small-scale SCT and RSL features. The CRISM Analysis Tool (CAT) plugin for ENVI software was used to process the CRISM scenes and carry out corrections, and generate summary products (based on multispectral parameters derived from reflectances for each CRISM observation) that can be used as a targeting tool to identify areas of mineralogical interest [6].

Laboratory experiments were performed to constrain the detectability limit of PAHs. The site of the laboratory experiments was the “Cold Surface Spectroscopy” facility (CSS) at the Institut de Planétologie et Astro-physique de Grenoble (IPAG) Grenoble, France, using the spectro-gonio radiometer and its CarboN-IR environmental cell, which have been specifically developed for studying planetary analogues.

Results: The detectability limit of PAHs has been established within SPRC and RSL analogues, end member spectra have been established for all components of interest, and new diagnostic absorption features for PAHs have been recorded at a number of wavelengths. While no evidence of PAHs was found in orbital imagery, it was discovered that PAHs are easier to detect as RSL analogues tend to dry out and salt crystals decrease the opacity of the substrate. For the SPRC, there are clear spectral differences between dust rims and non-rim regions of SCT, with indications that the initial stages of SCT pit formation result in lower dust content on pit rims with an increase in dust content as the fully formed pits become more circular and retreat laterally, leaving concentrations of dust behind.

Acknowledgments:
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3D IMAGING OF THE MOON FOR THE NASA ARTEMIS HUMAN EXPLORATION PROGRAMME

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Introduction: The EU FP7 iMars project (http://www.i-mars.eu) developed a completely automated digital photogrammetric processing system to generate DTMs and ORIs from Mars stereo imagery such as ESA HRSC, NASA MRO/CTX and HiRISE called CASP-GO based on the NASA-ASP open source platform. Since the end of iMars in 2017, thousands of CTX and tens of HiRISE 3D products have been processed. It is planned that CASP-GO will be integrated into ASP in future releases. ASP also includes the ability to generate DTMs from other planetary bodies. Here we present recent work on the Moon as part of the NASA/JPL Moontrek program (https://moontrek.jpl.nasa.gov) in which MSSL is providing new mosaiced products over large regions of the Moon from 0.5m LROC-NAC stereo-pairs.

Methods: Aside from the ASP core pre-processing, initial matching, subpixel matching, camera triangulation, and DTM generation, five additional workflows are used to improve the DTM quality.

LOLA to a new 20m DTM China [4] Figure 1 shows an example of this multi-resolution DTM. A search using the ASU JMars software alongside stereo acquisitions selected by the ASU LROC PDS were combined to map the stereo coverage over the final target of interest, Aristarchus crater.

Figure 2: SELENE-LOLA (background), Chang’E2 DTMs showing area of interest (Aristarchus crater) and the LROC-NAC stereo-pair coverage

The resultant multi-resolution and bundle-adjusted co-registered 1m 3D models will be provided with a 0.5m mosaiced and phase-angle corrected image for employment with Moontrek. VR will be employed by NASA for astronaut training using these data for the ARTEMIS program. The products will be made available through the ESA Guest Storage Facility described elsewhere [5]. An example animated visualisation will be shown using the NASA Ames DERT [6] system.


Figure 3: Copernicus: LROC-DTM + ORI example.
The Penetration of Solar Radiation into Martian Ice Analogues

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Introduction:
Icy surfaces behave differently to rocky or regolith-covered surfaces in response to irradiation because visible light can penetrate partially into the subsurface. Ices are highly translucent to visible and shorter wavelengths of light, whilst opaque in the infrared. This can cause a solid-state greenhouse effect (SSGE) to be induced [1], resulting in significant differences in the shallow subsurface temperature profile when compared to rocky surfaces. Of particular significance for modelling the SSGE is to quantify how much of the incident radiation the ice itself absorbs. We measure broad spectrum light absorption using the e-folding scale, or penetration depth of the ice, defined as the depth of ice required to reduce light intensity to 1/e of its surface value.

Mars hosts both water and carbon dioxide ices in the polar caps, seasonal deposits and diurnal frost cycles [2]. Unique surface features are observed in association with CO₂ slab ice deposits. Araneiforms, or ‘spiders’ are radially branching erosional features and only found within the seasonal CO₂ ice sheet in the southern polar region [3]. Springtime activity is observed as CO₂ jetting, generated by basal sublimation caused by an induced SSGE within the CO₂ slab ice. Similar features are seasonal furrows, found during the spring thawing of the northern seasonal polar cap [4]. Other relevant features include the gullies, which are actively forming in the absence of detectable liquid water, and thought to form by a similar mechanism to araneiforms, except occurring on slopes [5]; and Swiss Cheese terrain, observed only in the southern residual polar cap where exposed CO₂ ice overlies water ice, and forms unusual erosional features of quasi-circular flat bottomed pits and other lobate depressions [6].

It is therefore important to define the penetration depth of both ice compositions in order to effectively model the surface thermal regime, and therefore understand the different formation mechanisms of the features detailed above. Whilst measurements of light intensity through naturally occurring, or contaminated, water ice and snow samples have been conducted previously [7, 8], there has been a lack of data on CO₂ ices. Therefore, a suite of broad spectrum (300 nm – 1100 nm) light intensity experiments have been undertaken. Measurements have been made for of slab ice, snow and granular ices comprised of pure CO₂ and H₂O₂ to determine the penetration depth of these deposits based on grain size. These are vital parameters in heat transfer models for the Martian surface, enabling us to better understand surface-atmosphere interactions at Mars’ polar caps.

Methodology:
Slab ice samples were prepared by condensing CO₂ directly from the gas phase within a pressure vessel cooled by liquid nitrogen. This forms large CO₂ ice blocks, which were then cut to size and polished smooth. Dionised water ice was slowly frozen to form ice slabs. CO₂ snow was made by decompression directly from a liquid CO₂ cylinder. Water snow was made by spraying deionised water into a dewar of liquid nitrogen Snow the snow was sieved to <1 mm grain size, and stored in liquid nitrogen until use, thus minimizing sintering and contamination by water frost. ntainers at ~86°C to avoid sintering. All experiments were undertaken in an argon-filled chamber, which was first cooled with liquid nitrogen. This both reduced the sublimation rate of the CO₂ ice, and minimised water frost deposition on both the sample and the glass plate the sample is held on. For more details, see [9 & 10].

Results:
The penetration depth of broad-spectrum solar radiation has been measured for both water and carbon dioxide ices has been measured in the laboratory for the first time. The results, based on grain size from snow to slab ice, are used to determine an empirical model to give the penetration depth of an ice deposit, based on grain size and composition. The results can be utilized in radiative transfer models to study the formation processes of CO₂ jetting, which is responsible for creating araneiforms and seasonal furrows, and could help in determining the formation mechanism of dry gullies and Swiss Cheese terrain.

References:
MARTIAN ALTERATION VS TERRESTRIAL CONTAMINATION IN THE APATITE OF THE UNIQUE MARTIAN METEORITE NWA 8159.

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Introduction: The newly discovered martian meteorite Northwest Africa (NWA) 8159 is unique, as it samples an era and lithology on Mars (early Amazonian) that is not represented elsewhere in meteorite collections [1-5]. We are investigating NWA 8159 apatite to define the parental melt composition, potential source region volatile composition, and to determine the aqueous alteration processes that have affected this unique augitic basalt from Mars.

Methodology:
- Carl Zeiss Sigma Variable Pressure Analytical SEM analyses at the University of Glasgow.
- Electron Probe Microscopy at the University of Edinburgh → stoichiometric composition of NWA 8159 apatite grains.
- Transmission Electron Microscopy at the University of Sydney [FEI Temis - Z double-corrected 60-300 kV S/TEM] → NWA 8159 apatite texture, chemistry and nature of the Si-rich inter-grown phase.
- Atom Probe Tomography via the Cameca Local Electrode Atom Probe (LEAP) 4000X at the University of Sydney → 3D spatial elemental composition of the apatite.

Results: SEM-EDS observations revealed an extensive network of calcite veins running through the samples, a sure sign of terrestrial alteration. In addition, olivine cores were shown to contain areas of ‘iddingsite’ alteration. Apatite grains were found to be numerous, and commonly associated with magnetite phenocrysts. EPM analyses highlighted the F-rich nature of apatite, possibly indicating an F-enriched parental melt [6]. However, subsequent TEM and APT analyses [Figures 1-2] of selected apatite areas suggest substantial alteration has occurred throughout these grains, which were found to contain magnetite and Fe, Mg- and Al-rich phyllosilicates alongside apatite.

Discussion: Initial data indicate that NWA 8159 is extensively altered. However, the origin of the apatite and olivine core alteration is still unclear. The presence of C concentrations within the phyllosilicates indicate carbonate content – unfortunately based on this dataset it is not possible to determine whether this carbonate is siderite (probable martian origin) or calcite (probably terrestrial).

Introduction:
The scientific objectives of the ExoMars Rosalind Franklin rover [1] are designed to answer several key questions in the search for life on Mars. In particular, the unique subsurface drill will address some of these questions for the first time, such as the possible existence and stability of sub-surface organics. PanCam [2] will establish the surface geological and morphological context for the mission, working in collaboration with other context instruments. Here, we describe the PanCam scientific objectives in geology, atmospheric science and 3D vision. We discuss the design of PanCam, which includes a stereo pair of Wide Angle Cameras (WACs), each of which has an 11 position filter wheel, and a High Resolution Camera (HRC) for high resolution investigations of rock texture at a distance. The cameras and electronics are housed in an optical bench that provides the mechanical interface to the rover mast and a planetary protection barrier. The electronic interface is via the PanCam Interface Unit (PIU), and power conditioning is via a DC-DC converter. PanCam also includes a calibration target mounted on the rover deck for radiometric calibration, fiducial markers for geometric calibration and a rover inspection mirror.

References:
MULTIPLE SUPERROTATING STATES IN AN IDEALIZED MODEL OF THE ATMOSPHERE OF VENUS, A SLOWLY-ROTATING TERRESTRIAL PLANET

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Abstract:
We consider an idealized dynamical model of the Venusian atmosphere, starting from the terrestrial benchmark of Held and Suarez (1994). We use the same form of annually-averaged forcing in pressure coordinates as for Earth, but extrapolate from the reference pressure $p_0 = 1$ bar (which is also the surface pressure for Earth) to Venus’s much higher surface pressure $p_s = 92$ bar. Although such an atmosphere is still shallow compared to the radius of the planet, unlike Earth’s it is dynamically thick in the sense that the tropopause is many scale-heights above the surface: this allows room for more vertical structure to develop in the large-scale tropospheric circulation.

We use a planetary rotation rate appropriate for Venus; and we increase the relaxation times associated with the forcing, to take account of the increased atmospheric mass.

Using the Isca GCM code (Vallis et al. 2018), we find multiple superrotating states, dependent on initial conditions, sustained on time scales much longer (at least of the order of 10,000 days) than those of the forcing or of the planetary rotation. Whereas the maximum zonal wind obtained from zero initial conditions is too weak compared to Venus, other states exhibit zonal winds of Venusian magnitude. The strongly superrotating cases are associated with a more complex overturning circulation, featuring stacked cells like those seen by Lebonnois et al. (2016).

We examine the role of vertical and horizontal damping in our numerical experiments, and compare our results with simple theories based on the axisymmetric, inviscid, steady-state model of Held and Hou (1980).
Lunar SOURCE: A concept for a Lunar SOUnding Radar Cubesat Experiment

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Abstract:

More than fifty years after the “small step for a man” and the first human landing on another celestial body, there are still big questions on our natural satellite: “Is there water ice on the Moon?” and if so, “How much water is there?”, “Is there also liquid water?” and “At what depth?”? Although some missions, like the Japanese SELENological and ENgineering Explorer and the American Lunar Reconnaissance Orbiter, did not find a conclusive evidence to answer to these questions, last year the first question received an answer. Indeed, Dr. Shuai Li published a paper [1], using the data from Chandrayaan-1 mission. However, the last three questions remain open and further investigations are needed.

These three remaining questions have a fundamental importance to understand the structure of our solar system and eventually to try to search for life [2].

Thanks to Mars Express, and in particular MARSIS payload, and thanks to Mars Reconnaissance Orbiter, and in particular SHARAD instrument, we know that there is liquid water on Mars [3] and we know much more about the geological history of the Red planet [4].

Thanks to Cassini–Huygens we know that there is liquid water on Enceladus and two large missions, Europa Clipper and JUICE are going to investigate it [5].

Many of these missions have an instrument in common: the ground penetrating radar that uses a dipole antenna to investigate the subsurface of the celestial body.

The aim of this paper is to propose a nanosat mission (e.g. a 16U Cubesat) carrying on-board a sounding radar to analyse the lunar subsurface and to quantify the mass of ice present on the Moon. Moreover, we aim at investigating the possible presence of liquid water in the superficial layers (up to 300 m of depth).

The Lunar SOUnding Radar Cubesat Experiment (Lunar SOURCE) will use a 7.5-meter long dipole as radar antenna (based on Oxford Space Systems concept) that generates an HF signal having a 15-meter wavelength. The combination of these two parameters will give a beam-width of 78° and a maximum gain of 2.15 dB. The selected orbit gives a Signal to Noise Ratio (SNR) of ~45 dB at the nadir point, which enables the analysis of the subsurface interfaces down to a useful depth for water ice detection. However, due to the low altitude expected for this mission, the irregularities of the mass distribution of the Moon have a significant impact on the orbit stability and on the lifetime of the mission.

This paper analyses the possible orbits for mapping the lunar surface considering the achievable space coverage and the achievable mission lifetime.

The identification of the mission and system requirements draws the foundations for the concept study of the mission, enabling a preliminary selection and sizing of the main subsystems of the Cubesat.

The mission uses mainly Components Of The Shelf (COTS), apart for the sounder antenna and electronics. A preliminary cost estimation shows that the satellite could cost less than 20 million £ and that Lunar SOURCE could easily fly as a piggyback payload.

Following the philosophy of NovaSAR (mainly cost-driven technological solutions) and with the space technical capability spread across UK, and in particular with Oxford Space System’s deployable systems, and with a considerable radar expertise, in particular in the EMSIG EW Focus Group (even if we did not asked for their endorsement) the UKSA could be in the position of funding a mission with great potentiality for a cost that is cheap, compared to other planetary missions.

References:

MOLARDS ON MARS AND MERCURY: SIGNS OF VOLATILE LOSS

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Introduction: Molards are cones of debris that result from the disaggregation of ice-cemented blocks transported by mass movements [1] (Figure 1). Recently, we linked the origin of molards directly to permafrost degradation on Earth [2]. Permafrost conditions are a pre-requisite for forming the ice cement within the blocks, and its subsequent degradation triggers the mass movement leading to the formation of the final molards. In [2], we show that molards are recognisable in remote sensing data. In addition, we report that the distribution and morphology of molards give insights into landslide dynamics. This new terrestrial work led us to search for such landforms on other planets where the role of volatiles in landscape evolution is under debate. Volatiles are substances that easily change phase, for this work we refer to ices and solids (H₂O, CO₂, N₂, S, Cl) becoming gas or liquid. Our preliminary work has revealed mold-like landforms on Mars and on Mercury related with impact craters.

Mars - Hale Crater: Candidate molards are found in the ejecta flows of the one billion year old Hale Crater, which are similar in morphology and spatial distribution to molards found in the Mount Meager debris-avalanche deposits on Earth [4] (Figure 1). Hale impact has already been proposed to have occurred into ice-rich materials [5] and hence it is not unlikely that the ejecta may also have contained ice. The presence of molards suggests that not all the ice was melted by the impact and that the ice itself was contained within the pores of the soil, rather than massive sheets of glacial ice. In future work we aim to constrain both the initial ground ice content at the Hale impact, but also the conditions during ejecta emplacement.

Mercury - Caloris Ejecta: Conical mounds are found around the Caloris Basin on Mercury. We mapped their locations and found that their distribution is consistent with them being part of the Caloris ejecta blanket. Their shape and the fact that debris from their flanks buries surrounding materials (Figure 1) suggests they continued to evolve long after the basin was formed. Because their flank-slopes and shapes are similar to molards on Earth we suggest a similar formation via volatile loss. In the last few years Mercury has been revealed to be much more volatile-rich than previously thought [e.g., 3], and our discovery of candidate molards in the ejecta of the Caloris Basin suggests that the crust and mantle has been enriched in volatiles since the basin formed ~3.8 billion years ago.


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Figure 1. Left to right: A molard in the Móafellsfyrða landslide, which occurred in 2012, height ~20 m. Planview comparison between candidate molards in Hale crater ejecta, and molards in the landslide deposits at the foot of Mount Meager, where red arrows indicate similar features (flow boundary and molards embedded in flow deposits). Conical knob on Mercury where the yellow arrow indicates crater on Caloris Planitia partially obscured by knob material and a subtle notch in the knob is visible above this crater.
SULFUR BIOGEOCHEMISTRY AND δ³⁴S BIOSIGNATURES IN A COLD, HYPERSONAL ARCTIC SPRING

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Introduction: Axel Heiberg Island in the Canadian Arctic hosts unique hypersaline (>10 wt. %) and perennally low temperature (-5 to 8 °C) springs that precipitate sodium sulfate and chloride salts [1, 2]. Of these, Lost Hammer Spring has been studied as an analogue system to past and present hypersaline environments on Mars and Europa respectively [2,3], and provides an opportunity to investigate the microbiology of extreme low-temperature, hypersaline habitats. Previous metagenomic surveys have shown that sulfur cycling plays an important role here [4].

Fig. 1. A. Map of Lost Hammer spring. Pink stars denote sampling sites.

Field area and methods: Lost Hammer Spring (79.076856, -90.210472) emerges as a single outlet from a valley floor. A salt dome surrounds the vent, flanked by salt aprons and an outflow stream. Brine and sediment were taken from the vent, and at two downstream locations to a final distance of 15 m from the vent. At the time of sampling, the vent contained brine to a depth of ~50 cm with salt crystals dominating the bottom sediment. Vent and outflow brines ranged from pH 5.7 - 6, while temperatures increased from -3.6 °C (vent) to 1.8 °C (furthest outflow), becoming more oxic downstream (~0 to 7.7 mg/l DO) with a concurrent decrease in dissolved sulfide (~10 to 0 ppm). We investigated the microbiology and δ³⁴S values recorded along this spring system to explore sulfur biogeochemical cycling in these environments. DNA was extracted from sediments, and bacterial and archaeal communities characterised by 16S rRNA long read sequence assays, and shot-gun Illumina sequencing. Genes implicated in microbial S-cycling were investigated by metagenomic analysis. These data were combined with sulfate and sulfide δ³⁴S from brine and sediment to investigate sulfur-based metabolisms, biogeochemical cycling, and stable isotope biosignatures in a system of relevance to present-day Europa, and Hesperian Mars.

Results: LH Spring geochemical analysis reveals a mildly-acidic hypersaline sulfate-chloride spring, characterized by temperature, DO, and dissolved sulfide gradients. The active stream channel sits within salts including Na-sulfates thermaindite and mirabilite, and halite [2]. 16S rDNA assays show microbial sulfate reduction is likely conducted by Desulfocapsa sp and Desulfuromonas sp., which make up a small proportion (<10 %) of the spring communities. Halotolerant Gilisia instead dominates the communities along the spring. Metagenomic analysis reveals a complete dissimilatory S-reduction pathway, in addition to carbon fixation via the reductive citric acid cycle. δ³⁴S isotope values are consistently positive (~+22 ‰) for both water and sedimentary sulfate, and consistently negative (~22 to -29 ‰) for both water and sedimentary sulfide. As such, Sulfur within Lost Hammer Spring is extremely fractionated by microbial processes, resulting in δ³⁴Sulfate-pyrite fractionations of 51.8 ‰ at the vent, to 47.5 and 44.5 ‰ at LH-1 and LH-2 respectively, despite the effectively infinite reservoir of sulfate available.

This study shows how extreme habitats such as cold, hypersaline environments can facilitate the production of strongly fractionated S isotopes during microbial sulfate reduction due to stress imparted on the microbial communities. This demonstrates the importance of the environmental geochemistry, itself recorded within sedimentary deposits and precipitates, on the formation of stable isotope biosignatures and the likelihood that they can be easily distinguished from abiotic processes.

THE UK FIREBALL NETWORK: A NEW CAMERA NETWORK AIMING TO RECOVER METEORITE FALLS IN THE UK

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UK Fireball Network: The UK Fireball Network (UKFN) is a new network of all sky digital cameras in the UK. The primary aim of the UKFN is to image fireballs and recover meteorite falls with their orbital contextual information intact [1]. The UKFN utilizes the hardware and software heritage developed by the Desert Fireball Network (DFN) project and forms an integrated part of the emergent Global Fireball Observatory (GFO) [2,3].

The UKFN is a collaboration between Imperial College London, the University of Glasgow and Curtin University, with additional links to the University of Cambridge, the Natural History Museum London and Open University. So far five cameras have been installed with another planned for December (Fig. 1A,C). Eventually the UKFN will total 10-12 observatories that provide double station coverage of the night sky across the UK (Fig 1A). It is anticipated from the mass flux rate of extraterrestrial material to Earth that 1-2 meteorite dropping fireballs will be observed by the UKFN each year [4]. Additionally, we will also record data for meteors that will improve our understanding about what regions of solar system material is being delivered to the Earth from.

The UKFN also forms part of an initiative called the UK Fireball Alliance (UKFAll), including video camera networks UKMON and SCAMP to develop protocols for organizing meteorite fall recovery operations in the UK. This initiative has already had several joint fireball observations (Fig. 1B).

The last recovered meteorite fall in the UK was nearly 30 years ago, and it is the aim of the UKFN, GFO and UKFAll together with the UK community to rectify this. Who is in?


Figure 1. A) Light pollution map of the UK. Installed UKFN cameras (blue dots) and planned camera sites (black and white dots). B) Fireball observed by the UKFN, on the 29th October 2019. C) UKFN camera installed at Galloway Astronomy Centre.
GEARING UP FOR HAYABUSA2: ESTABLISHING ATOM PROBE TOMOGRAPHY FOR ANALYSIS OF RYUGU SAMPLES

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Introduction: Upcoming missions to primitive asteroids including JAXA’s Hayabusa2 mission to the C-type asteroid Ryugu will return pristine samples of this water rich body to Earth for study in laboratories around the world. The total mass of sample available for study is likely to be around ~100 mg. Thus, maximizing data output from the smallest possible sample volumes is crucial for getting the greatest scientific benefit of this and other missions. Atom Probe Tomography (APT) is a relatively new tool in the geological and planetary sciences [e.g. 1] and is capable of measuring the nanoscale 3D distribution of ions in small ~100×100×1000 nm$^3$ volumes [2]. As it requires such minute sample volumes for each measurement, APT will be pivotal for analyzing the returned asteroid samples. We have studied a suite of materials analogous to those soon to be returned from Ryugu by APT to establish optimal sample preparation protocols and APT operation conditions. We also aim to characterise nanoscale features that we may then expect to observe in materials returned from Ryugu by Hayabusa2.

Methods: Using a focused ion beam method [3], we prepared APT samples of terrestrial serpentine (Ronda peridotite, Spain), a serpentine-rich area of CM chondrite Allan Hills (ALH) 83100, a matrix region of an ALH 83100 chip that had been heated to 800°C, and the naturally heated CM chondrite Pecora Escarpment (PCA) 91084. In addition, APT samples of the terrestrial serpentine and unheated ALH 83100 were prepared by FIB and transferred into the atom probe under cryogenic conditions.

The room temperature serpentine APT samples were analyzed in a LEAP 4000 atom probe. APT settings such as laser energy were varied every 1-2 million ion detections during the run to evaluate the optimum analytical conditions for this material. The meteorite samples were analyzed under identical APT operating conditions to aid comparison between datasets.

Results and discussion: Preliminary results indicate that (i) serpentine runs moderately well at a variety of APT analytical conditions, (ii) FIB preparation is key for data collection, and (iii) SiO opal-like nanophase spheres were detected within terrestrial serpentine (Fig. 1).

Initial APT results are promising and can provide 3D nanoscale information from serpentine-like minerals similar to CM chondrites and thus, the expected major mineral components of the asteroid Ryugu. Results from the nanoscale structures detected within CM chondrite APT samples, and the implications for the nanostructures we may detect in samples from that asteroid Ryugu, will be presented at the meeting.

SYN-TECTONIC SEDIMENTATION IN VALLES MARINERIS: A PUNCTUATED DECLINE OF WATER ON MARS?

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Introduction: Numerous medium and large alluvial fans are distributed across the surface of Mars, commonly at the interior margins of impact craters and topographic escarpments. Many alluvial fans are thought to have formed intermittently during the Hesperian and Amazonian\(^1\), eras generally regarded as cold and dry\(^2\). However, comparatively few alluvial fans have been identified in Valles Marineris, Mars’ vast equatorial canyon system, and those that have are often set in isolated basins. We have used CTX images (6 m/pixel) and digital elevation models (DEM; 20 m/pixel) to map and characterise ~ 150 newly identified alluvial fans and bajadas across Valles Marineris.

Results: The alluvial fans are ~ 1-20 km in size, lobate, and contain both negative and positive relief distributary channels on their surfaces, consistent with the morphology of other martian alluvial fans\(^1\) (Figure 1). In addition, impact craters are also embedded within the fan deposits, suggesting their formation was intermittent over prolonged periods of geologic time. Many of the alluvial fans have undergone subsidence through repeat normal faulting, which has implications for understanding the interplay between fluvial, sedimentary, tectonic and erosional processes throughout Valles Marineris. Fan deposits often occur at discrete elevations, separated vertically by several hundred meters of normal faulting. Subsequent fan deposits stratigraphically overlie many normal faults, indicating periods of syntectonic sedimentation. Other alluvial fans identified show no signs of normal faulting.

Discussion: We note that the alluvial fans are best preserved in the geologically younger canyons of Valles Marineris. The age of the alluvial fans is unclear (many of the surfaces are too small to accurately date with crater statistics). However, the presence of alluvial fans across multiple canyons in different states of preservation, both faulted and not faulted, suggests fan formation occurred throughout the development of Valles Marineris, from the late Noachian to the Amazonian\(^3\). The presence of alluvial fan embaying the Hesperian and Amazonian megaflood-formed features in eastern Valles Marineris is particularly interesting as it indicates the fans formed after the main phase of outflow channel formation. However, liquid water must have continued to be available at the surface, at least intermittently, in order to form the fans. Our results challenge the paradigm that Amazonian aqueous processes were primarily characterised by the rapid release of sub-surface water\(^2\).


Figure 1: Perspective view of a CTX digital elevation model showing alluvial fans in Eos Chasma, Valles Marineris, which are cut by normal faults. The faulting suggesting the fans formed as Eos Chasma was forming.
Topographic and Morphological Study of a Potential Palaeolake and Drainage System in the Oxia Planum Catchment

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**Introduction:** The ExoMars rover is due to land at Oxia Planum in 2021, and a key mission objective is to sample and analyse deposits with a prolonged aqueous history for the presence of biosignatures [1]. The area of the landing site meets these criteria as it (1) exhibits extensive outcrops of phyllosilicate mineralogy, and (2) is situated in the lowlands adjacent to a sedimentary fan and the termination of a highland valley network at the planetary dichotomy. However, clay bearing units in the landing ellipse may represent allochthonous and/or autochthonous deposits [2], and a better understanding of possible sediment sources in the drainage catchment area will be crucial to understanding Oxia Planum.

Numerous studies in western Arabia Terra have identified fluvial and palaeolake systems near the dichotomy [3, 4, 5], and others indicate the dichotomy in this region as the site of past groundwater upwelling [6, 7] or the palaeoshoreline of an ocean [8]. Possible palaeolakes have been identified in the Oxia Planum catchment, and noted as particularly relevant to the detection of biosignatures as ancient lacustrine environments could have hosted habitable conditions and contributed biological material to sediment sinks at the landing site [9, 10]. This work expands on previous studies characterising the Oxia Planum catchment area [9, 10], and will (1) surveying the area for further palaeolakes, (2) conduct a detailed analysis of multi-crater palaeolake system (Fig.1), and (3) examine a potential shallow inter crater lake outside of the catchment area.

**Observations:** Geomorphological features were mapped using CTX, HiRISE, and THEMIS images in ArcMap. Topographic data aided feature mapping and has been mosaicked from 465 m/pixel MOLA and 50-200 m/pixel HRSC digital elevation models (DEM), with a number of 20 m/pixel CTX DEMs derived from ISIS and SOCET SET.

Fluvial valleys and sedimentary fans were mapped across the study area. Valley segments beginning within closed basins or those that breached the downslope edge of basins were interpreted as being outlet valleys of open-basin palaeolakes, and the extents of these palaeolakes were then estimated based on the elevation required for spillover through the outflow valley (Fig.1). In addition, a number of basins with only inlet valleys were identified as possible closed-basin palaeolakes.

**Figure 1** – Detail of an open-basin palaeolake within the Oxia Planum drainage catchment showing: sedimentary fans (yellow triangles), incised valleys (green lines), and possible palaeolake extents (blue areas). (CTX, HRSC, MOLA DEM over CTX images)

Some examples of open-basin palaeolakes show evidence of multiple fill levels and basin breaching events, as well as fine sedimentary structures within their floors.

**Discussion:** Preliminary results indicate some new intra-crater open-basin palaeolakes which are not identified in previous studies and catalogues. These palaeolakes are shallow and hosted in intra-crater basins. Some are situated within the Oxia Planum catchment and are therefore possible sources of material ultimately deposited at the landing site in the lowlands. However, one example falls outside the catchment area defined on the current topography, and more high resolution DEMs will be produced to determine the hydrological relationship of this palaeolake to the catchment area.

A complex system of palaeolakes (Fig.1) also identified in previous works [9, 10] will be the focus of a further detailed mineralogical and sedimentary study to determine the history of filling and spillover events.

Mapping Jupiter’s Temperatures, Aerosols and Ammonia via VLT/VISIR Imaging in 2016

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Introduction:
The VISIR mid-IR imager (5-25 µm) on the Very Large Telescope (VLT) has been providing infrared spatial and temporal support for NASA’s Juno spacecraft, constraining atmospheric thermal conditions in the upper troposphere (100-700 mbar) and stratosphere (1-10 mbar). Our pre-Juno-arrival dataset (January-August 2016) demonstrated that Jupiter’s North Equatorial Belt (NEB) began a northward expansion in late 2015, consistent with the 3-5 year cycle of NEB activity. We have extended this analysis to coincide with Juno’s perijove encounters, once every 53.5 days. Our early 2017 data has been useful in the multi-wavelength study connecting thermal data at cloud-tops with radio observations at depth to investigate moist convection in and South Equatorial Belt (SEB) [1]. Using a new technique, we derive zonally-averaged temperatures, aerosols and ammonia distributions from centre-to-limb curves, and use the improved priors to assess the structure of the Great Red Spot and other prominent vortices and provide a comparison of the upper-tropospheric aerosols and ammonia at the Equator to the findings of Juno’s near-infrared and microwave observations.

The VISIR observations during the Juno epoch contribute to a time-series of VLT imaging that now spans over a full Jovian year (2006-2018). Observations in eight narrow-band channels sense stratospheric temperatures (7.9 µm), tropospheric temperature (13.0, 17.6, 18.6, 19.5 µm), aerosols (8.6 µm) and ammonia (10.7 and 12.3 µm), and are inverted via our optimal estimation retrieval algorithm, NEMESIS [2]. Binning these data with respect to emission angle is significantly more constraining than previous attempts to fit these VISIR datasets, suggesting that the centre-to-limb variations contain significant information about the vertical structure. In this paper, we report on the structure of the GRS (Fig 1) and prior to the beginning of the Juno epoch (January-August 2016) and use the data to provide cloud-top estimates of equatorial temperatures, ammonia and aerosols forming part of a time-series during the Juno epoch to compare to Juno’s perijove observations.

Recent findings from Juno suggest that ammonia is strongly enhanced at Jupiter’s equator, with the region over the NEB also being more depleted than SEB. This is consistent with previous thermal-IR spectroscopic analyses [7, 8], which suggest strong equatorial upwelling, but have confirmed that this zone of elevated ammonia persists to great depths below the clouds. By inverting zonal-mean VISIR observations, taking into account their dependence on emission angle, we confirm that VISIR imaging is sensitive to this equatorial ammonia maximum, allowing us to map its variation with longitude and with time through the full decade-long dataset.

Summary and conclusions:
VISIR thermal imaging provides a regular source of information on the temperatures, aerosols and ammonia distributions associated with the phenomena studied by Juno. They also place the Juno epoch into the wider context of Jovian variability over a full ~12 year orbit. Future work will focus on extending the study into the long-term variability of the cold polar vortex and the EZ of Jupiter to provide direct comparisons with deep structures observed at microwave wavelengths.

Summary and conclusions:
DEVELOPMENT OF OXIA PLANUM SIMULANT RELEVANT TO EXOMARS MISSION

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Introduction: The key objectives of the ExoMars rover are to search for signs of life and characterise the geochemical/water environment as a function of depth [1]. To achieve this, Oxia Planum, a clay-rich plain, has been selected as the landing site, due to abundant mineralogical evidence of aqueous activity and its astrobiological potential [2,3]. To assist in data interpretation, simulants mimicking the region’s mineralogy are required. The aim of this project is to develop regolith simulants that can be used to assist in the interpretation of data returned from the ExoMars rover and in habitability investigations.

Target mineralogy: Differential erosion rates at Oxia Planum has exposed three distinct units [4]:

1) A clay unit (mid-Noachian in age) is concentrated in the eastern outcrop. CRISM data shows the presence of Fe-phyllosilicates as well as sporadic Al-phyllosilicates thought to overlay Fe-phyllosilicates. Such layering is evidence of a weathering profile in an aqueous environment [5,6].

2) A depositional unit (late Noachian in age), potentially a fluvial deltaic fan, in which hydrated silica is detected [4].

3) A younger volcanic unit (Amazonian in age) that protected the underlying clay and deltaic units from erosion. It is thought to be rich in pyroxene and plagioclase (similar unit at Mawrth Vallis) [7,8].

Simulant design: CRISM data suggests Mawrth Vallis has a similar formation history to Oxia Planum [8]. Therefore, we have used mineralogical information from Mawrth Vallis to refine mineral selection for simulants. We have also made adjustments to minerals composition based on discrepancies between orbital data and insitu data from the MSL at Gale crater. For example, the distribution of olivine and pyroxene differed when analyzed by MSL and alkali feldspars were not observed from orbit but were detected by MSL [9, 10]. Using geological and mineralogical data from remote sensing, 5 simulant lithologies have been identified representing the stratigraphy in the clay unit.

Simulant one: Al-rich clay layer. Represents the upper clay region. This will be dominated by smectite minerals, and contain vermiculite, kaolinite, hydrated silica, allophane and quantities of hematite. Sulfates could be added in small quantities, to represent their deposition in fractures at Mawrth Vallis.

Simulant two: Al-rich clay with ferrous material. Represents the contact of Al-rich clays and an underlying ferrous material. Therefore, it will be similar in mineralogy to simulant one but contain a relatively larger proportion of Fe oxide and Fe hydroxide.

Simulant three: Fe-rich layer. Represents the lower clay region, which contains Fe-rich smectites (major component) with some Mg-phyllosilicates. Olivine and pyroxene will as be added in smaller quantities.

Simulant four: Fe-rich layer with ferrous material. Represents blending of the Fe-rich layer with the ferrous material above. This simulant will contain all minerals in simulant three plus Fe oxide and Fe hydroxide.

Simulant five: Fe-rich layer (which can have a varied Fe oxidation state). This simulant will be rich in Fe-rich clays. CRISM data is unclear about the clay’s Fe speciation, therefore, it will be possible to vary the Fe3+/Fe2+ ratio in a similar fashion to [11].

Characterisation: Simulants will be characterized using instruments akin to RLS (Ramen Laser Spectrometer) and ISEM (Infrared Spectrometer for ExoMars) instruments on board the ExoMars rover as well as standard geological techniques, such as Scanning electron microscopy (SEM) and electron microprobe analysis in order to refine mineral chemistries.

Uses: These simulants can be used to help interpret data returned from instruments onboard the ExoMars rover from a range of potential lithologies that could be found at Oxia Planum. Additionally, these simulants incorporate the longitudinal mineralogical changes in the clay unit, relevant to the ExoMars drill. They could also be used in a range of experiments to assess the habitability of this region.

Acknowledgements: AD and NKR would like to thank the RAS for funding towards this work.

Noble gas and halogen behaviour during impact melt processing in the early inner Solar System

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**Introduction:** Chondritic impact melt can inform on how the chemistry of bodies in the early inner Solar System were affected by impact melt processing. The presence of vesiculation within chondritic impact melt implies volatile redistribution during melting [1]. We are conducting a study to quantify the extent and nature of impact-melt-induced volatile redistribution, focusing on the behavior of noble gases and halogens in both the unmelted host (OC) and impact melted (IM) fractions of ordinary chondrites. We consider the behavior of volatiles in relation to the petrology and chemistry of the OC and IM fractions. We also use $^{40}$Ar-$^{39}$Ar dating to determine if varying volatile budgets could be explained by determining the chondrites’ impact histories.

Six ordinary chondrites were selected for this study (Table 1). A range of groups, petrologic types, shock stages and IM cooling rates were selected for a representative picture of the behavior of volatile elements in ordinary chondrites during impact melt processing. Here we report noble gas and halogen investigations from OC and IM fractions of Chelyabinsk and Chico.

<table>
<thead>
<tr>
<th>Meteorite Name</th>
<th>Fall or Find</th>
<th>Group / type</th>
<th>Shock Stage</th>
<th>IM Cooling Rate ($^\circ$C/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chelyabinsk</td>
<td>Fall</td>
<td>LL5</td>
<td>S4</td>
<td>~$5 \times 10^6$ [2]</td>
</tr>
<tr>
<td>Chergach</td>
<td>Fall</td>
<td>H5</td>
<td>S3</td>
<td>unk</td>
</tr>
<tr>
<td>Chico</td>
<td>Find</td>
<td>L6</td>
<td>S6</td>
<td>~0.1 [3]</td>
</tr>
<tr>
<td>Gao-Queenie</td>
<td>Fall</td>
<td>H5</td>
<td>unk</td>
<td>~$4 \times 10^4$ [4]</td>
</tr>
<tr>
<td>Kilabo</td>
<td>Fall</td>
<td>LL6</td>
<td>S3</td>
<td>unk</td>
</tr>
<tr>
<td>Orvinio</td>
<td>Fall</td>
<td>H6</td>
<td>unk</td>
<td>~$4 \times 10^2$ [5]</td>
</tr>
</tbody>
</table>

Table 1. The ordinary chondrite suite selected for this study. unk = not reported in current literature.

**Methods:** Mass spectrometry is used for both noble gas and halogen analyses. Noble gases are released through laser step heating and analyzed on the Thermo Scientific Helix MC™ noble gas mass spectrometer. Halogen analyses employ the neutron irradiation noble gas mass spectrometric technique of [6]. For halogen analyses and $^{40}$Ar-$^{39}$Ar dating, sample gas is released through laser step heating and analyzed on the Thermo Scientific Argus VI™ noble gas mass spectrometer. Petrological investigations use Scanning Electron Microscopy, and Electron Probe Microanalysis.

**Observations:** Both Chico and Chelyabinsk have higher concentrations of noble gases in the IM fraction than in the OC. Halogens only partially show this behavior: although the Chico IM fraction has higher bromine (Br) and iodine (I) abundances than OC, it is depleted in chlorine (Cl). In Chelyabinsk, the IM has higher abundances of Cl and Br but a similar abundance of I in both fractions. In terms of petrology, the Chico IM contains large vesicles and abundant chlorapatites, whereas, apatites are absent in the Chelyabinsk IM which contains occasional smaller vesicles.

**Interpretations:** Our observations point to multiple controls on volatile behavior prior to and during impact melting. Elevated IM noble gas concentrations in both chondrites could be related to diffusion path length [7]. During shock, volatiles diffusing from OC grains only have to diffuse the length of the grain, whereas, volatiles in the IM have to diffuse through the entire length of the melt [7]. Inconsistent halogen concentrations in the IM fraction could imply diffusion is less important than the behavior of halogen-hosting phases during melting. However, it is unclear how the Chico IM fraction’s abundance of chlorapatites relates to its relative depletion in Cl.

Melting conditions may also play a role in controlling volatile behavior as the large melt volume and slow cooling [5] of Chico would have allowed volatiles a long time to diffuse. Conversely, the quenched microcrystalline melt of Chelyabinsk [2] would have allowed little time for volatile diffusion. Literature data and our investigations show Chico and Chelyabinsk’s differing impact histories as the Chico IM likely formed at ~500 Ma [3] whereas the Chelyabinsk IM likely formed at ~3200 Ma [2]. This could be influencing varying volatile relationships between the chondrite fractions and our chondrite suite’s range of impact histories (Table 1) will allow exploration of this.

CONTINUING CHARACTERIZATION OF OXIA PLANUM, THE LANDING SITE FOR THE EXOMARS ROSALIND FRANKLIN ROVER

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Introduction: Oxia Planum (OP) will be the landing site for the European Space Agency/Roscosmos 2020 ExoMars Rosalind Franklin rover. With the primary goal of searching for signs of past and present life on Mars, the ExoMars rover will investigate the geochemical environment in the surface and shallow subsurface over a nominal mission of 218 martian days (sols) [1]. To meet this ambitious mission goal, and for the results of the geochemical experiments to be meaningful, it is crucial to consider the geological processes that might affect the potential for the formation, concentration and preservation of biomarkers within strata exposed in the landing ellipse. Here, we describe the landing site [2] and review the ‘current working hypotheses’ for its geological history. We also present ongoing work by the Rover Science Operations Working Group (RSOWG), remote sensing ‘macro’ sub group and plans for mapping the landing site.

Oxia Planum: OP is located at the transition between the ancient terrain of Arabia Terra and the low-lying basin of Chryse Planitia (Figure 1). OP forms a shallow basin, open to the north, characterised by clay-bearing bedrock units, and is considered to be Noachian (>3.7Ga) in age. The working hypothesis [2] states that there have been at least two distinct phases of aqueous activity within the landing site area. During the Noachian, the first phase of activity deposited ~100 m of layered material, which are rich in the clay-rich compositions observed today. These claybearing units comprise Mg/Fe smectites lower in the stratigraphy, overlain by more Al-rich phyllosilicates. After a substantial hiatus, the second phase of aqueous activity included a fluvio-deltaic system. This fluvial activity post-dates the clay-rich layered unit, and is associated with the younger set of channels in Coogoon Vallis, which feeds into the Oxia basin. There is abundant evidence for intense erosion across OP. There are isolated buttes, perhaps part of a regional extensive layer that overlies the clay-bearing unit, and a dark, pyroxene bearing resistant, capping unit of Amazonian age (<3 Ga) that crops out in association with inverted landforms. Despite this erosion, crater statistics indicate that the clay-bearing rocks are Noachian in age, but have only recently been exposed. This should mean that cosmic ray bombardment and damage associated with exposure to organic biomarkers, the objective for ‘Rosalind Franklin’, have been minimal.


Figure 1: Oxia Planum on (a) Mars and (b) in Arabia Terra in the context of its catchment. (c) ExoMars landing ellipses in the Oxia Basin.
High-frequency modelling of the effects of 3D crustal structure and atmospheric sources detected by InSight on Mars

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Since landing on Mars in November 2018, InSight has revealed that the Red Planet’s seismicity is clearly different to Earth’s. Two striking differences observed by the SEIS instrument are the extremely long duration of the waveforms, which may last up to several minutes, and the unusual polarization of the ambient noise data, which is opposite to that seen on Earth.

Explaining these features using conventional (terrestrial) source and structural properties is problematic, and hence high-frequency modelling is an invaluable tool for exploring whether these effects may arise from strong crustal heterogeneities or atmospheric processes. This is especially important given the single-station constraint.

Using the high-frequency seismic modelling code AxiSEM3D, expanded to include an atmospheric layer and absorbing upper boundary condition, we explore what the effects of strong crustal scattering and atmospheric excitation may be.

From a structural point of view, we sample a significant portion of the possible scatterer parameter space, including depth distribution, mean free path, size and perturbation strength. The spectra of the long-duration reverberations may be mimicked by specific combinations of these parameters.

From a source point of view, we investigate whether atmospheric pressure sources at a variety of heights, distances and durations may explain the observed polarization, and consider whether complex atmospheric source-time functions may contribute to the observed waveforms.
INVESTIGATING OXYGEN ISOTOPE HETEROGENEITY IN CM CARBONACEOUS CHONDRITE REGOLITH BRECCIAS

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Introduction: CMs are the most common carbonaceous chondrites and represent the largest collection of meteorites that may sample C-class asteroids. Previous research has robustly established that CMs define a spectrum of partial serpentinitization as a result of aqueous alteration [1]. Understanding the nature of this alteration is key to understanding the evolution of water in early formed asteroids in addition to unravelling possible geological context of the CM parent body(ies). However, ambiguity problems remain. Petrographical and chemical heterogeneity is acknowledged and well-studied between separate CM specimens, yet it is also apparent that individual samples exhibit strong intra-sample variation - i.e. they are regolith breccias [2,3]. This raises interesting questions considering much past research on the evolution and nature of the CM parent body(ies), and indeed the nature of the early solar system, has revolved around bulk analyses of these meteorites and not necessarily on the range of lithologies that are often observed.

Objectives: To investigate the oxygen isotope heterogeneity among the clasts of LON94101 and make systematic comparisons to detailed mineralogical and petrographical observations.

Methods: The clasts in LON94101 will be microsampled using a special modified extraction procedure [4] and a New Wave Instruments MicroMill™ (in order to preserve spatial context. The objective is to remove milligrams of powder to be analysed for oxygen isotopes using laser assisted fluorination at The Open University. Each clast will be characterised alongside oxygen isotope work using a variety of techniques, including SEM and XRD.

Results and discussion: Initial characterisation of several polished blocks of LON94101 reveals a vast range of lithologies that differ substantially in texture and mineralogy. The severity of aqueous alteration is established by assessing the abundance and composition of the phyllosilicate rich matrix (Mg#: Mg/Mg+Fe), the degree of coarse phase alteration (e.g metal, chondrules and chondrule mesostasis) and the morphology and composition of cronstedtite-tochilitite intergrowths. CM2s define a mixing line of slope ~0.7 in oxygen three isotope space [5]. Oxygen isotope of single CM2s (E.g. LEW85311) by different authors and institutions [5,6] plot far apart on this slope, reflecting oxygen isotope heterogeneity between sample powders and thus, variation in chips distributed. The range of clasts and aqueous alteration phenomena observed in single regolith breccia (like LON9401) are, with some confidence, derived from a single parent body. Oxygen isotopes and detailed mineralogical investigations of these clasts will establish more robust geological context, including the conditions of aqueous alteration on the asteroid (such as water:rock ratio and temperature). If the clasts span the known range of CM2 oxygen isotope measurements, current thinking regarding the geology and structure of CM source bodies will be challenged, providing insight into a big question in meteoritics: do CMs sample a single, heterogeneously altered parent body, or multiple homogenous ones?


Above: A segment of a BSE mosaic of LON94101. Two clasts are clearly visible. A dark, chondrule poor clast, surrounded by a lighter, chondrule rich phase. This image displays two of five lithologies present in the whole, 1cm sized chip.
JUPITER’S TROPICAL CIRCULATION REVEALED VIA JUNO RADIOMETRY AND GROUND-BASED INFRARED SPECTROSCOPY

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Introduction and Background:
NASA’s Juno mission has now completed more than twenty close flybys of Jupiter (known as peri-joves), providing a swathe of new insights into the interior, atmosphere, and magnetosphere of this archetypal giant planet. Jupiter’s clouds are transparent at long wavelengths, permitting Juno’s microwave radiometer (MWR, [1]) to explore the deep atmospheric circulation below the clouds that define the familiar banded appearance. Via inversion of brightness temperatures in six channels in the 1.4-50 cm range, Li et al. [2] revealed: (i) a planet-wide depletion of NH₃ gas down to tens of bars (i.e., it was not well-mixed with altitude below the 0.7-bar cloud base); (ii) a band of enhanced ammonia wrapped around Jupiter’s equatorial zone (EZ) between the prograde zonal jets at 6.9°N/7.2°S; and (iii) strong depletion of ammonia in the North and South Equatorial Belts (NEB/SEB). We discuss how this structure can be reconciled with the proposed overturning circulation of Jupiter’s tropics, where zonal jets forced by the convergence of eddy momentum flux in the mid-troposphere (p>1 bar) imply rising motions in belts and sinking motions in zones; whereas the decay of the zonal winds with altitude implied rising motions in zones and sinking motions in belts in the upper troposphere (p<1 bar, Fletcher et al., [3]).

Plumes and Hotspots:
The discussion above deals with the zonal average (i.e., assuming the belts and zones are similar at all longitudes). However, spatially-resolved mid-infrared spectral maps from Cassini and ground-based spectroscopy revealed that the NH₃ enrichment was concentrated in equatorial plumes in the 2-6°N region [4]. The equatorial plumes are also dark at radio wavelengths sensed by the VLA [5]. These plumes are white and reflective in visible light [6], and are located between the prominent dark “hot spots” that exist on the prograde jet at 6.9°N, slightly further north. The Galileo probe descended into one of these aerosol- and volatile-depleted hotspots in 1995 [7], leading us to suspect that its derived abundances were not representative of Jupiter’s global values. The plumes and hotspots are distorted by the zonal wind field, with reflective tails extending in a southwest direction towards the equator, and bordered to east and west by dark streaks (“festoons”) emanating from the southwestern corners of the hot spots. The plumes and hotspots are therefore expected to exhibit extreme contrasts in NH₃ concentration (and potentially other species, like PH₃ and H₂O). Characterising the conditions within these meteorological structures is therefore essential if we wish to know how representative Juno-derived abundances are of the planet’s bulk.

Gemini and Juno:
To characterise conditions within Jupiter’s equatorial plumes and hotspots, we explore the MWR-derived brightnesses during Juno’s first 10 peri-joves, finding that some encountered plumes (e.g., PJ4), some encountered hotspots (e.g., PJ7), but that neither showed the contrasts expected from the Galileo-probe results. We combine this with high-resolution spectral mapping of Jupiter’s equator in March 2017 from the TEXES instrument [4] mounted on Gemini-North (Fig. 1), allowing us to map temperatures, phosphine, ammonia and aerosols in the 0.1-0.7 bar range. We conclude that Juno did not encounter a ‘mature’ hotspot during the first 10 orbits, and that hotspots exhibit (i) spatial heterogeneity within the dark formations themselves; and (ii) differences from hotspot to hotspot. Juno did encounter the edges of hotspots and plumes, and spatial maps of brightness temperatures suggest that these are ‘weather-layer’ phenomena, restricted to p<10 bar and not penetrating down to the deepest levels probed by Juno.

Figure 1: Hubble (top) and TEXES (bottom) maps showing plumes (blue/yellow arrows) and the PJ4/5 locations. The TEXES map is a 3-colour image from spectral windows sensing CH₃D and PH₃ near 8.6 μm.

References:
FREEZING-INDUCED FRACTIONATION OF ICE, GLASS AND SALTS FROM SIMULATED ENCELADUS OCEAN FLUIDS

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Introduction: The Saturnian moon Enceladus exhibits large cryovolcanic plumes sourced from a subsurface ocean [1], which contain evidence of endogenic organic chemistry and ongoing hydrothermal activity at the core-ocean boundary [1-3]. Salt-rich ice particles observed in the plumes by the Cassini spacecraft are interpreted as rapidly frozen ocean spray [4] thus studying them provides a means of probing the chemistry, habitability and potential biology of an extraterrestrial ocean. However, little is known about how ocean constituents evolve as they are transported towards the extreme cold at the Enceladus surface. We investigated the partitioning of ice and non-ice materials and the pH-dependence of cryogenic mineral formation using simulated Enceladus ocean fluids. As thermal conditions inside the vents are unknown, we investigated two thermal end-member scenarios of ice particle production: flash-freezing (≥100 Ks⁻¹), and slow freezing (~1 Kmin⁻¹) to provide new constraints on the range of possible products of cryovolcanism at Enceladus.

Findings: Glass formation and ice templating. We show for the first time that fluids with Enceladus ocean composition form ice-templated aqueous glass when rapidly flash-frozen. In the interior of frozen droplets, a solidified brine-vein network was observed, which had formed despite the extremely rapid cooling rate (Fig. 1A). Bubbles of gases exsolved at the glass transition were incorporated into the glass. If plume particles result from a flash-freezing mechanism, the production of cryovolcanic glass at Enceladus should be expected.

Mineralisation via direct crystallisation versus devitrification. We found that crystallisation of salt minerals occurred either directly, by precipitating from freezing brine during slow freezing, or growing from glass upon re-warming of flash-frozen samples. These contrasting mechanisms were reflected in the distribution of crystals. Flash-frozen samples exhibited random crystal distributions whereas crystals produced by slow freezing were arranged in lamellar or globular clusters of locally distinct crystal types (Fig. 1B,C). These latter textures are explained by relative solubility; as more soluble minerals (such as chlorides) form late in the precipitation sequence, they force less soluble minerals (such as carbonates) into aggregates. Measurements of bulk mineralogy showed that carbonate mineral assemblages can function as a probe for parent fluid pH, as the dominant carbonate phases differed between upper and lower pH estimates for Enceladus’s ocean. Furthermore, some phases were only observed in slowly frozen samples, demonstrating that their presence could be used as an indicator of freezing rate.

Our experiments show that different cryovolcanic products are possible in Enceladus plume particles, including vitrified glass and crystalline material, depending on their thermal history. Whether Cassini encountered glass-bearing particles at Enceladus depends on the specific thermal histories of the particles, which are currently unknown. Proposals for future missions also centre around plume particle analysis [5]. Based on our results, non-destructive measurements of plume particles could open powerful new avenues of investigation at Enceladus.


Fig. 1. A. Vitrified brine vein network interior of flash-frozen droplet. Imaged at 123 K. B. Crystals formed through re-warming flash-frozen glass. C. Crystals formed through slow freezing.
ACTIVE JOSTLING CAMPUS TECTONIC BLOCKS ON VENUS

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Introduction: Tectonically, much of the Venus surface resembles the terrestrial continents [1,2,3], as expected on the basis of their similar strength profiles [4,5]. One area of Venus, here referred to as Nuim Campus, is similar in size and shape to the Tarim Basin, an exotic continental terrane in NW China. Despite these similarities, detailed mapping of these two terranes reveals important differences consistent with a thinner crustal thickness on Venus: if Earth’s continents are analogous to drifting icebergs, then the Venus crust would be a sea of pack ice.

Crustal Blocks: In its simplest definition, a terrane is a fault-bounded block that may be considered a crustal-scale allochthon, or a continental microplate. It usually denotes a stratigraphically distinct accreted continental fragment (called an exotic terrane); the 1500 × 600 km Tarim Basin is a distinctive example of an accreted exotic terrane.

In the absence of oceanic plate tectonics, blocks on Venus are unlikely to be exotic or accreted, and so in this strict sense the concept of terranes may be limited to highland plateaux [6]. However, in its simpler meaning, fault-bounded crustal blocks are almost ubiquitous [2]; here we assign the Latin term campus (lit., a field or plain; pl. campi) in describing these landforms.

Rather than being transported across the planet by plate tectonics as exotic terrains, campi are inferred to be locally mobile, jostling with their neighbours in response to subcrustal stresses [7,8], but remaining within the same geographical area.

Continental Crust: The existence of low-density continental crust on Venus is uncertain but probable [9,10]. The most likely candidates are the highland tesserae: Alpha, Ishtar, Ovda, Tellus and Thetis. Each appears to consist of a core region, the origin of which is uncertain, perhaps by downwelling and contraction [11], or by upwelling and extension [12]. Surrounding the core are various tectonic belts that are reminiscent of Proterozoic terrains surrounding Archaean cores in Tellurian cratons, which appear to have similarly developed by continental-like accretion [6,13]. Regardless of their origin, it is probable that they therefore record a long and complex history. Continental crust on Venus may provide a cold, deep keel that interacts with mantle convection, providing a slow directionality to jostling campus movements, allowing them to accrete plains campi at their margins. Movement of campus blocks away from the equatorial rifts may also explain the height of Ishtar, which is everywhere in compression.

Figure 1: Example campi and their likely current relative motion.

Conclusions: If Earth’s continents were likened to drifting icebergs, the Venusian crust would be a sea of pack ice. The ultimate fate of lowland campi appears to be either fragmentation and volcanic burial, destroying their surface expression, collision and accretion onto the margins of highland tesserae. The highland tesserae record a long history of collisions with regional plains units through either modern, campus-related movements, or perhaps through earlier conventional plate tectonic processes. Many of these accreted terrains are highly eroded and thus reveal both the deeper structure of plains units and their past nature, perhaps in a cooler and wetter environment.

LARES: Laboratory Analysis for Research into Extraterrestrial Samples

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Introduction: LARES is a network of planetary scientists working in laboratories with specialist instrumentation for analysis of extraterrestrial material. This project is an initiative to upgrade current instrumentation in readiness for return of samples from the Moon, asteroids and Mars. The project is a development of the UK Cosmochemistry Network, which was funded by STFC and linked the Natural History Museum, the Open University and the University of Manchester. LARES is a much bigger initiative and hopes to include all research groups with an interest in analysis of extraterrestrial materials; to date, 19 separate institutions have joined the project. The currently-stated objectives are as follows:

Objectives: (1) equip the UK with a suite of state-of-the-art laboratory instrumentation, building upon existing infrastructure, so that we are internationally leading when bidding for material from sample return missions; (2) use this investment to understand better the origin and evolution of the Solar System and exoplanetary systems, and the conditions for life beyond Earth; (3) use our scientific base to establish a training network for Ph.D. students and provide career development opportunities for Fellows, Early Career Researchers and staff, to build capacity and capability in STEM for academia and industry; (4) leverage the investment to provide impetus for building a European Sample Curation Facility.

Key stakeholders: UKRI, the UK Space Agency and the 19 academic institutions in LARES are key stakeholders. Additional stakeholders include astronomers, Earth and materials scientists, space and high technology industries and STEM education and outreach professionals.

Scientific drivers: Multi-scale detailed analysis of extraterrestrial materials at sub-nanometre resolution provides insights to nucleosynthesis and stellar evolution, astrophysical environments (including the protoplanetary disk), Solar System dynamics, planetesimal formation, planetary evolution and the prebiotic processes that led to the origin of life. This activity drives advances in analytical technology; it requires that maximum information is obtained from minimal amounts of irreplaceable samples.

The first objective of LARES is to ensure that the UK remains world-leading in this field, has a state-of-the-art instrument suite that strengthens a skills base at the forefront of analytical science and enables development of cutting-edge instrumentation. This will enable us to lead international efforts to understand Solar System and planetary evolution (Objective 2) and train the next generation of research leaders (Objective 3).

Areas of excellence: LARES consortium members are internationally recognised for excellence in optical, electron and X-ray microscopy, atom-probe tomography, microspectroscopy and organic, light element, noble gas, stable and radiogenic isotope mass spectrometry, as applied to extraterrestrial materials. Research is supported by the world-famous meteorite collection at the NHM, and we exploit Diamond’s internationally-leading beamlines. LARES will complement and magnify the impact of existing facilities, building on our research expertise.

International Relevance: As well as enabling tremendous advances in understanding planetary evolution from existing extraterrestrial samples, LARES will prepare the UK community for analysis of materials returned by missions to asteroids, the Moon and Mars. We are participating in the NASA-ESA Mars Sample Return (MSR) campaign, but for Europe to obtain the greatest benefit, it must have its own Sample Curation Facility (SCF) equipped to deal with the unique analytical challenges of returned martian material – including handling and analysis of material under the protocols demanded by planetary protection requirements. Objective 4 of LARES is to provide impetus for placing a European SCF on the ESFRI (European Strategy Forum on Research Infrastructure) roadmap so that it is both a key part of the international planning process, and the attractiveness of the UK as a location improved.

Current Status: LARES was formed in response to a call for Indicators of Interest from STFC announced in July 2018. The call stated: “STFC has launched a consultation with research communities, designed to identify new world class science and technology proposals for potential future investment. The aim is to develop an ambitious portfolio of outline business cases for priority projects that relate to our strategic scientific and research infrastructure objectives, covering our remit, and driven by our communities”. Projects costing up to £50M were encouraged. The LARES proposal (which was for £36M over 5 years for new equipment and staff) was rated highly and is one of the main priorities of the Solar System Advisory panel. As such, it is now part of STFC’s strategic roadmap.

Next Stage: The ESFRI roadmap is being refreshed, and there is a call for inputs from communities. We will use the opportunity offered by BPSC to discuss how we can take LARES further, possibly through a funding request to STFC’s PPRP.
Energetic and Thermodynamic Limits on Continental Silicate Weathering Strongly Impact the Habitability of Wet, Rocky Worlds

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Abstract:
The classical concept of the “liquid water habitable zone” as presently understood relies on the silicate weathering feedback to stabilize climate across a range of instellations. However, the representation of the silicate weathering feedback that is used in rocky exoplanet weathering and climate stability studies does not account for either the thermodynamic limit on the concentration of silicate weathering products in runoff (Maher & Chamberlain 2014) or the energetic limit on precipitation set by planetary instellation (Pierrehumbert 2002).

Using our 0-D CO$_2$- and energy-balance model (with a very simple hydrological model), we find that when the thermodynamic limit is included, rocky planet climate loses sensitivity to silicate dissolution kinetics and is instead controlled by runoff and the impact of pCO$_2$ on solute concentration in runoff, which is mediated by chemical thermodynamics instead of kinetics. Simulations of the climates of planets whose weathering behavior includes the thermodynamic limit on concentration are sensitive to land fraction, CO$_2$ outgassing rate, and parameterizations of hydrology and surface properties (like lithology and soil age). Changing these parameters leads to large variations in the width of the effective outer edge of the habitable zone (defined as the instellation where planetary temperature falls to 273.15 K).

When the energetic limit on precipitation is included, under some parameter combinations, a maximum precipitation is reached by planets at low instellations, which leads to the decoupling of temperature and precipitation for planets beyond that instellation. Simulations of planets in this regime have a weathering flux controlled by pCO$_2$, since runoff ceases to be temperature-dependent and instead decreases linearly with instellation. By removing one of the primary feedbacks on CO$_2$ accumulation, the energetic limit on precipitation may lead to some planets having very warm climates near the outer edge of the habitable zone.

In summary, the inclusion of energetic and thermodynamic limits in our simulations of continental silicate weathering on rocky, ocean-bearing exoplanets leads to a diversity of stable climates throughout the habitable zone, ranging from >350 K to freezing, depending on a complex interplay of poorly-understood factors.
WHAT IS THE OXYGEN ISOTOPE COMPOSITION OF VENUS?
The case for sample return from Earth’s “sister” planet.

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Introduction: The oxygen isotope composition of Venus is currently unknown. However, this measurement (Δ¹⁷O) would have first order implications for our understanding of the origin and early evolution of the inner Solar System. In particular, it would provide critical evidence concerning the extent of isotopic mixing in the inner Solar System.

The bimodal Solar System: On plots such as ε²⁶Cr vs. ε¹⁷⁰Ti and ε²⁶Cr vs. Δ¹⁷O Solar System materials define two distinct groupings (Fig. 1) [1, 2]. One comprises the carbonaceous chondrites and a minor subset of achondrites; the other is defined by all other Solar System materials. It was suggested by [1] that the carbonaceous chondrite group (CC) may represent material formed in the outer Solar System and the non-carbonaceous chondrite group (NC) in the inner Solar System.

A homogeneous inner Solar System? The diversity displayed by the NC group appears to support an isotopically heterogeneous inner Solar System (Fig. 1). However, this conclusion may be premature. Apart from the Earth, Moon and Mars, the other NC lithologies plotted in Fig.1 are all asteroidal, with the mass in the asteroid belt estimated to represent just 0.04% that of the Earth [3]. Although much more massive than the asteroid belt, Mars is anomalously small compared to either Earth or Venus. One of the drivers for the formulation of the “Grand Tack” model was to explain the relatively small size of Mars [4]. As a result of the inward and then outward migration of Jupiter, the “Grand Tack” model predicts that the feeding zone for Mars was significantly impoverished. This suggests that Mars is also not fully representative of the inner Solar System. While we have samples from the Moon, the Earth-Moon System is fully representative of the inner Solar System. 

Sorting out the Moon-forming giant impact: Paradoxically a returned sample from Venus should help to settle the origin of Earth’s Moon. The canonical giant impact model has become difficult to reconcile with evidence that the Moon and Earth are essentially identical with respect to many isotopic systems, in particular oxygen [6]. However, it has been proposed that as a result of high levels of mixing in the inner Solar System the giant impactor Theia and proto-Earth had similar isotopic compositions [7]. If the Earth and Venus are nearly identical isotopically this would indicate that the inner Solar System was well mixed, relaxing the requirement for high-temperature homogenization in the aftermath of the giant impact [7]. Alternatively, a distinct oxygen isotopic difference between Venus and Earth implies a lesser degree of inner Solar System homogenization [6]. Hence, Theia would likely have differed significantly from the proto-Earth, requiring a high energy impact to form the Moon [5, 6].

Additional benefits of Venus sample return: Whether isotopically distinct from, or nearly identical to Earth, the information provided by a sample from Venus would have profound implications for our understanding of how the terrestrial planets formed [8]. Analysis of such a sample would provide a firm basis for assessing similarities and differences between the evolution of Venus, Earth and Mars [8]. Venus is Earth’s planetary twin and deserves to be better studied and understood [8].

Sample return from Venus: A grab-and-go sample return scenario has been outlined by [9]. Other configurations, such as a combined surface and atmosphere sampling mission, are also feasible.


Fig. 1 Plot of ε²⁶Cr vs. Δ¹⁷O for all major Solar System lithologies [1, 2].
Assessing the relationship between crystal orientation and shock in the Yamato nakhlites.

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Introduction:

Deformation within olivine crystals is an important factor in determining the shock level within meteorites [1,2]. Experimental studies on individual grains have tightly constrained the mechanisms of olivine crystal deformation within terrestrial settings but little work has been done to investigate olivine crystal deformation from other planetary bodies where sample preparation is often made independent of any textural fabric [3-5]. Here we assess the relationship between crystal orientation and the expression of shock deformation within olivine crystals within the three Martian Yamato nakhlite stones (Y-000593, Y-000749, and Y-000802).

Methods:

We analysed five thin different thin sections representing all three known stones of the Yamato nakhlites (Y-000593,127-A; Y-000593,106-A; Y-000749, 64-A; Y-000749,72-A; Y-000802,36-A) using large area mapping (LAM) electron backscatter diffraction (EBSD) at the ISAAC imaging facility, University of Glasgow. Samples were run at a 5 µm (Y-000593,127-A; Y-000749,64-A; Y-000802,36-A) and 3 µm (Y-000593,106-A; Y-000749,72-A) stepsize using a Zeiss Sigma variable pressure field emission gun scanning electron microscope (SEM; VP-FEGSEM) with a NordlysMax3 EBSD detector. Patterns were indexed using Aztec analysis software v3.3 from Oxford Instruments. Fabrics within each section were identified using MTEX toolbox for MATLAB with a kernel halfwidth of 10 [6,7]

Results and Interpretations: Three of the five studied Yamato nakhlite sections were shown to have some form of textural fabric present. The percentage of olivine within each section ranges 2.04 – 12.3 % using EBSD analysis. Many of the olivine crystals within the sections are present in either clusters or bands. Individual thin section analysis shows that the overall olivine slip system varies between each analysed section. This differs from the consistent slip-systems observed in the dominant mineral augite. The observed deformation and orientation of each olivine grain within each sample contribution to the overall observed olivine slip-system will be discussed at the meeting.

Acknowledgements: We thank the Japanese Antarctic Meteorite Centre for the loan of the samples used in this study; M.R. Lee (Y-000593,127-A; Y-000749,64-A; Y-000802,36-A) and J. Day (Y-000593,106-A; Y-000749,72-A).


Figures 1: Inverse pole figure (IFP) [A], grain relative orientation deformation (GROD 0-5°) [B], and equal area lower hemisphere projection [C] for an olivine grain within sample Y-00079, 64-A.
HOW DOES VENUS LOSE ITS HEAT? GLOBAL IMPLICATIONS OF SMALL-SCALE RESURFACING

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Introduction: Despite their similar size and composition, the different geological histories recorded at the surface of Venus and Earth are evidence of their different heat loss regimes. The majority of heat loss on the Earth is due to plate tectonics and gives rise to mantle cooling. The lack of plate tectonics on Venus suggests that more heat is generated in the mantle than can be lost at the surface, resulting in a net warming of the mantle. The apparently reduced surface heat flow on Venus is probably about 8-25 mW m⁻² [e.g. 5], and is most likely lost through a variety of methods, such as hotspots, large volcanoes, and rifting. Here we aim to determine new insights in the contribution of smaller-scale resurfacing mechanisms on Venus by analyzing a geological map made at the full resolution of the Magellan SAR data.

Methods: This study concentrates on the volcanism observed in a single 'F-Map' (12 x 12') region when mapped at the full resolution (~75 m/px) of Magellan SAR image data. Previous mapping efforts have only been conducted on a regional (1,500,000) scale. The Aglaonice region is situated ~1200 km to the northwest of Alpha Regio, and was selected as there are no large topographic rises, rifts, or large volcanoes, nor major tectonic alteration; instead this region appears to be typical of corona and plains materials on Venus.

Results: The volcanism can be categorized according to source region:

Corona-Related Volcanism. Corona-related flows have a total surface area of approximately 0.43 x 10⁶ km², equivalent to about 27% of the total surface area of the F-Map. Most of the coronae have temporally distinct flow units, which are identified by their appearance in the SAR image. No definite source vents are visible at any of the flows, although in many cases units can be traced to a general area of small-scale volcanism or concentric fracturing.

Ridge-Related Volcanism. One of the more surprising outcomes is the identification of nine individual occurrences of lava flows mapped regionally as plains material, which appear to emanate from extensional fractures at broad, topographically-raised ridges. These flows vary in size from only about 10 km in width to over 150 km in length, and account for approximately 6% of the total surface area of the F-Map, similar to several of the largest plains material units.

Small-Scale Volcanism. Small-scale volcanism, in the form of vents, volcanoes and fissures, is ubiquitous in the F-Map, contributing about 10% of the total surface area. As small volcanoes and vents likely exist below the resolution of Magellan SAR data, the small volcano density analysis represents a minimum value. A total of 2919 small volcanoes or vents <10 km in diameter were identified in the F-Map, of which 1250 were considered to be definite and 1669 to be potential. For the total of 2919 small volcanoes, the mean diameter is 1.6 km, with a standard deviation (SD) of 1.1 km. The mean diameters of the definite and possible populations are 1.9 (SD = 1.2) and 1.3 (SD = 0.9) km respectively.

Implications: Mapping at the full resolution of Magellan SAR image data shows some important differences from a regional scale approach. Flow units attributable to coronae using a local scale mapping method increase by 28% compared with a regional scale mapping method. By estimating the thickness of these flow units, it appears that coronae are probably underlain by magma bodies of a similar size to those at large volcanoes on Venus, although they are most likely not emptied during eruption. The large range of relative ages of ridge flows suggests that eruptions were initiated and controlled by local stress regimes and melt production rates. In the absence of volcanic centers, these flows are probably fed by a system of dikes, which are common in areas of extension and rifting. Scaling up the 2919 volcanoes observed in the F-Map to a surface area equivalent to the surface of Venus results in 973,000 small volcanoes or vents over the entire planet, a value similar to the exponential distribution estimate of 931,000. Given that this simple analysis is for a ‘typical’ area of Venus, with no high-density shield fields, then we expect that small volcanoes probably make a significant, although by no means solitary, contribution to the resurfacing on Venus.

The future use of higher resolution SAR image data (e.g. EnVision) will be able to identify independent sources of resurfacing and heat loss on Venus.

Assessing the survivability of biomarkers within terrestrial material impacting the lunar surface

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Introduction: The Moon’s rich impact history is exemplified by the Late Heavy Bombardment (LHB), an epoch circa 3.9 Ga ago when the terrestrial planets experienced frequent, large-scale impact bombardment [1-4]. During this time, Earth would have experienced numerous giant hypervelocity impacts [5], potentially ejecting terrestrial material into Moon-crossing orbits [6]. This has led to the proposal that such ejecta could be preserved on the lunar surface as terrestrial meteorites [7-9]. These could provide a geological record predating the period for which the earliest evidence of life exists on Earth in the form of biomarkers. Here, we have used the iSALE-2D shock-physics code [10-12] to determine the pressure and temperature regimes of simulated terrestrial meteorites impacting the lunar surface, in order to gauge the survivability of biomarkers in the projectiles.

Methods: We simulated non-porous and porous sandstone projectiles (dia. = 0.5 m), vertically impacting a basalt target at 2.5 and 5 km/s, the most likely and upper limit of the vertical velocity component found via analytical methods by [7] for terrestrial meteorites impacting the Moon, respectively. Oblate and prolate projectiles were also investigated but without porosity. Initial porosity [12] of the target basalt layer was varied between 0-70%, based on various locations across the lunar surface [13,14] and the porosity of the impactor was varied between 0-40%, to investigate a variety of sedimentary materials. The strength of the materials was modelled using the method described in [11], important for resolving both shock and shear heating. Simulations used lunar gravity (1.62 m/s²) and a surface temperature of 273 K. Each model used 100 cells per projectile radius (cppr), improving resolution on [9]. Tracer particles recorded pressure and temperature in the projectile material during the simulation. Pressure and temperature regimes were then compared to known thermal degradation parameters for particular amino acids and microfossils [15,16].

Results: Fig. 1 shows the most favourable conditions for survival of biomarkers, in the simulations we modelled. Using the method described by [17], amounts of amino acids arginine, valine, and glutamine would only be reduced by 8%, 16%, and 23%, respectively. At the rear of the projectile, lycophyte megaspores would survive with little alteration, according to the survival pressures/temperatures (<1 GPa/630K) of metamorphosed examples [16]. Fig. 2 shows the least favourable conditions for biomarker survival. In this case, both pressures and temperatures are too high for any substantial proportion of amino acids or lycophytes to survive. Results between these extremes show a range of biomarker survival.

![Fig. 1: Plot of peak pressures (left) and temperatures (right) in a solid sandstone projectile after impacting a 70% porous basalt target at 2.5 km/s.](image)

![Fig. 2: Plot of peak pressures (left) and temperatures (right) in a 40% porous sandstone projectile after impacting a solid basalt target at 5 km/s.](image)

Conclusions: With the aid of numerical modeling, we show that biomarkers within terrestrial meteorites can probably survive in significant quantities after impact with the Moon. Increasing projectile porosity is detrimental to the survival of biomarkers, whereas increasing porosity in the target increases the chances of surviving projectile material.

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THE DISTRIBUTION OF PEAK-RING BASINS ON MERCURY AND THEIR CORRELATIONS WITH THE HIGH-Mg/Si TERRANE

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Introduction: As part of the target prioritisation necessary for the Mercury Imaging X-ray Spectrometer (MIXS), we have identified a need for a catalogue of all craters that still retain a central peak (or peak-ring) structure. During the preparation of the catalogue, a correlation was noted between peak-ring basins and a region with high Mg/Si values determined by MESSENGER XRS [1]. We report on the statistical analysis carried out to confirm the correlation and explore impact as a mechanism for the elevated Mg/Si values.

Complex Craters. Complex craters and basins, which still have the peak structures visible (hereafter referred to as ‘peaked craters’), are understood to uplift material from deep crustal and upper mantle levels (e.g. [2]). Recent work on Lunar peaked craters confirm that the central peaks act as ‘drill cores’ into the lower strata [3]. Analysis of the peaks reveals compositions different from the surrounding terrain.

The High-Mg/Si Terrane. The High-Mg/Si Terrane (HMT) on Mercury exhibits the highest Mg/Si ratios as well as low Al/Si ratios. It covers an area from approximately 120° W to 45° W and 10° S to 50° N, with an area >5,000,000 km² [1].

Methods: The HMT was initially defined by Weider et al. [1], however a precise definition was required for robust statistical analysis. It was determined that the best approach was to use a one-tail hypothesis test to define confidence contours, so the mean and error values from Nittler et al. [4] were used. This gives the hypotheses, \( H_{C,0}: \frac{Mg}{Si} = 0.436 \), \( H_{C,1}: \frac{Mg}{Si} > 0.436 \). Using the error, \( \sigma = 0.106 \), we can determine the confidence contours for the HMT.

10,000 random points were selected from across the surface of Mercury and used to generate statistics for the whole surface. These points acted as the centres for circular buffers, with an area equal to that enclosed by the specific confidence contour. Another one-tailed hypothesis test was then carried out. Let \( \mu \) be the mean number of basins within the buffer radius and \( C \) be the actual number of basins within the specific confidence contour, then we have the general hypotheses, \( H_{B,0}: C = \mu \), \( H_{B,1}: C > \mu \), which can be tested for different confidence contours and crater sub-sets.

Three catalogues have been used for the analysis in this work: A catalogue of all Mercurian craters that retain a central peak structure, created by the authors for the express purpose of target prioritization for MIXS. Key features were visually categorised as MIXS-T can likely resolve these features; Baker et al. [6], which catalogues all of the craters on Mercury with diameter ≥20 km.

Excavation depth and stratigraphic uplift was calculated for key basins using methods outlined in [7] and [8], respectively.

Results: The greatest overall confidence level (97.68 %) is for the intersection of the Baker and Peaked Crater sets, within the 2σ-contour. Figure 1 shows a confidence map for this data set. The Fassett sets exhibited confidence distributions which do not coincide with the Baker ∩ Peaked Crater distributions, or the HMT. The 7 basins intersecting the contour were unlikely to have excavated mantle material, although all but 1 uplifted mantle material to within ~10 km of the basin floor.

Conclusion: There is a strong statistical correspondence between peak-ring basins and the HMT. It is considered highly likely that the basin impacts have revealed primitive igneous material that is high in Mg, which is present at depths not normally revealed by other basin-sized impacts. Future observations by MIXS will allow the imaging of basin features to identify primitive, high Mg compositional signatures, which will help us to understand the evolution of Mercury’s crust and mantle.

References:

Figure 1. Confidence map for the data set Baker ∩ Peaked Crater basins with a 2σ-buffer size. The 10000 random points indicate the centre of buffers, coloured to indicate the confidence level for rejecting \( H_{B,0} \) within each buffer. The colour boundaries have been chosen to represent confidence levels of ≤ 1σ (purple), 1σ-2σ (blue), 2σ-3σ (green), 3σ-4σ (yellow) and 4σ-5σ (red). The mean±2σ contour, derived from [4], is shown to indicate the HMT and buffer size used. The map uses a Mollweide projection, centred on 0° East.
Modelling Water-Rock Interactions in the Sub-surface Environment of Enceladus.

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Introduction:
Understanding the geochemical cycles occurring at the water-rock interface on Enceladus is crucial for establishing the potential habitability of the sub-surface environment. Using data collected by the Cassini spacecraft (2005-2017) [1, 2] and estimates of the starting composition of the sub-surface ocean on Enceladus, we have modelled how the ocean interacts with a silicate simulant representing the rocky interior. The results from these models define a hypothesized modern ocean chemistry and provide an insight into the geochemical reactions occurring at the water-rock interface. The results from this work support observations made by Cassini, suggesting our chosen starting conditions could provide an insight into the history of Enceladus.

Methodology:
We have used thermochemical modelling (CHIM-XPT) to determine the chemical composition of the sub-surface ocean.

We have defined the chemistry for the silicate interior based upon the chemical composition of a CI carbonaceous chondrite [3]. To test different hypotheses as to the origin of the sub-surface ocean and icy exterior, we have run two models using different starting chemistries for the sub-surface ocean fluid:

Model 1 – Dilute NaCl Solution. This model is based upon the theory that the sub-surface ocean originated as almost pure water [4]. NaCl has been detected in the plumes of Enceladus and E-ring of Saturn and in the model balances the charges of the reactions.

Model 2 – Cometary Ice Fluid. This model assumes that the water originated from a cometary source [4] and uses a cometary fluid composition, based upon data collected from 67P [5]. The dominant species within the starting fluid are therefore H₂O, NaCl, NH₄⁺, HCO₃⁻, HS⁻ and SO₄²⁻.

Physical Conditions. Both models were run at 50, 90 and 120 °C, [6] determined that a temperature of 90 °C or more is required to form the SiO₂ particles that have been measured in the plumes of Enceladus. Pressures were 50 and 80 bar; [6] hypothesized 80 bar pressure at the water-rock interface because of the combined depth of the water ice and ocean fluid, and the gravitational data measurements.

Gravitational measurements imply that the silicate interior of Enceladus is likely to be porous [7], however the extent of this porosity if unknown. We explored this uncertainty by running both models at a high temperature (350 °C) and high pressure (150 bar) to recreate geochemical reactions occurring within the silicate body.

Further assumptions were made based on Cassini data: 1) hydrogen gas (detected in the plumes) is generated in the sub-surface, indicating ongoing hydrothermal activity [8]; 2) high temperature reactions take place in the sub-surface that enable the formation of colloids, detected as solid SiO₂ particles in the plumes [6]; 3) the pH is between 8.5–10.5 based on compositional data [9]; 4) the sub-surface ocean is dominated by salts (NaCl, KCl) [10].

Results:
Sub-surface Ocean. The model outputs mostly generate a range of pHs between 9–10.5 at the water-rock interface. For the higher temperature and pressure runs, the pH is lower and falls between 7–8. The dominant species in the fluid are NaCl, KCl and NaHCO₃, which aligns with the Cassini observations. Both models produce aqueous SiO₂, which supports the detection of the solid particles within the plumes.

Gases and Minerals. All the gases at the rock-water interface are dissolved into the aqueous solution. These include H₂O, CO₂, CH₄, NH₃ and H₂S, all of which have been detected in the plumes.

Serpentine is the dominant mineral precipitated, accounting for approximately 50 wt.%. This supports the suggestion that serpentinisation reactions are ongoing on Enceladus and are potentially responsible for some of the high heat flux detected on the south polar region.

Conclusion:
Initial analysis of the results from these models, the mineral composition, sub-surface ocean fluid and the gas phase show good agreement with the Cassini data, suggesting the silicate simulant designed may be a good representation for the silicate interior of Enceladus.

GEOCHEMICAL AND TEXTURAL ANALYSIS OF METAL PARTICLES ENTRAINED IN IMPACT MELT IN CBA CHONDRITE GUJBA

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Introduction: Impacts are central to the formation and evolution of planetary and asteroidal bodies, via accretion, surface modification and, in some cases, eventual breakup. A range of physical (e.g. impact angle, target and impactor size, density, and state of the target body’s atmosphere and hydroosphere) and chemical (e.g. target and impactor mineralogy and volatile abundance) parameters can influence the effects of a given impact [1].

We aim to understand the effects of chemical parameters with a focus on the behaviour of metal within impact melts. Some metal forms as a result of impact processes, and some metal is inherited from precursor (target and impactor) lithologies. For impact melt environments, processes such as reaction pathways and physical emplacement, and effects of conditions such as pressure, temperature, oxygen fugacity, and gravity are not completely understood. We are investigating the geochemistry and textures of metal particles in contrasting impact melt environments, on the Moon and in chondrites. We plan to use observed compositions of impactor-derived metal to constrain the type of impactor that caused the collision [2]. This would help to understand whether Solar System impactors have varied over time [3]. However, it requires an understanding of the effects of incorporation of impactor metal into impact melts.

The CBA chondrites are a group of meteorites that may have formed from an impact melt-vapour plume resulting from collision of two asteroids [4,5]. They are characterised by millimetre-to-centimetre scale, metallic particles (60-80 vol. %) and olivine chondrules (20 vol. %) within a silicate-dominated impact melt matrix (<5 vol. %) [6-8]. Metal particles range in morphology from rounded to angular, and many contain arcuate sulphide inclusions which define metal subgrain boundaries [6-8].

Analytical Method: Gujba sample 1 is a 1.5 x 2.0 cm polished thick section with metal particles up to 4 mm in size. Sample 2 is a 3.0 x 1.5 cm polished block with metal particles up to 6 mm in size. We collected quantitative compositional data on Sample 1 using a Cameca SX 100 Electron Microprobe, and back-scattered electron imaging and major element X-ray mapping using a FEI QUANTA 650 FEG-ESEM. We performed electron backscattered diffraction (EBSD) analysis on Sample 2 using a TESCAN MIRA3 SEM equipped with an OI Symmetry EBSD detector, to investigate the microstructure of the metallic particles.

Results: We classified metal particles by morphology and relationship with impact melt (Fig. 1):
A. Rounded particles with predominantly smooth edges.
B. Predominantly rounded particles with some ragged edges.
C. Sub-angular particles that are not distinguishably rounded, with predominantly ragged edges.
D. Sub-angular metal entrained in impact melt.
E. Fine grained (<10 μm) metal entrained in impact melt.

We performed analyses on each of these categories to investigate variations in composition and microtexture. EPMA data for Ni, Co, P and Cr concentrations seem to discriminate between the morphological categories. Preliminary analysis of the EBSD data shows that particles of all categories are recrystallised, with myriad subgrain boundaries and complex variation in crystallographic orientation and size range of subgrains. Further analyses will explore these observations to attempt to link them together, although recrystallization may reflect a later thermal overprint.

Interpretation: Metal in Gujba has clearly interacted with the impact melt. Physical deformation is apparently accompanied by chemical variations within metal particles. We will look for similar variations in metal particles in sample suites from other bodies such as the Moon.

PHOTOGRAMMETRY FOR CREATING HIGH FIDELITY 3-D MODELS OF GEOLOGICAL AND METEORITE SAMPLES

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Introduction: Photogrammetry uses two-dimensional images to determine accurate information about the surface of an object [1]. Using a suite of images with overlapping features, it is possible to generate a three-dimensional model of the object [1]. We aim to use photogrammetric methods to create high-fidelity three-dimensional models of meteorite samples collected by the UK-led Lost Meteorites of Antarctica project [2,3]. We will be using the technique as part of our characterization and classification of the recovered meteorites, providing a detailed record of the samples for curation and for determining sample volumes and densities. Sample volumes will be useful for preliminary classification with a combined electrical conductivity, magnetic susceptibility probe [4]. We aim to understand how these properties vary with sample volume and mass. Sample densities are useful for a variety of reasons, for example to better understand gravimetric data from orbiters [5,6], and to understand material properties of planetary bodies [7]. Sample density is difficult to calculate via non-destructive techniques, so being able to calculate sample volume without even touching the sample is highly beneficial.

Most geological studies involve splitting rock samples and performing a range of destructive or semi-destructive analyses. Once completed, it is no longer possible to view the sample as a whole. Through the production of detailed, true-colour, three-dimensional sample models, we preserve an accurate record of the pristine sample. This is especially important when the sample is small or rare - such as meteorites and extraterrestrial samples returned by missions. Such models, which can be viewed at multiple scales, may be used to help inform decision-making about sample cutting for preliminary analysis or for understanding the spatial relationship between later scientific discoveries. This technique only subjects the sample to visible light, meaning that there is no modification of the surface, a goal which has also been achieved using three-dimensional laser scanning [5].

Three-dimensional models of rare samples are a powerful tool for teaching and outreach [8,9]. Integration with other digital records, such as thin section photos or computed tomography datasets would be a useful way for students or the public to engage with the samples and sample science in a way which is limited if valuable samples cannot be on display.

Method: The sample is placed on a turntable in a controlled light environment to minimize shadows and reflections on the sample surface. Photographs are captured using a high resolution (>25 MP) DSLR camera at 5° rotational intervals. Photographs are captured in RAW format, comprising an unmodified two-dimensional record of the entire sample, and then processed to ensure accurate colour and remove unsuitable images. The images are processed using Agisoft Metashape, a professional software for photogrammetry applications [10], which matches pixels in different images to simulate the camera’s position relative to the sample. These pixels are used to produce a sparse three-dimensional point cloud, then a dense three-dimensional point cloud that is verified for accuracy, before being used to produce an ultra-high-quality mesh. The mesh is a three-dimensional object which comprises the record of the sample shape. The texture of the sample is layered over the mesh to produce the final model [10].

Figure 1: Screenshot of 3-D model of a sample of H5 ordinary chondrite Gao Guenie within the Metashape workspace.

Results: We have examined a range of samples of differing size (terrestrial rocks, impact crater shatter cones, meteorites) and produced high quality models that capture sample exteriors in their entirety (Fig. 1). Agisoft Metashape has volume measurement capabilities and allows for model size calibration to known size measurements on the sample surface. Further research into sample surface area and volume measurements is ongoing to understand the uncertainty in measurements derived by this technique.

Fast and slow water ion populations in the Enceladus plume

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Introduction:

Enceladus is the sixth largest moon of Saturn and was studied by the Cassini-Huygens mission to the Saturnian system. The investigation consisted of 22 targeted flybys of the moon that covered a variety of flyby velocities and geometries.

The most startling find of the flybys was the discovery of an outgassing plume emanating from around the moon’s south pole (Dougherty et al., 2006). The plume's composition is dominated by water, confirmed by measurements of neutral and ion densities in the plume of Enceladus (Tokar et al., 2009, Waite et al., 2009, Coates et al., 2010), in addition to remote UV measurements (Hansen et al., 2011). The plume was also found to originate from diffuse sources and collimated geyser-like jets, fueled from a subsurface ocean.

The plume gas emission has been shown to contain two distinct water components, a thermal population and a supersonic population (Teolis et al., 2017).

The thermal component arises from sublimation or through molecules interacting with fissure walls. The bulk velocities of these neutral water molecules in the plume have been estimated to be between 500-750 m/s. The supersonic water population has been associated with driven fast gas emission from fissures. Some studies have found velocities from 1200 m/s up to 2600 m/s (Hansen et al., 2011). Other studies have suggested Mach numbers up to 10, corresponding to jet velocities of 6 km/s (Teolis et al., 2017).

Methodology:

Ion velocities have been measured during the Enceladus E3 and E5 flybys using the Cassini Plasma Spectrometer (CAPS) instrument on the Cassini spacecraft. Data from three sensors in the CAPS instrument have been examined from two flybys that occurred during 2006. Positive ion measurements from the CAPS Ion Beam Spectrometer and Ion Mass Spectrometer have been used to measure positive ion velocities. The CAPS Electron Spectrometer has been used to complement the positive ion findings with measurements of negative ion velocities.

Results:

Two positive ion velocities are found, with the fast ions (2.3-5.8 km/s) originating from the high-speed neutral gas emission and slow ions (0.2-2.2 km/s) associated with the low-speed thermal gas emission from Enceladus (Teolis et al., 2017). Negative ions were found to be near stationary or northerly travelling, implying a deceleration mechanism within the plume. A tentative detection of fast negative ions was also recorded for one of the flybys. These findings will aid in future modelling of plume dynamics.

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FE-REDOX CHANGES IN ITOKAWA SPACE WEATHERED ZONES

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Introduction: The Hayabusa spacecraft returned material collected from the surface of S-type Asteroid 25143 Itokawa. The spectral darkening and reddening of the asteroid surface is due to space weathering (the bombardment by electrons and protons in the solar wind), partly accounted for by the presence nanophase iron (npFe³⁺) particles [1]. In this study we investigate Fe-redox changes in the dominant Fsiliicate phase of the space weathered zones of Itokawa grains from the first Hayabusa touchdown site.

Samples and Methods: FIB lift-out sections were obtained for TEM and X-ray synchrotron nano-probe analyses. Three of the sections have been analysed for Fe-K X-ray Absorption Spectroscopy (XAS) using the I14 X-ray Nanoprobe Beamline at the Diamond Light Source synchrotron. This is achieved by a series of XRF maps measured at varying energy increments, between 7000 and 7300 eV (focusing primarily on the XANES energy region) and processed using Mantis 2.3.02 to isolate regions of interest. Fe-K XAS spectra are produced from these regions and normalised in Athena 0.9.26.

HAADF-STEM and Bright Field (BF) imaging of the SW zones is obtained using the JEM ARM200CF instrument at ePSIC, Diamond Light Source.

Results: The partially amorphised space weathered (SW) zones were successfully identified in HAADF-STEM imaging. Vesicular blistering is observed in some regions of the SW zones (Figure 1a), measuring up to ~60 × 20 nm, with the long-axis parallel to the external surfaces. It is thought that these blisters occur due to the segregation of low-mass H²⁺ and H⁻ ions from the solar wind implanted in the SW zones, also observed in previously studied Itokawa [2] and lunar samples [3]. An Fe metal chemical composition could not be confirmed, but npFe⁰ particles were observed within the SW zone (Figure 1b), identified as small white particles no larger than ~2-3 nm in diameter, similar to previous studies of Itokawa samples [2].

The XANES maps were successful in isolating spectra for the SW zone and the grain substrate core mineralogy. The 1s→3d pre-edge centroid positions (the intensity-weighted average across baseline subtracted peaks) varied from the ferrous (Fe²⁺) position at ~7112.9 eV up to ~7113.3 eV. Based on a ferric-ferrous ratio (Fe³⁺/ΣFe), defined by standard reference minerals, the centroid results suggest variable increases in ferric content in the SW zones, between 0.00 and 0.14 (±0.03), compared to the grain cores. Positive shifts in the absorption edge positions for SW zones also support these results.

Discussion: The npFe⁰ particles in lunar regolith have been shown to contain oxidized Fe [4]. However, our Fe-K XANES results show the oxidation also occurring in the Fe-silicate dominant phase of the SW zones. The ferric amorphous component of the surface grain space weathered rims may be responsible for some of the reddening and darkening observed in space weathered surfaces of S-type asteroids [1]. To test this new hypothesis, space weathered lunar regolith grains are being studied using the same techniques. Further investigations will also include samples from Asteroid 162173 Ryugu, to be returned by the Hayabusa 2 spacecraft in late-2020.

THE MARSQUAKE SERVICE FOR INSIGHT: RESULTS FROM THE FIRST YEAR OF OPERATIONS ON MARS

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Introduction: InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) landed successfully on Mars on November 26th 2018 and SEIS, the seismometer package was fully deployed by February 2019. So far, SEIS is exceeding performance expectations in terms of noise and many seismic events have been detected. Prior to landing the MarsQuake Service (MQS) was set-up to create and curate a seismicity catalogue for Mars.

MQS structure and procedures: MQS consists of a team of seismologists working to analyse the data as soon as it arrives from Mars. In preparation for operations, the MQS team developed single station location and characterisation algorithms, created a software framework that manages the data flow that includes these approaches, and tested the methods and operational procedures via a suite of blind tests. The MQS approach for determining distances includes use of an a priori set of plausible martian models that can be refined once constraints from observed signals are included. The frontline analysis team has been operational since the first seismic data arrived from on the deck on Mars.

Seismic activity observed so far: MQS has seen over 200 events so far although of these only a few have clear and coherent arrivals of P and S waves. The events observed show a variety of characteristics, including those that only show low-frequency energy in the 1 – 10 second band, others that show high-frequency content up to several Hz, and a collection that excite an ambient vibration at 2.4 Hz.

Seismic Noise on Mars: The seismic noise on Mars is dominated by atmospheric excitation such that most detections are observed in the early evening after sun-down. Thanks to the APSS (auxiliary payload sensor suite) wind and pressure sensors we are able to distinguish noise from tectonic seismic signals.

Conclusions: Since its deployment on the surface of Mars, SEIS has recorded hundreds of potential seismic events. In this talk we will share the work of MQS and give an update on the catalogue of events seen so far.

Acknowledgements: The SEIS team acknowledges the supports of NASA, CNES, UKSA, SSO and DLR for the experiment funding and of the SEIS operation team for delivering SEIS data: https://www.seis-insight.eu/en/public-2/seis-instrument/seis-working-groups-team
EXPLORING CLOUDS AND COMPOSITION OF ICE GIANTS WITH GROUND- AND SPACE-BASED TELESCOPES USING VISIBLE/NEAR-IR

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Introduction: Uranus and Neptune, known as the ‘Ice Giants’, are amongst the most mysterious planets in our Solar System. Their extremely cold temperatures at the cloud tops means that their main bulk constituents, thought to be rock and normally ‘icy’ materials such as H2O and NH3 are condensed well below their main visible cloud decks. In this presentation we will describe new observations of these planets that: A) show that gaseous H2S is present above the main cloud decks of these planets at ~ 3 bar, indicating that these clouds contain H2S ice; B) show that the abundance of CH4 at the cloud tops changes greatly with latitude; and C) show that the polar ‘cap’ of Uranus can at least be partly explained by the lowering of methane abundance at polar latitudes.

Detection of H2S: Observations of the near-infrared spectra (1.45 – 1.80 μm) of Uranus and Neptune made with the NIFS integral-field spectrometer at the Gemini/North telescope in 2009 and 2010 have been used to directly detect, for the first time, the presence of hydrogen sulphide (H2S) in the atmospheres of both Uranus and Neptune [1, 2]. The observed cloud-top presence of H2S constrains the deep bulk sulphur/nitrogen abundance to exceed unity for both planets and adds to the weight of evidence that H2S ice likely forms a significant component of the main observable cloud deck.

Detection of latitude variations of CH4: Observations of Neptune made in 2018 using the newly available Narrow Field Mode (NFM) of the MUSE integral-field spectrometer at the Very Large Telescope in Chile have been used to probe the latitudinal variation in cloud-top methane abundance [3]. The spectral range of these observations (480 – 930 nm) includes a collision-induced absorption band of hydrogen that can be used to distinguish between cloud-top height variations and variations in the methane (CH4) abundance. We find that the cloud top mole fraction of methane decreases from ~ 5% at equatorial and mid-latitudes to values closer to 3% at polar latitudes, in rough agreement with an earlier analysis of HST/STIS Neptune observations [4]. A similar latitudinal variation of cloud-top methane abundance for Uranus was found by HST/STIS in earlier observations [5], which suggests similar depletion mechanisms act in both planets’ atmospheres.

Figure 1. Left Panel - mean brightness of Neptune at 800 – 860 nm recorded by VLT/MUSE in 2018, showing discrete methane clouds overlayersing uniform H2S cloud base. Right Panel - PCA analysis of MUSE data showing distribution of component that captures methane abundance, showing lower methane abundance in south polar region.

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Nature of Uranus’s Polar ‘cap’: Observations of Uranus made in 2014 using the SINFONI integral-field spectrometer at the Very Large Telescope, covering the spectral range 1.44 – 1.86 μm have been used to probe the latitudinal variation of haze in Uranus’ atmosphere [8]. These observations suggest that the brighter appearance of Uranus’s northern polar region is due in part to the lower abundance of CH4 at these latitudes rather than to the development of a haze layer. A reanalysis of HST/WFC3 observations, made from 2014 to 2018 is currently underway to determine the relative contribution of these two effects at visible wavelengths.

Bibliography:

IN-SITU MANUFACTURING OF SOFTWARE DEFINED SPACECRAFT

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Introduction:
With approximately one earth escape space science and/or exploration mission launched each year globally, there is scope for dramatically increasing the rate of mission deployment through innovative mission design and deployment approaches. We present how the Spacecraft-on-Demand system has progressed from concept towards practical implementation, and laboratory and in-orbit validation of an approach that could dramatically increase the pace of space science and exploration. This is achieved by moving from infrequent large monolithic expensive spacecraft designed and manufactured on earth, to frequent small fractionated low-cost spacecraft missions manufactured in space by the thousand.

Mission design capture and decomposition:
A goal of Spacecraft-on-Demand is to allow scientific users to create new missions without having to know the specifics of the engineering challenges. A structured format has been created for capturing the traditional scientific traceability matrices used to define missions suitable for processing by the initial implementation of the Spacecraft-on-Demand tool chain.

This tool chain assembles, produces and/or schedules the individual elements required to implement a fractionated mission design using knowledge of existing assets on earth and in space such as communications resources, spacecraft manufacturing facilities, the resources and materials available at each site, and launch opportunities, to generate a range of minimum viable spacecraft designs, trajectories and communications plans to collect the science data requested.

Optimizations for time, cost, material availability, reliability and other parameters provided by the user are computed, and the resulting files are passed to robots that have been developed to manufacture (spacecraft printers) and operate (ground stations) individual printed spacecraft. If the science requirements make it too resource expensive/impossible to find a solution, then warnings or errors are raised so constraints can be relaxed if feasible.

Spacecraft synthesis:
To validate all elements of the system from end to end, a spacecraft printer to print test spacecraft is currently being built for demonstration in orbit.

Originally conceived as a 3U CubeSat, the in-orbit spacecraft printer demonstrator has been refactored as a 1U design (10x10x10cm) due to budget and launch opportunity constraints. Although limiting in terms of the mass (<500 g) and volume (<0.25.l) of printable materials that can be carried, such a system will still permit demonstrating the manufacturing of ten or more spacecraft with instruments, avionics, communications, power, propulsion and compute, comparable in complexity with the more than one hundred <5g spacecraft of the KickSat missions [1].

Spacecraft planned to be printed include a Space Weather Buoy/Solar Sail Test Bed [2] and a Mars Meteorological Microlander proof of concept [3] which have also been manually breadboarded to confirm they are viable. All materials that will be used to print them such as photovoltaic material, polymer dispersed liquid crystal substrate, shape memory alloy and silver loaded epoxy are readily available and inexpensive.

Towards flight:
High-fidelity virtual simulations of the spacecraft printer and printed spacecraft have been developed to support mission decomposition, spacecraft synthesis, mission planning and operations. Performance of spacecraft printer and printed spacecraft are being validated before flight in a physical laboratory-based space simulator capable of being flown on parabolic flights.

Two opportunities for <90-day low earth orbit spacecraft printer tests have been identified, and satisfying the technical, safety and licensing requirements of both options has been substantially completed. The mission has been designed to print and deploy ten printed spacecraft of increasing complexity in the week before the spacecraft printer is due to deorbit to minimize orbital debris. If the low altitude technology demonstration missions are successfully completed in 2020, it is anticipated that the first spacecraft printers for science missions could be available to fly in 2021.

Bibliography:
MOBILITY OF HALOGEN ELEMENTS IN ORDINARY CHONDRITE BRECCIAS

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Introduction: The behaviour of volatile elements in the early Solar System is of fundamental importance for considering the volatile inventory of the early Earth and other terrestrial planets. Recent models show that there were two isotopically distinct reservoirs in the protoplanetary disk, represented by carbonaceous chondrites (CC) and non-carbonaceous chondrites (NCC), which are proposed to represent materials formed beyond and within the orbit of Jupiter, respectively [1,2]. Volatile elements are typically considered to be concentrated in carbonaceous chondrites, which contain a high abundance (up to 50%) of fine-grained matrix, in which volatiles are mostly hosted. However, if these chondrites represent materials formed beyond Jupiter, they would not be the main source for building the terrestrial planets. In order to understand the behaviour of volatile elements in the inner Solar System, we need to understand their abundances and distribution in ordinary and enstatite chondrites.

The asteroid parent bodies of ordinary chondrites (OCs) are not usually considered to be the sites of volatile activity. However, there is undeniable evidence for the presence of metasomatic fluids during metamorphic heating, which clearly involves movement and redistribution of volatile species [e.g. 3-5]. Our recent studies of feldspar and phosphate minerals in OCs have shown that chemical transport occurs throughout the range of metamorphism, from petrologic type 3 to 6 [6-8]. It is important to recognize these effects, for correct interpretation of ages determined for early solar system events using chronometers such as Al-Mg, I-Xe and Pb-Pb.

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The ratio of Cl/F in the phosphate mineral apatite records heterogeneity among different OCs that appears to post-date thermal equilibration, and which implies the presence of late-stage, dry and halogen-rich fluids that might have arisen either from impact processing, or degassing of partial melts in the asteroid’s interior [6-9]. In particular, we observed that the Cl/F ratio of apatite in two regolith breccias, Zag (H3-6) [6] and Kendleton (L3-5) [8], is extremely variable. This heterogeneity appears to be associated with regolith processing, which implies that fluid activity could have persisted long after thermal metamorphism ceased. In order to investigate this process further, we have carried out a study of apatite abundance, grain size distribution and compositional characteristics, in a wider set of unbrecciated and brecciated H chondrites. Our goal is to understand processes affecting halogen element behaviour in ordinary chondrite asteroids.

Results: We have studied apatite in 13 H chondrites, including six unbrecciated chondrites of petrologic types 4 to 6, and seven H chondrite breccias. Apatite is a ubiquitous minor mineral in all samples (~0.1 to 0.2 vol %), with typical grain sizes 20 - 300 μm. We describe apatite composition in terms of the atomic ratio Cl/(Cl+F), referred to as Cl#.

Unbrecciated H chondrites include Avanhandava (H4), Richardson (H5), Oro Grande (H5) and Estacado (H6) [7] as well as Benld (H6) and Kadonah (H6) studied here. Mean apatite compositions (by EPMA) differ slightly among these chondrites (mean Cl# from 0.75 to 0.90), but there is a limited range in each, for example in Benld, Cl# = 0.86 ± 0.03.

Brecciated H chondrites defined as black (shock-darkened: [10]) OCs include Olmedilla (H5), Cereseto (H5), Supuhee (H6) and Jamkheir (H6). Apatite compositions are heterogeneous in these chondrites, e.g. Cereseto, Cl# = 0.83 ± 0.14, with a range from 0.54 to 0.99. The highest Cl contents, with Cl# > 0.95, occur in clasts of lower petrologic type.

Gas-rich, H chondrite regolith breccias [10] include Zag (H3-6), Leighton (H5) and Canga de Onis (H5). Apatite is heterogeneous in Leighton and Canga de Onis (Cl# from 0.79 to 1.00, and 0.81 to 0.96 respectively), but not as extreme as in Zag (Cl# from 0.45 to 0.99 [7]). In Leighton and Zag, dark, unequilibrated clasts have the highest Cl contents.

Discussion: Apatite is a sensitive recorder of volatile activity on OC asteroids. We find that H chondrite breccias in general record extended halogen activity. As we observed a similar effect in L3-5 Kendleton [8], it appears that this observation also applies to other OC parent bodies. Since volatile mobility appears to be related to brecciation and regolith processes, it likely persisted well beyond the period of metamorphism on OC chondrite parent bodies. Near-surface mobility of halogen elements is possibly activated by heating resulting from impacts.

COMET INTERCEPTOR: AN ESA MISSION TO AN ANCIENT WORLD

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Introduction:
In June, 2019, a multi-spacecraft project – Comet Interceptor – was selected by the European Space Agency as its next planetary mission, and the first in its new class of Fast (F) projects. The mission’s primary science goal is to characterise, for the first time, a dynamically-new comet or interstellar object. Such an encounter with a comet approaching the Sun for the first time will provide valuable data to complement that from all previous comet missions, which have by necessity studied short-period comets that have evolved during their time orbiting near the Sun from their original condition. Planned measurements of the target include its surface composition, shape, and structure, its dust environment, and the composition of the gas coma. A unique, multi-point ‘snapshot’ measurement of the comet-solar wind interaction region is to be obtained, complementing single spacecraft observations made at other comets.

Mission Overview:
The spacecraft will be delivered to Sun-Earth Lagrange Point L2 with the ESA Ariel mission in 2028, and will by default be placed in a holding location suitable for later injection onto an interplanetary trajectory to intersect the path of its target. A suitable new comet would be searched for using ground-based observatories prior to launch, and after launch if necessary, with a short period comet serving as a backup destination. With the advent of powerful ground-based facilities such as the Large Synoptic Survey Telescope, LSST, the prospects of finding a suitable dynamically new comet nearing the Sun for the first time are very promising. The possibility may exist for the spacecraft to encounter an interstellar object if one is found on a suitable trajectory.

When approaching the target, two sub-spacecraft – one provided by ESA, the other by the Japanese space agency, JAXA, would be released from the primary craft. The main spacecraft, which would act as the primary communication point for the whole constellation, would be targeted to pass outside the hazardous inner coma, making remote and in situ observations on the sunward side of the comet. The two sub-spacecraft will be targeted closer to the nucleus and inner coma region. We shall describe the science drivers, planned observations, and the mission’s instrument complement, to be provided by consortia of institutions in Europe and Japan.

Further Information:
The mission team’s website is www.cometinterceptor.space, and progress on the project may also be followed on Twitter at @cometintercept
COMPOSITIONAL MAPPING OF EUROPA WITH VLT/SPHERE

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Introduction: Europa is the second of the Galilean moons from Jupiter. Its surface is composed of water ice, with significant contamination from sulphuric acid hydrates and potentially salts [2, 6]. Infrared spectra from the Galileo orbiter Near-Infrared Mapping Spectrometer (NIMS) [3] provide the highest spatial resolution IR spectra of Europa but with limited coverage in many locations. In recent years, ground-based adaptive optics observations in the infrared with Keck/OSIRIS [2] and VLT/SINFONI [6] have provided new insights into the distributions of surface materials on Europa.

Data and method: Observations of Europa’s anti-jovian hemisphere were taken during VLT/SPHERE [1] science verification in December 2014. The SPHERE Integral Field Spectrograph produces image cubes with 38 wavelength channels from 0.95 to 1.65 μm (R ∼ 30). It has a high spatial resolution, with a pixel size of 7.46 mas/px, corresponding to ∼25 km/px at Europa. Accounting for diffraction, this allows features ∼150 km across to be resolved. For example, Europa’s largest lineae (at ∼225°W, ∼45°N) are resolved in Figure 1.

Our observations have been reduced using the standard ESOREX pipeline and custom image cleaning and mapping code to produce mapped spectral cubes of Europa’s anti-Jovian hemisphere. Images were photometrically corrected using the Oren-Nayar reflectance model, allowing regions at large phase angles to be mapped accurately, providing significant improvements over the standard Lambertian model [7]. This allows our mapping to reach latitudes ∼70°, higher than previous studies which typically extend to 50° - 60° [2, 4, 6].

We analyse these mapped cubes by fitting to laboratory spectra from reference cryogenic libraries. The fitting routine uses Markov Chain Monte Carlo modelling to produce compositional maps for the observed hemisphere of Europa. These reference spectra include water ice, sulphuric acid, and hydrated salts. We have developed an implementation of the Hapke bidirectional reflectance model [5] which we use to model a broader range of species, including distributions of ice grain sizes. The use of Monte Carlo techniques allows a greater exploration of the endmember parameter space, enabling uncertainties on endmember abundances to be estimated.

Results: Comparison of our SPHERE data to Galileo/NIMS data show strong similarities (see Figure 1) and spectral modelling results are consistent with previously observed compositional features. These include the leading-trailing hemisphere difference in water ice fraction and the structure of non-ice material from the anti-jovian point (180°W, 0°N) to Powys Regio (∼140°W, ∼0°N).

Fig 1: Comparison of SPHERE observation with selected NIMS observations with similar coverage and resolving very similar features. Images show normalised 1.30 / 1.51 μm spectral ratio which is indicative of water ice fraction.

Fig 2: Example fitting result using our Monte Carlo fitting routine on an icy location of Europa.

References:
Introduction The CM carbonaceous chondrites are the most abundant meteorite group to have experienced significant alteration by extraterrestrial water. The CMs have similar mineralogy, textures and chemical compositions and it has long been thought that they are derived from a single parent body [e.g. 1]. Most also have very short (<2 Myr) cosmic-ray exposure (CRE) ages that could reflect the break-up of a water-rich near-Earth asteroid (NEA) [2]. However, there are distinct peaks in the CRE age distribution of CM chondrites at ~0.1, ~0.2, ~0.6 and ~2 Myr [3] and Takenouchi et al. [4] reported that the highly altered CM1 chondrites often have the shortest CRE ages. A correlation between the degree of alteration and CRE age hints at either multiple collisional events on a single complex asteroid or CM chondrites derived from more than one parent body.

Takenouchi et al. [4] inferred the degree of alteration in CMs from petrographic observations but this is challenging, hampered by fine-grain sizes (<1 μm) and sample heterogeneity. We are therefore using X-ray diffraction (XRD) and thermogravimetric analysis (TGA) to rapidly quantify the bulk mineralogy and H₂O content of CM chondrites. On the CM parent body(ies) fluids transformed anhydrous silicates into phyllosilicates, meaning the phyllosilicate fraction (PSF) (total phyllosilicate abundance / (total anhydrous silicate + total phyllosilicate abundance)) measured using XRD can be used to infer the degree of alteration [e.g. 5]. Similarly, TGA mass loss between 400 – 770°C is attributed to the dehydroxylation and dehydroxylation of the phyllosilicates and can be used to estimate H₂O abundances [e.g. 6]. As the PSF and H₂O abundances can be determined for a large number of CM chondrites our aim here is to use them to constrain the relationship between hydration and CRE age.

Is there a correlation? We find that there is a relationship between the degree of aqueous alteration and the CRE age of a CM chondrite, although at this stage the statistics are still limited. Fig. 1 shows that highly altered CM1s (PSF >0.8, H₂O >10 wt%) have the shortest (~0.2 Myr) CRE ages, whereas the CM2s (PSF ~0.7–0.75, H₂O ~9 wt%) have CRE ages of ~0.6–2 Myr. The two CMs with CRE ages of ~0.1 Myr are yet to be analysed by XRD/TGA but one of them, ALH77306, is described in the Meteoritical Bulletin as lacking chondrules, a typical feature of the CM1s. There are also a significant number of CMs with poorly constrained CRE ages of >3 Myr that on average appear to be intermediate altered (PSF ~0.77, H₂O ~6.5 wt%).

Fig. 1. Average PSF and H₂O abundances for CMs with CRE ages of ~0.2, ~0.6, ~2 and >3 Myr. Error bars aren’t shown for clarity but are on the order of 5–10%.

How many parent bodies? The friable nature of the CM1 chondrites could be biasing our sampling i.e. only those with short CRE ages make it to Earth. However, we note that the fully altered (PSF >0.9) CI1 chondrites typically have CRE ages of ~3 Myr [e.g. 7]. Instead the trends shown in Fig. 1 could represent subsequent impacts exposing increasingly deeper regions of a single layered parent body. We have previously suggested that the CM1 chondrites were altered at higher temperatures likely to be found within the interior of a parent body [8]. One issue with the multiple impact scenario is that water-rich asteroids are predicted to disrupt in large collisions and not preserve an impact record [e.g. 9].

An alternative explanation is that the CM1 chondrites are derived from a distinct parent body. We reported that the bulk oxygen isotopic compositions of the CM1s are lighter than the CM2s, in contrast to longstanding model predictions [10]. The effects of weathering on highly altered samples still need to be constrained but this suggests that the CM1s formed from different fluids and/or rock compositions, possibly on a separate parent body.

An archive of atmospheric CO$_2$ in the Martian rock record

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Introduction: Mars’ “missing” carbonates

Carbon dioxide was likely the main constituent of Mars’ Noachian atmosphere given expected outgassing behaviour during crustal formation, yet carbonate-bearing bedrock exposures (namely the iron(II)-carbonate siderite; FeCO$_3$) remain surprisingly uncommon at the surface [1, 2]. Nevertheless, carbonates have long been recognised within Martian meteorites, often associated with minerals that require at least neutral pH to form [e.g., 3]. Carbonate-rich rocks have also been increasingly recognised from orbit in Noachian terrains, especially where subsurface lithologies are exposed [2]. Together, this suggests that some environments produced carbonates while others did not.

At least two possibilities may account for the relative paucity and stratigraphic distribution of carbonate minerals on Mars: either 1) the partial pressure of Noachian CO$_2$ was significantly lower than the ~1 bar required to stabilise liquid water [4], raising to question what alternative atmosphere supported the early Martian surface; or 2) carbonate formation on early Mars was strongly controlled by kinetic factors that may have restricted deposition to specific environments.

In this study, we experimentally investigate anoxic water-rock interactions between acidified fluids and ferromagnesian minerals to more closely examine the processes that control the precipitation of Fe-(II)-carbonate minerals.

Methods: Experimental geochemistry

Water-rock experiments were conducted in closed vessels at varying water-rock ratios (W/R), initial pH, and dissolved CO$_2$ content. Experiments were conducted with synthetic fayalite (Fe$_2$SiO$_4$), natural forsterite (Mg$_2$SiO$_4$; Fo$_{>90}$), or mixtures of the two. Strictly anoxic conditions were maintained during experimentation within N$_2$/H$_2$ glove-boxes.

Results:

Solution samples analysed via Inductively Coupled Plasma Optical Emission Spectrometry reveal that, in almost all cases where initial dissolved CO$_2$ was equivalent to >0.5 bar, siderite was continuously supersaturated. This means, thermodynamically, a precipitate is expected to form. Despite this, in all experiments no trace of siderite or related iron carbonate minerals were found. X-Ray Diffactometry and Fourier Transform InfraRed Spectroscopy revealed unreacted pure fayalite/forsterite, and Fe(II)-carbonate was not identified in samples via Scanning Electron Microscopy or Energy Dispersive X-Ray Spectrometry (EDS). Across all of the conditions investigated, only one experiment provided qualitative evidence for mineral precipitation (pH 8.2, 1.0 bar CO$_2$, and with 50:50 fayalite-forsterite) in the form of nanometre-scale plates, although the specific phase cannot be determined on the basis of analytical techniques employed here.

Discussion: Where should carbonates form?

Set in a kinetic framework, our experimental data indicate that anoxic water-rock systems on Mars evolve along a chemical pathway that only surpasses the threshold for spontaneous Fe(II)-carbonate nucleation under specific conditions of high alkalinity. Because the alkalinity of a given aqueous system on early Mars would have been controlled by the balance between atmospheric CO$_2$ and silicate mineral dissolution, we suggest that high water-rock ratio aqueous environments, especially those at the early Martian surface and buffered by high pCO$_2$, would have been less likely to cross requisite nucleation thresholds for Fe(II)-carbonate. On the other hand, sub-surface environments where alkalinity produced from mafic wall-rock alteration may overwhelm acidity contributed by a high pCO$_2$ atmosphere, would have been more likely to overcome kinetic barriers and precipitate Fe(II)-carbonate. This is consistent with Fe(II)-carbonate formation in rock-dominated fractures of several Martian meteorites, and general indications that Fe(II)-carbonate may constitute a larger portion of Mars than previously thought [2].

Conclusions:

Our experiments demonstrate that Fe(II)-carbonate precipitation is subject to strong kinetic control under chemical conditions relevant to the early Martian surface. These kinetic factors explain, at least in part, why carbonate minerals formed via low temperature water-rock interaction may be rare at the Martian surface but more abundant with depth.

MICROBIAL MORPHOLOGIES THROUGH THE EYES OF THE EXOMARS CLOSE-UP IMAGER

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Introduction: The Rosalind Franklin rover, part of the ExoMars 2020 mission, hosts a wide array of analytical equipment that will be used to search for potential biosignatures at its landing site, Oxia Planum. The Close-up imager (CLUPI) has the ability to obtain high resolution images [1], with the potential of identifying biologically driven morphologies, such as microbially induced sedimentary structures (MISS) [2].

Methods: To assess the potential of CLUPI in identifying such biosignatures, a systematic imaging campaign was conducted on the 3.2 Ga Moodies Group of the Barberton Greenstone Belt, South Africa. The MISS were captured using a Sigma SD15, fitted with a 105 mm fixed length f/2.8 lens, emulating the CLUPI system. Images were taken on a range of exposure conditions and outcrop types: from pristine rock surfaces to those that were very weathered and altering the distance from 300 cm to 15 cm as well as the viewing angle to the targets to simulate non-ideal imaging situations. More than 620 images were collected from 17 sites of biolaminations ranging from tufts, to onlapping and draping conglomerate clasts, to those influenced by fluid escape features and desiccation.

Results: MISS were identified in varying depositional systems comparable to what may be found in Oxia Planum, the rover landing site.

With images close to targets, impressive detail can be resolved, although context of the images is lost when non-flat targets limit the field-of-view (Figure 1). All these images will be made available in a database to help guide and inform scientists in their interpretation of the sedimentary features imaged by CLUPI. This database provides a wide range of biological morphologies and associated depositional environments that are believed to be appropriate analogues for those expected on Mars.

Acknowledgements: We wish to thank Dr Matthew Gunn (Aberystwyth University) for the loan of the CLUPI Emulator for this project, as well as to Dr. Claire Cousins (University of St Andrews) for her support and direction in the project. We also acknowledge funding from the Laidlaw Scholarship Programme.

Background:
The problem of forward contamination within planetary protection is becoming an increasingly important issue in astrobiology, with plans for crewed missions to Mars in the coming decades. Forward contamination, the inadvertent delivery of Earth microbes to other celestial bodies, can pollute the Martian surface and interfere with the search for indigenous Martian life. Vehicles and other equipment can be sterilized; however, bacteria associated with the human body (commensal bacteria) and thus carried by future astronauts cannot be removed. It is therefore important to understand how these microbes may propagate onto the Martian surface. On Earth, a meaningful analogue of a Mars habitat has been constructed near Hanksville, in Southern Utah. The Mars Desert Research Station (MDRS) is used to carry out research on a variety of subjects under simulated Martian conditions, to better prepare for future missions on the Red Planet.

Objective:
The main objective of this study is to evaluate the effect of human presence on a Martian analogue landscape through genetic analysis and comparison of microbial species from the inside of the MDRS habitat, as well as the adjacent soil. A study of this nature can improve our knowledge of microbial dispersion from space habitats onto a Mars analogue soil. Additionally, this can help to mitigate the future risk of forward contamination on Mars. Preliminary results have shown that the nature of the soil can greatly interfere with the presence of microbes.
MODELLING THE ASCENT AND ERUPTION OF PICRITIC LUNAR MAGMAS

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Introduction: Volatile magmatic species, such as H$_2$O, CO$_2$, SO$_2$, and CO, play an important role in planetary volcanic systems, affecting the transport and rheology of magma. Quantifying the volatile content of the lunar interior is valuable for understanding the thermal and magmatic evolution of the Moon, as well as understanding the interconnected formation of the Earth and Moon [1]. Petrological modelling and geochemical analysis of meteorites and returned samples has been used to study the volatile content of lunar magmas [2, 3], with improvements in analytical instruments facilitating more precise measurements [4]. Several problems remain with measurements of volatiles in lunar samples and meteorites, such as: post-crystallisation diffusion of volatiles from apatite on the lunar surface, and terrestrial contamination and alteration of water-bearing minerals within meteorites [3]. Hence, the volatile content of lunar magmas has yet to be constrained with certainty. We propose a volcanological approach to infer the volatile contents of different lunar magmas, and plan to verify our model’s consistency with lunar volcanic deposits observed in remote sensing datasets.

Method: A Fortran 90-based terrestrial magma ascent model has been modified for lunar applications. The model has previously been used to calculate various eruption conditions for the 2007 Strombolian eruption, and for scenarios such as equilibrium and disequilibrium crystallisation in basaltic systems [5]. Numerous parameters were adjusted for lunar conditions, such as: gravity, pressure, oxygen fugacity, H$_2$O solubility, and CO solubility. The main parameters varied were: major element chemical composition of the magma, and volatile (CO, H$_2$O) content. The H$_2$O content of the magma was varied between 4 and 745 ppm [4], and CO content was varied from 50 to 500 ppm [6]. The model produced depth profiles for gas exsolution, viscosity, mass flow rate, and several other ascent conditions.

Results: Model solutions for five compositions of picritic glass bead, from low-Ti (green and yellow glasses) to high-Ti (orange, red, and black glasses) [7, 8], have been produced – e.g. Figure 1. Magma major element composition had the greatest effect on the viscosity of the ascending magma. Meanwhile, volatile content had the greatest effect on the depth at which volatile exsolution initiated, as well as magma velocity and gas/melt relative velocity. Results indicate that magma fragmentation would not occur within the conduit, suggesting that fragmentation occurred when the magma reached the surface. Finally, the radius of the modelled conduit was the key control on mass flow rate.

![Figure 1: Volume fraction of exsolved gas during ascent of a low-Ti, green picritic magma, with various initial volatile contents, assuming a conduit of 20 m diameter.](image)

Future Work: Ascent and at-vent conditions calculated by the magma ascent model will be used in a ballistic eruption model. This eruption model will be used to estimate the extent and thickness of deposits of picritic glass beads. Satellite images of the lunar surface will also be analysed, in order to collect photogrammetric measurements of pyroclastic deposits. The ISIS3 (Integrated Software for Imagers and Spectrometers) and Ames Stereo Pipeline image processing packages will be used to manipulate LRO (Lunar Reconnaissance Orbiter) images to create digital elevation models [9, 10]. The magma ascent and eruption models will essentially be inverted, to provide estimates of the volatile content of lunar magmas, consistent with the morphology of the deposits.

THE DRAGONFLY NEW FRONTIERS MISSION TO TITAN

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Dragonfly:

Dragonfly, a relocatable lander for Titan, was selected in June 2019 as NASA's next mission in the New Frontiers PI-led mission class (Elizabeth Turtle of APL is the PI). Dragonfly will be launched in 2026 and will arrive in 2034, almost exactly one Titan year after (and thus at the same Titan season as) the Huygens descent.

At Titan, Dragonfly will land using a set of eight rotors in interdune plains near the Selk impact structure. It will spend typically two Titan days (Tsols) at each landing site, conducting imaging, meteorological and seismological monitoring, surface elemental composition measurements via neutron/gamma-ray spectroscopy, and surface sampling by drill with analysis by laser desorption- or gas-chromatograph – mass spectrometry.

Dragonfly beams its data back to Earth via its own steerable high-gain antenna (retracted for flight). During the Titan night, the vehicle is largely dormant (except geophysical and meteorological measurements, and occasional night-time imaging using LED illuminators, including ultraviolet LEDs to search for fluorescence typical of polycyclic aromatic hydrocarbons), and the power output of the MultiMission Radioisotope Thermoelectric Generator (MMRTG) is used to recharge a large battery.

Rotorcraft flights last several tens of minutes, during which time the vehicle can tens of kilometers, although the typical advance towards Selk will be less than this.

The decline in MMRTG output is gradual, and no significantly life-limiting factors constrain the mission, which is nominally more than 2.5 years. Some dozens of flights are expected in this period (during which meteorological measurements and image data are acquired).

The fundamental operations concept (RTG power trickle-charging a battery overnight for brief rotorcraft flights) was advocated two decades ago. The combination of technological capability and scientific opportunity/demand after Cassini has set the stage for an exciting new paradigm in planetary exploration, made possible by the unique Titan environment.

Figure 1. Operations concept of Dragonfly

Bibliography:


INITIAL OBSERVATIONS OF THE MARS SURFACE ENVIRONMENT USING THE INSIGHT SOLAR ARRAYS

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Introduction:

The current from solar arrays on Mars landers provides a measure of the light flux incident on the panels. Spacecraft power telemetry can therefore provide a window on the Mars environment. Historically, such engineering telemetry has not been made publicly available in a routine manner. However, because the seismic instrumentation on the InSight mission is sensitive to a wide range of environmental factors (including magnetic fields as well as meteorological conditions), the solar array currents, presently recorded at ~0.5 minute intervals for a few hours per day, are archived on the Planetary Data System (PDS) along with other InSight mission data. These data provide interesting information on dust and clouds, and also detect Phobos eclipses and lander operations.

Data:

Typical data are shown in figure 1: the current history has a broadly sinusoidal form with elevation angle (and thus with time), although slightly broadened ‘tails’ occur at dawn and dust due to atmospheric scattering.

Long-term Variation: InSight landed at \( L_E = 295.5^\circ \) and peak power would be expected to decline seasonally, mostly due to the increasing Mars-Sun distance. Steady accumulation of dust on the solar arrays has also degraded their output (as expected) and present energy production is about half of the \( \sim 4 \) kW-hrs per day achieved at the start of the mission.

The shape of the diurnal curve (figure 1) depends slightly on the distribution of dust and ice clouds in the atmosphere. Currents are slightly above zero after geometric sunset, and seasonal variations in this twilight intensity have been noted.

Short-Term Variations:

Short-term variations, typically up to \( \sim 1\% \) of the mean value, can be detected by subtracting a smoothed curve from the data. These variations are often quasiperiodic, probably reflecting structures in the planetary boundary layer.

Dust devil shadows may be observable, although the relatively short duration of dust devil encounters (a few seconds) is not well-captured by the slowly-sampled data.

Brief shadows of the moon Phobos were detected during several eclipses around 100 sols after landing. Shadows are sometimes observed depending on the position of the robot arm.

Conclusion:

Solar array currents, which are acquired routinely for operations in any case, provide a ‘free’ dataset that provides valuable situational awareness on the Martian surface.


Figure 1. Two typical diurnal records. Large gaps occur where the lander is asleep. Peak power dropped appreciably between Sol 4 and Sol 200, due to seasonal change and due to the accumulation of dust on the solar panels.
The Challenges of Basic Characterisation of Mars Material under Containment

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**Introduction:** All Mars material retrieved by a Mars Sample Return (MSR) mission must be kept under stringent containment and contamination control until assessed safe for release to the wider community. This poses significant challenges to the Basic Characterisation (BC) of samples that will have to be carried out in this environment [1]. We are investigating BC inside a Double Walled Isolator (DWI), a likely containment environment [2]. Inside, it seems likely that the sample tubes will first be weighed, imaged, the head gas extracted, and then the contents removed and imaged. The most important analytical tool for BC is thus a visible light imager. It is proposed that imaging science goals can be divided into three categories:

**TABLE 1: Proposed imaging science goals**

<table>
<thead>
<tr>
<th>Goal name</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Extra-terrestrial matter</td>
<td>Image data related to the science goals</td>
</tr>
<tr>
<td>(EM)</td>
<td></td>
</tr>
<tr>
<td>Mission artefacts</td>
<td>Rover and spacecraft contamination</td>
</tr>
<tr>
<td>Terrestrial artefacts</td>
<td>Contamination from Earth sources, re-entry &amp; DWI onwards</td>
</tr>
</tbody>
</table>

This imager will perform close-up sample inspection and BC analysis which will offer our first glimpse at the EM the rover has collected. Its role will be to inspect the sample tube seal integrity, image coarse dust on the outside of the tubes, examine sample composition (consolidated or rock fragments, regolith or liquid), search for morphological biosignatures, check for visible contamination from Earth or Mars, measure optical characteristics, map geological features like grain size, preliminary rock and mineral identification, and early recognition of unusual or high priority features; all for both samples, and witness plates and analogues. These data will be used to inform Preliminary Examination (PE) and to catalogue samples for subsequent analysis [1].

**Double Walled Isolator:** A DWI is a tightly controlled environment for BC and PE operations within containment. With ESA and Thales Alenia Space, Leicester has developed and demonstrated a DWI breadboard (BB). This DWI is an ultra-clean class III bio-safety cabinet offering BSL-4 containment and supporting a large variety of analytical techniques and their requisite instrumentation. The Mars Science Planning Group workshop 2 (pre-decisional) found that the BB demonstrates the feasibility of cabinet isolation as the primary contamination control method [2]. DWI will operate in an ISO 5 or 6 cleanroom. An Interface Flange (IF) allows scientific instruments (e.g. SEM, X-ray CT, or sterilisation equipment) access to the working volume; with larger instruments partially outside the DWI while the IF seal maintains double seal isolation. An industry standard Rapid Transfer Port (RTP) enables contained safe transfer of samples and smaller equipment in and out of DWI [3].

**Instrumentation Development:** An upgrade of the DWI with new features, called the DWI BB6, is underway at Leicester (see Fig. 1). An instrument box has been designed which will allow interconnection of multiple DWIs, permitting sample and instrument transfer. Continuous workflow would be possible in a line of DWIs. A BC imager would also be accommodated in this instrument box. With a 316 stainless steel housing, the imager will consist of a non-contact zoom camera with variable optics capable of micrometre over scales from mm down to microns. A high power optical microscope is planned to enable imaging of dust picked up on the surface of sample tubes (dust diameters down to \( \approx 3 \) \( \mu \)m [4]). In the absence of BC and PE instrument engineering requirements, the instrument will be designed based on NASA's tier 1 and 2 contaminants list, with operation shedding no particles or affecting the DWI’s ISO 1 environment. Accompanying these instruments will be an illumination system optimised for the multiple imagers.

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THE LOST METEORITES OF ANTARCTICA: METEORITES FROM THE FIRST FIELD SEASON

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Introduction: Meteorites are the only natural source of material from beyond the Earth, providing invaluable evidence of how the Solar System formed and evolved. Over 66% of the total classified meteorites to date have been found in Antarctica [1-3], in part due to the ice dynamics and high katabatic winds producing highly concentrated localized Meteorite Stranding Zones (MSZs).

The Lost Meteorites of Antarctica Project

The Antarctic project [4] aims to explore new MSZs for meteorites using several methods: (i) investigation of ice flow regimes in Antarctica to locate suitable exploration sites; (ii) development of more sophisticated models to predict burial depths of different meteorite types in different field settings; (iii) developing technology to identify ice trapped iron-rich meteorites; (iv) collecting surface located meteorites to determine productiveness of field settings; and, ultimately (v) collecting sub-surface meteorites and classifying them to test the hypothesis that iron-rich meteorites are likely to lie buried a few cm below the surface [5].

In Austral Summer 2019, a two-person team searched for surface meteorites upon two Antarctic icefields: the Outer Recovery and Omega Nuna-tak icefields, south of the Shackleton Mountain Range / Recovery Glacier region. We recovered a postulated 36 meteorites, ranging from ~2 mm to 20 cm in size. In-field testing using an AnMETMET magnetic susceptibility and electrical conductivity device indicates that the sample types collected include two possible iron-rich meteorites, several ordinary chondrites, and at least three iron-poor meteorites, possible achondrites [6,7]. The meteorites were shipped frozen and arrived in the UK in July 2019.

Preliminary Examination Plan (PEP): The samples are being curated and preliminary examination is being undertaken in clean class 10000 conditions. Details of all materials and tools used, and any other possible contaminants that the meteorites may be exposed to, will be recorded in the curation database for every stage of the process. Tools are limited to stainless steel 304 and aluminum [8].

The meteorites were collected in sterile low density polyethylene (LPDE) bags and we will retain these and other collection materials as witness plates. Any residual ice or water will be retained. Our plan to undertake the meteorite preliminary examination, classification activities and storage is:

1) The meteorites will be thawed in an exsiccator under vacuum.
2) The meteorites will be photographed, described, weighed, and measurements of magnetic susceptibility and electrical conductivity made.
3) High resolution photogrammetry will be carried out, to create a full 3D surface image [9].
4) A CT-scan of each meteorite will provide a curation record and inform where to break/cut the meteorite when sub-sampling.
5) The rock will be split or cut, preserving as large a main mass as possible, to make thin sections and a polished block.
6) SEM and EPMA data will be collected and used to detail the petrography, define the mineral chemistry and classify the meteorite.

Fig. 1. Fusion crusted chondritic meteorite collected from the Outer Recovery icefield.

Colour Peak – an analogue environment for late Noachian Mars

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Introduction: The surface of Mars cannot sustain liquid water today, but there is evidence that water was present during the Noachian era. The transition of the martian climate from the wet Noachian to the dry, late Hesperian would have resulted in saline surface waters that were rich in sulfur species [1–4]. Terrestrial analogue environments that possess a similar chemistry to these proposed waters can be used to develop an understanding of the diversity of organisms that could have persisted under such conditions. Here we present the chemistry and microbial community of one of those analogue environments [2], the highly reducing sediment of the springs of Colour Peak, a sulfidic and saline spring system located within the Canadian High Arctic.

Methodology: In this study, molecular and geochemical techniques were used to investigate the sediment of the Colour Peak Springs on Axel Heiberg Island. Both DNA and RNA were extracted from the microbes present in the sediment using a novel extraction technique that was developed to overcome issues associated with low biomass and the high concentrations of inhibitory substances. The microbial community was then characterised by the amplification and sequencing of 16S rRNA and 16S rRNA gene amplions produced from the extracted nucleic acids.

The elemental composition of the fluids and sediment of Colour Peak was determined by ICP-OES. This data was then compared with brines, the composition of which were determined based on the chemistry of the “Rocknest” sand sample at Yellowknife Bay, Gale Crater (Mars) by thermochemical modelling [5]. This fluid chemistry was also used to calculate Gibbs free energy values to identify metabolic pathways that would be viable in this defined chemistry.

Results and Discussion: Analysis of the chemistries of the Colour Peak fluid and sediments confirmed a chemical composition that was similar to the thermochemically modelled fluid derived from in-situ measurements of the chemistry of Gale crater sediments. This similarity in elemental composition confirms the classification of Colour Peak as an appropriate analogue environment to investigate the habitability of proposed former martian aqueous environments.

16S rRNA gene and 16S rRNA profiling of the Colour Peak microbial community revealed it was dominated by bacteria associated with the oxidation of reduced sulfur species and the fixation of carbon dioxide. Gibbs free energy values calculated using the chemistry of the modelled martian fluid demonstrated that the oxidation of reduced sulfur species was also a viable metabolism in this chemical environment under both aerobic (using modern day concentrations of oxygen in the martian atmosphere [6]) and anaerobic (denitrification-enabled [7]) conditions. This supports that this metabolism is thermodynamically viable using both modelled and environmental proxies for the chemistry of former martian aqueous environments.

Non-autotrophic, fermentative bacteria were also detected as active in the microbial community. Given the low concentration of carbon in the sediment and the persistence of bacteria that are dependent on an exogenous supply of organic carbon, the community profile suggests that the sulfur oxidising bacteria might be driving primary production in this environment. The potential for the sulfur oxidising bacteria to enable the survival of heterotrophic bacteria within the sediment has implications for the viability of metabolisms on Mars; as syntrophy may facilitate a greater diversity of metabolisms.

Conclusion: This study highlights the potential role of oxidation of reduced sulfur species as a metabolism on Mars, which needs further characterisation with regards to its viability in a martian context. It also shows the importance of community dynamics and the role of syntrophy when considering the viability of metabolisms under terrestrial and martian chemical conditions.

Acknowledgements: MCM would like to thank the STFC and the school of EEES for funding this project.

POTENTIAL IDENTIFICATION OF SUBLIMATION-DRIVEN DOWNSLOPE MASS MOVEMENTS ON MERCURY.

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Introduction: Mass movement has been recognised on many Solar System bodies. Evidence of laterally restricted mass movement on Mercury has previously been limited to a single documented location, inside the pyroclastic vent NE of Rachmaninoff crater (inside Nathair Facula) (Fig 1). Here we describe further examples.

Systematic Survey: Following the serendipitous discovery of further features in Martins Crater (Fig 2), we have completed a systematic survey of high resolution (<20mpp) NAC imagery in the Hokusai (H-05) quadrangle.

From this, we have identified 123 individual potential slope features in 82 images from our survey of the 9099 available images. These features occur on steep slopes with a fresh appearance, and the rate of landform evolution on Mercury means that these features must be geologically young. We measured all the features identified. The lengths varied from 0.17 km to 8.9 km. However, of the 123 features measured, 61% (75) were under 1km in length, with a median length of 790m.

The survey identified features with different morphological expressions, so we have split them into two categories. These are where the feature is defined primarily by either topographic expression, or as an albedo feature. Albedo features show a strong preference for being located on an equator-facing slope. We note that these slopes receive the strongest insolation.

Fig. 1: The slope features in the vent within Nathair Facula. Red dashes indicate location of vent rim and downslope direction. Image resolution: 6.4m/pixel (NAC: EN1028933034M)

Fig. 2: Slope features in Martins Crater (~285 km N of Nabokov). Features in high incidence angle image (NAC: EN0252295266M)

Triggering Mechanism: Given that slope streaks are not found on all young steep slopes, it is probable that there is a factor other than simply young age that triggers slope streaks on Mercury. We have compared the Mercury slope streaks to similar features on the moon [e.g. 1, 2] and Vesta [e.g. 3]. Triggering mechanisms suggested for mass-movements on the Moon are seismic shaking from moonquakes and nearby impacts. We have been unable to find a quantifiable link between mapped tectonic feature on Mercury and the locations of slope streaks. Slope features were not notably clustered around large impacts, and examples are found in craters overprinting large recent impacts. The features inside the Nathair Facula vent appear to start at a hollow-producing layer [4]. Mercury’s hollows are a landform linked to recent volatile loss at the surface. This, along with the strong preference for albedo features to occur on equator-facing slopes, may suggest the albedo slope lineae may be linked to, and triggered by, contemporary volatiles on Mercury.

Introduction: We are currently undertaking detailed (1:3M) geological mapping of the Derain (H-10) quadrangle of Mercury. This is as part of a coordinated European project to produce a complete set of geological maps [e.g. 1,2,3,4,5] in advance of BepiColumbo’s arrival at Mercury. This mapping will aid mission planning and provide scientific context for BepiColumbo observations.

Data and Methods: The map is being produced in ArcGIS 10.5 using data from NASA’s MESSENGER mission. Mapping is being conducted principally using the 166 m/pixel (meters per pixel) BDR mosaic. This is complemented by a range of other MESSENGER products, in particular: Enhanced Colour (665 m/pixel), low incidence mosaics and the Global DEM (665 m/pixel). Features of particular interest are also investigated using individual frames from MESSENGER’s Narrow Angle Camera. We are preparing this work in line with previous work (e.g. [1]) and Planmap guidelines and standards [6]. As the map is intended for publication at 1:3M, line work is being prepared principally at 1:300k in line with prior work [e.g. 1]. We are also mapping a 5° border beyond the Derain Quadrangle to allow better integration with adjoining maps.

Units: We are aiming to produce mapping that is consistent with other geological mapping underway. This includes mapping crater degradation with both the 3-Class degradation scheme [1] (as shown in Figure 1.) and the 5-Class degradation schemes [7].

Progress and Ongoing Work: This work is close to completion with all major units having been mapped in the 3-class system. Superficial deposits are nearly completely mapped. We hope to publish during 2020.


Figure 1: Current state of mapping in the Derain Quadrangle.
GEOLOGICAL MAPPING OF THE NERUDA QUADRANGLE (H-13), MERCURY

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Introduction:
The Neruda Quadrangle (H-13), Mercury, is one of the final uncharted regions on the planet. With ESA-JAXA’s BepiColombo mission underway, it is imperative that a full set of comprehensive geological maps is produced prior to the spacecraft’s arrival, to provide context for BepiColombo’s studies. Geological mapping of H-13 has commenced as part of the PLANMAP project to map the entire planet at a scale of 1:3M [1–7].

Data and Methods:
The primary base map to be used is the 166m/pixel high-resolution monochrome global mosaic. Additionally, the 665m/pixel enhanced colour global mosaic as well as narrow-angle camera (NAC) images are used for interpretation and quality control. All data were obtained by MESSENGER’s Mercury Dual Imaging System (MDIS). ArcGIS software is used for mapping following both USGS and PLANMAP practices. The map is projected as a Lambert Conformable Conic (Figure 1). To enable accurate correlation with neighbouring quadrangles, a 5° overlap is being mapped.

Mapping Units and Features:
Mercury’s geological terrains are divided into four overarching units: Crater Materials, Smooth Plains, Intermediate Plains and Intercrater Plains [8]. Crater Materials are further subdivided based on the degree of crater degradation with both three class [2] and five class classifications being mapped [8].

Structural features such as lobate scarps, wrinkle ridges and high-relief ridges are distinguished using linework.

Acknowledgements:
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References:

Figure 1 – Mapping focus: Neruda Quadrangle (H-13)
PETROLOGICAL CHARACTERIZATION OF THE CARBONACEOUS CHONDRITE AGUAS ZARCAS: IMPLICATIONS FOR UNDERSTANDING ASTEROID NYGU

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Carbonaceous chondrites are aqueously altered meteorites with a relatively high-water content (~9 wt%; [1]). Nyugu, the target asteroid for the JAXA Hayabusa2 sample collection mission, is thought to be of a similar composition as these meteorites, which might shine a light on one of the most prominent questions of planetary science: the origin of Earth’s water.

Aguas Zarcas is a carbonaceous chondrite classified as a CM2 (Mighei-like). After its confirmed fall on the 23rd of April 2019, it has been petrographically described by L. Garvie (Arizona State University, USA) and its oxygen isotopic composition analysed by laser fluorination by K. Ziegler (University of New Mexico, USA) [2].

In this study, we define the petrological subtype of the Aguas Zarcas meteorite using the method described by [1], which employs simple and accessible petrological techniques to define the degree of aqueous alteration of CM carbonaceous chondrites.

Petrological Observations.

Previous petrographic observations (2]) have described the presence of two main lithologies: one chondrule-poor (80 areal%) and the other chondrule-rich. The studied thin sections seem to all be within the chondrule-supported sections of the meteorite and the chondrule-rich/chondrule-poor dichotomy doesn’t seem to be visible on our study’s scale. Initial observations of three thin sections of the meteorite have shown a distinct fusion crust which helps highlight that there has been little-to-no terrestrial alteration.

The following features have been defined from preliminary petrographic observations:

- The chondrule mesostasis has been completely altered and replaced entirely by phyllosilicate, which is consistent with any degree of aqueously alteration of such a carbonaceous chondrite.
- As in any aqueously altered carbonaceous chondrite (from CM 2.2 to 2.6, according to the classification; [1]), phyllosilicates are abundant within the matrix.
- Metallic Fe-Ni bearing phases are rare. The exact proportion will be quantified by future geochemical analysis.
- Mafic silicate phenocrysts, such as olivine, have been almost completely altered in most cases and replaced with calcite.
- Large areas of TCI (tochilinite-cronstedite intergrowth) dominate the matrix. The exact volume percentage will be better defined using EDX mapping.
- The sulfides do not seem to present any rinds of oxides which further shows the absence of terrestrial alteration within the sample [3].
- Dolomite can be found alongside calcite within altered chondrules, as identified by Raman spectroscopy.

These preliminary observations indicate that Aguas Zarcas is a CM 2.2 according to the scale defined in [1]. Subsequent work will focus on two aspects: EDX mapping and Raman spectroscopy.

Geochemical mapping (EDX). These observations are to be confirmed and complemented by geochemical analysis and mapping to define the extent of Fe-Ni bearing phases and PCP areas, as well as their compositions within the samples.

Raman Spectroscopy. Preliminary Raman spectroscopy analysis reveal the presence of calcite alongside dolomite within chondrules, such as the ones in Fig. 1. Further investigation will be done concerning the tochilinite-serpentinite supported matrix in order define possible mineralogical variations.


Fig. 1. Reflected light image showing a well preserved chondrule with its rim, surrounded by a fine-grained rim (FGR), amidst a tochilinite-serpentinite supported matrix.

ASTrAEUS: AERIAL-AQUATIC TITAN MISSION PROFILE

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Introduction:

The Cassini-Huygens mission gave rise to a much more comprehensive understanding of Saturn and its moons, but it was developed at a time when, aside from Earth observation, only 3 spacecraft - Pioneer 11 and Voyagers 1 and 2 - had directly observed these bodies. This data was used to understand the conditions at Saturn and on the surface of Titan, informing the engineering design and scientific payloads of the Cassini-Huygens spacecraft. Now, following the great success of this mission a much more comprehensive picture of the Saturnian system has now been created, inevitably raising more questions demanding further exploration, while also gathering the data which paves the way for this.

Titan. Titan presents a particularly attractive target for further in-situ exploration. Key questions about the composition of the surface liquid and abundance of methane in the body's atmosphere have not been answerable using the limited spatial coverage of Huygens or the obscured observations of Cassini. These questions, when considered alongside the discovery of Titan to be supportive of prebiotic chemistry in one of the most chemically complex environments in the solar system, become among the most important in better understanding the solar system.

In-situ measurements. Previously proposed missions offering in-situ observation of Titan have included a high altitude balloon (Reh, 2009), surface lake submarine (Oleson, Lorenz and Paul, 2015), and heavier-than-air aircraft (Barnes et al., 2011). However, the ASTrAEUS (Aerial Surveyor for Titan with Aquatic Operation for Extended Usability) is not designed for operation in a single environment, but instead for both aerial and aquatic conditions, meaning science questions answerable by access to both mediums can be addressed.

ASTrAEUS:

Heavier-than-air flight on Titan gives a go-to science capability, helpful in detecting sources of methane outgassing or evaporation in the atmosphere, along with other atmospheric and surface anomalies. This method of atmospheric traversal also proves easier on Titan than on Earth due to the decreased gravitational acceleration and increased atmospheric density. Incorporating water sampling mechanisms into such a vehicle however, proves unfamiliar. The operation of the ASTrAEUS aerobot can be seen in Figure 1 and has heritage in robotic work inspired by observations of the natural world - the field of bioinspiration and biomimetics.

One key requirement of a platform capable of surface liquid sampling on Titan is that any manoeuvre carries a relatively small associated risk. Therefore, the ASTrAEUS uses a manoeuvre which both needs little to no control authority and supports a wide range of entry attitudes. This ‘plunge diving’ manoeuvre has previously been replicated robotically in a mechanical gannet seabird (Liang et al., 2013) and involves the wings of the aircraft sweeping back, causing a loss of lift and the vehicle to ‘plunge’, nose first, into the surface liquid. Further development of this work by Siddall and Kovač (2014) has produced a vehicle capable of relaunch by ejecting a mass of liquid collected passively from the area of launch, eliminating a large percentage of propellant mass.

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Bibliography:

THE NATURE OF REMNANT ROUNDED MOUNDS NORTH OF THE EXOMARS 2020 LANDING SITE

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Introduction: Oxia Planum is a region situated on the western margin of Arabia Terra, and is the selected landing site for the ESA and Roscosmos ExoMars 2020 Rosalind Franklin rover [1]. It occupies a transitional area between the heavily-cratered southern highland terrain and the smooth northern lowlands, and is predominantly characterised by flat, extensive, clay-rich, Noachian-aged deposits [2]. Oxia Planum is bordered by Chryse Planitia to the west, Acidalia Planitia to the north, and the greater part of Arabia Terra extends to the east and south. Distributed across northern Oxia Planum are hundreds to thousands of kilometre-scale mound-like landforms. A few examples of these mounds are present near the landing ellipses for the ExoMars 2020 rover (figure 1), but they are more common towards the north and west of the area. Despite being a widespread geomorphological feature in this important highland-lowland transitional region, their origin and position within the stratigraphy are poorly understood. This study investigates the morphology and distribution of these landforms, to try to better understand their stratigraphy and the depositional environments of the materials that compose them. A suite of measurements will be made primarily using CTX data (6 m/pixel; [3]): size, morphology, orientation. This data will be compared and combined with HiRISE [4] and CRISM [5] data to gain further insight into their formation. Two mounds with particularly interesting features are discussed here.

![Figure 1: A) MOLA topographic image underlain by HRSC-MOLA blendshade depicting the study location within NW Arabia Terra. B) THEMIS image of Oxia Planum showing ExoMars landing ellipse (orange) and location of mounds in far northwest.](image)

Descriptions of the Mounds: The mounds vary considerably in morphology: some are mesas - orthogonal, flat-topped and laterally extensive, but others are buttes - convex-up, smooth and eroded. Often, these two morphological end-members are geographically or stratigraphically juxtaposed, with some examples exhibiting multi-level 'tiers' or morphologies that belong to both end-members. Their diameters range from hundreds of metres to a few kilometres, with estimated heights above the surrounding topography ranging between tens of metres and hundreds of metres. Some examples are highly eroded and are barely recognizable as individual entities above the relief of the Oxia Planum plains. Irrespective of morphology, the mounds are easily distinguishable from the clay-bearing units of Oxia Planum by their low thermal inertias, as well as their characteristically high albedos. Multi-tiered mounds typically exhibit multiple layers that each possess a range of thermal inertias and albedos, which probably reflects compositional or lithological variations. The mounds are sometimes preferentially located on the inferred rim locations of large (> 10 km) infilled ‘ghost craters’ in the areas north and west of Oxia Planum. However, many more examples do not appear to have any spatial relationship with ghost craters and are isolated from other mound clusters. Additional populations of mounds are observed at the margin of northern Xanthe Terra and Chryse Planitia, as well as near to the mouth of Mawrth Vallis.

Where available for multi-tiered mounds, HiRISE data reveal three discrete units: 1) a lower plateau unit that is geomorphologically similar to the extensive clay-rich Noachian deposits that characterise Oxia Planum, 2) a high-albedo layered unit, and 3) a capping unit, which is morphologically similar to the lower plateau unit. These attributes are exemplified in one such multi-tiered mound 500 km north of Oxia Planum, where stratification is visible at the sub-metre to metre scale. This stratification closely resembles the widespread stratified deposits observed at Mawrth Vallis (e.g. [6]; figure 2). The layering is spatially consistent over tens to hundreds of kilometres horizontally and exhibits evidence of complex pinching and lensing in places, suggesting that multiple depositional events occurred over a prolonged amount of time. The steady, rhythmic layering and lack of observed inclined structures are inconsistent with emplacement by aeolian processes. Instead, we suggest that sedimentary deposition in a lacustrine or marine environment, or emplacement as a layered igneous body, is more likely. The unit is traversed in an ESE-
WNW direction by widespread fractures and extensional faults, with fault throws of up to 5 m. A potential dyke has also been identified, with a similar orientation to the faulting. These features do not appear to permeate into the clay-rich lower clay-rich Noachian deposits of Oxia Planum, perhaps suggesting that the mound material predates the widespread deposition of the plains material.

Figure 2: comparison of stratification between A) HiRISE image within a multi-tiered butte in southern Acidalia Planitia (PSP_009313_2065), and B) HiRISE image of similar but thicker layers within Mawrth Vallis (PSP_006465_2045).

A flat-topped mesa located 400 km north of Oxia Planum contains 10 to 20 m diameter polygonal features exposed in large erosional windows on its upper surface (figure 3). These polygonal features are defined by high relief margins and high-albedo interiors. We suggest these are infilled fractures, perhaps formed by mineralisation from hydrothermal fluids or subsequent sedimentation. It is unknown whether this fractured unit, and the stratified unit seen in the complex mounds, are laterally equivalent, but some stratification in the fractured unit is seen that is similar to the previous example, 105 km to the north-west.

Figure 3: HiRISE of polygonal features atop a mound in S. Acidalia Planitia (ESP_017884_2050).

**Conclusion:** In summary, these landforms display morphologies and features that vary both stratigraphically and laterally. A holistic understanding of their distribution, geology and geomorphology is essential in order to understand their position in the regional stratigraphy, as well as the ancient extent of the Mawrth-like layering seen in some examples of these landforms. This will allow for further insight into the geological history of this important highland-lowland transitional area.

**References**
A morphological classification to facilitate a comparison between Martian and Terrestrial inverted channels.

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Introduction:
Recent studies have revealed the presence of inverted fluvial channels in Arabia Terra [1], one of the oldest areas on Mars (mid- to late Noachian [2] in age). Inverted channels are ancient river systems which are preserved in positive relief because the channel material was more resistant to erosion than the surrounding sediments (due to armouring or secondary cementation), thus protecting the morphology of the channel body from erosion [3]. Inverted channels are used for paleo-hydrological reconstructions for both Earth and Mars (e.g. [4]). However, significant variations in inverted channel morphology are observed throughout Arabia Terra [e.g. 5, 6] indicating that these systems are complex. For future interpretation, calculations and comparisons between terrestrial and martian inverted channels, we have devised a classification scheme which considers differences in (i) planimetric morphology, (ii) cross section shape, and (iii) upper surface morphology. Since terrestrial river systems show a correlation between plan view morphology, cross section types, sinuosity and slope, these fluvial parameters were also calculated to understand whether they can provide information about the paleo-topography. Here we present the results of sinuosity and slope calculations for over 700 inverted channels in Arabia Terra.

Methodology:
Sinuosity (S) is defined as the ratio between the length of the inverted channel ridge and the direct length, the distance between the starting and ending points of the inverted channel. Based on the sinuosity the inverted channels were defined as Straight (S<1.05), Sinuous (1.05<S<1.50) and Meandering (S>1.5). To calculate inverted channel sinuosity we applied the approach of [7] for remote sensing analysis of eskers. Since inverted channels present a wide range of length, sinuosity values were calculated considering different segments lengths (5-10-20-40 km) to isolate different stream orders, assuming longest sections are generally the highest order streams. The slope angle was calculated from the start and end point of the inverted channel segment, by sampling the MOLA height of each. The relationship between inverted channels slope and sinuosity was studied separately for all the classes of the classification scheme.

Results:
Inverted channels in Arabia Terra are mainly classified as Sinuous, with a Sinuosity value range between 1-1.25, and have slopes of between 0.1°-0.6°. We found that lower slope channel segments have higher sinuosity for segment lengths of 10-20 km, but there is not a strong correlation in general between inverted channel sinuosity and slope. This result is perhaps not surprising, as Arabia Terra is a highly eroded region, and the current slope probably does not correspond to the slope at the time of the formation of the fluvial systems.

Figure 1: Sinuosity (top) and degree slope (bottom) values for 757 inverted channels mapped in Arabia Terra.

ARE $\delta^{13}$C AND QUADRUPLE S ISOTOPES ROBUST BIOSIGNATURES IN MARS-RELEVANT GEOTHERMAL SYSTEMS?

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Introduction
Relic hydrothermal systems are a key target in the search for evidence of past microbial life on Mars, as analogous environments on Earth are known to support chemolithotrophic life with a high preservation potential in the geologic record [1]. Hydrothermal systems can provide basic elements for life and redox couples for metabolism [2], and traces of these processes can be recorded in stable isotope ratios. We explored the utility of biological isotope fractionation as a biosignature in hot spring pool deposits using two geochemically distinct Icelandic geothermal systems: Rhyolitic Kerlingarfjöll and basaltic Kverkfjöll. By investigating contrasting systems, differences in microbial biogeochemistry can be identified, allowing for organic carbon $\delta^{13}$C and inorganic quadruple S isotopes ($\delta^{34}$S, $\Delta^{33}$S and $\Delta^{36}$S) values to be assessed as potential isotopic biosignatures recorded in the sedimentary record.

Results
Kerlingarfjöll pools have temperatures from 20 to 60 °C with circum-neutral pH, while Kverkfjöll pools have temperatures of 16.8 and 20 °C, and a pH range of 1-3. Kverkfjöll has very high SO$_4^{2-}$ (0.61 to 171.04 mM), whereas Kerlingarfjöll SO$_4^{2-}$ ranges from 0.91 to 9.8 mM. In both locations, geothermally-sustained, shallow, ephemeral pools 1 – 3 m in size host lithotrophic microorganisms adapted to anoxic environments.

Total Organic Carbon (TOC) weight % abundances in sediments range from 0.11 to 0.24 % at Kerlingarfjöll, and 0.34 to 0.42 % at Kverkfjöll. The $\delta^{13}$C$_{TOC}$ values at Kerlingarfjöll vary from -16.8 to -23.5 ‰, and from -19.2 to -23.5 ‰ at Kverkfjöll, showing evidence for biological CO$_2$ fixation (Fig.1). Sedimentary pyrite $\delta^{34}$S values are more negative at Kerlingarfjöll (-4.45 to -2.34 ‰) compared to Kverkfjöll (-2.36 to -0.70 ‰), with smaller range in values complicating the distinction between biological from volcanic processes (Fig. 1).

Biological metabolism processes perform slightly different isotope mass-dependent fractionation laws that are measurable in multiple sulfur isotopes systems. This variations are measurable in $\Delta^{33}$S ($= \delta^{33}$S - 0.515 $\times$ $\delta^{34}$S) and $\Delta^{36}$S ($= \delta^{36}$S - 1.90 $\times$ $\delta^{34}$S) even when $\delta^{34}$S values are the same [3-5]. Microbial sulfate reduction and microbial sulfide oxidation follow this measurable small differences in mass-dependent relationship [4-6].

Large $\Delta^{33}$S values (0.08 and 0.13 ‰) occur for Kerlingarfjöll pools with lightest $\delta^{34}$S, whereas for the other pools $\Delta^{33}$S variations are smaller (0.01 to 0.04 ‰). 16S rRNA phylogenetic DNA assays show that these pools (with lightest $\delta^{34}$S and largest $\Delta^{33}$S) are dominated by complex S cycling, sulfate reducing bacteria and thiosulfide and sulfide oxidation occurring, whereas Kverkfjöll is dominated by sulfide and iron oxidation.

These results suggest that $\Delta^{33}$S provide key constraints on this complex S cycling in Kerlingarfjöll hydrothermal pools, and demonstrates how quadruple S isotopes can provide a new potential biosignature tool for Mars exploration and sample return.

References:

Table 1. Relative $\delta^{34}$S CRS versus $\delta^{13}$C TOC (%).

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<th>$\delta^{34}$S CRS (‰)</th>
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Fig.1. Plot with sedimentary $\delta^{34}$S$_{CRS}$ versus $\delta^{13}$C$_{TOC}$ (%). $\delta^{34}$S from sedimentary CRS comprises pyrite and elemental sulfur, extracted with Chromium Reducing Solution.
TRANSFER OF BIOMARKERS IN THE PHOBOS-MARS SYSTEM: HYPER-VELOCITY IMPACT INVESTIGATIONS USING A LIGHT GAS GUN.

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Introduction and Motivation: Planetary Protection (PP) policies are designed to protect all Solar System bodies from forward and backward contamination during space exploration, in order to preserve potential life, as well as its precursors and remnants. Each space mission is individually categorised (I-V) based on experimental and/or theoretical findings by internal and external advisory groups [1].

In 2024, the Japan Aerospace Exploration Agency (JAXA) plans to launch the Martian Moons eXploration (MMX) mission with the main scientific goal of clarifying the origin of the two moons of Mars (Phobos and Deimos). To achieve this goal they plan to land, most likely on the larger moon Phobos, a CNES-DLR rover, for ground-truth analysis of the surface [2]; and the main JAXA lander, equipped with a double sampling system to obtain a soil scoop and >2cm soil core for sample-return in 2029 [3].

As a discrete Solar System body, Phobos is not considered habitable owing to its extreme temperatures, harsh radiation environment and lack of nutrient supply [4]. However, its proximity to Mars and short orbital period led to the hypothesis that Phobos could sweep up particles ejected from large impacts into the martian surface [5]; models suggest that Phobos’ regolith could include up to ~250 ppm of martian ejecta material [6,7]. Considering that the surface of Mars has many “Special Regions” that could have been habitable in the past [8], it is not unreasonable to suggest that, if life developed in these areas and subsequently left behind biosignatures, an impact into one of these areas could eject material containing biologically significant material, which could then deposit on the surface of Phobos.

Following this consideration, studies have taken place to investigate the feasibility of unsterilized material being transferred from Mars to Phobos (e.g. ESA’s SterLim [9] and JAXA [10,11] teams). Using specific microbes these simulations make assumptions about the life involved in the transfer process and by combining theoretical and practical experiments they may introduce uncertainties.

Experiment plan: This study involves a series of impact and heating experiments that coherently simulate the conditions martian material, containing biomarkers, would experience throughout the transfer process from Mars to Phobos (Fig. 1&C).

Defining biomarkers. Past investigations [9-11] have used Mars-analogue terrain to advise on the biological loading of martian material, however, this makes broad assumptions about the life that exists, or may have existed, on Mars. Therefore, this study will use a solution containing specific organic biomarkers designed to represent the basic level of biosignatures that could exist on the martian surface.

Ejection from Mars. A martian basalt analogue will be doped with the organic solution, which will be subjected to impact using an inert projectile (Fig. 1A). An ejecta capture method currently in development will collect ejected particles for subsequent analysis. Atmospheric ascent. Collected ejecta particles will be heated to simulate aerodynamic heating during martian atmospheric ascent (Fig. 1B).

Deposition onto Phobos. Processed particles will then be fired into a Phobos regolith simulant and subsequently analysed (Fig. 1C).

Implications: Results from this project will provide insight into the likelihood of martian biosignatures being present within Phobos’ regolith and furthermore whether they could be identified in returned samples.


Fig. 1: Conceptual diagram of experiment plan
Fig. 2: AALGG at the Open University
The First Look at Mars with PanCam: ExoMars2020 spectral instrument suite emulator data of Martian Meteorites.

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Introduction:
The ExoMars 2020 Rosalind Franklin rover will be launched in 2020 with a suite of spectral instruments to investigate the Martian surface [1]. The context instruments: the Panoramic Camera (PanCam), Wide Angle Camera (WAC) NIR multi-spectral stereo imaging system in the 440nm-1000nm range [2], the High-Resolution Camera (HRC), a 5° field of view sub-mm resolution mast mounted colour imager [2] and the Infrared Spectrometer for ExoMars (ISEM), a 1° spot size NIR hyper-spectral imaging system in the 1150-3300 nm range [3], will be imperative in the selection of drill and analysis sites. Analogue instruments for PanCam, ISEM (300-2500nm range) and HRC were used here in studying martian meteorites to investigate the spectral and spatial capabilities of the instruments. Meteorites were imaged at minimum mission configuration, in semi-directional lighting and operated under mission-similar protocols, i.e PanCam imaging at a minimum distance of 2 m, visual selection of HRC target regions and comparative ISEM targets within PanCam scenes [2].

Figure 1. Tissint BM 2012,M1, (a) RGB imaged with LWAC PanCam emulator at 2m. (b) RGB imaged with HRC emulator at 2 m.

Figure 2. (a) Tissint BM 2012,M1, VNIR reflectance spectra from PanCam emulator [4], visible region ISEM emulator. (b) Tissint spectral regions of interest.

The PanCam region of interest was selected to mirror the ISEM spot size at this configuration, although obvious hot pixels were excluded from the resultant spectra. Both of the distance spectra methods retain similar shapes, with a slight drop in reflectance expected due to the imaging systems. There appears to be a divergence in the spectra at approximately 750 nm, the source of which is currently unknown. The region of interest will be inspected for pixel irregularities and a secondary calibration method applied.

Next Steps:
A Thorough investigation of all martian meteorite data and secondary imaging will take place to fully quantify the spectral instrument suite capabilities. Other meteorites and ESA Martian analogues have already been imaged with the spectral instruments and will be processed next to expand the spectral sample and parameter mapping databases for ExoMars2020. Automated continuum removal and feature identification will be implemented to aid identification of targets on Mars. A database of the spectral features of minerals of interest will be developed to compare with in situ targets during tactical mission timelines.

3D IMAGING TOOLS AND GEOSPATIAL SERVICES FROM JOINT EUROPEAN-USA COLLABORATIONS

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Introduction: The EU-FP7 iMars project (http://www.i-mars.eu) developed a completely automated digital photogrammetric processing system to generate DTMs and ORIs from ESA-HRSC and NASA-MRO/CTX and HiRISE called CASP-GO based on the NASA-ASP open source platform. Since the end of iMars, thousands of CTX and tens of HiRISE 3D products have been processed. It is planned that CASP-GO will be integrated into ASP in future releases. The CTX DTM products have been visually assessed and a ≈3000 subset are now available from the new ESA Guest Storage Facility based at the ESAC-PSA. We describe this new distribution mechanism with a global coverage of CTX products.

Methods: Aside from the ASP core pre-processing, initial matching, subpixel matching, camera triangulation, and DTM generation, 5 additional workflows are used to improve the DTM quality.

Products: The CASP-GO processing chain was applied to generate ~5,300 NASA Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) stereo-derived 3D imaging products using the MSSL-Imaging processing cluster and the Microsoft Azure® cloud computing platform [1]. These DTMs cover ~18% of the Martian surface at 18m/pixel compared to the current HRSC DTM coverage of around 50% with grid-spacing from 50m/pixel to 150m/pixel. Figure 2 shows their overall distribution when compared against processed HRSC level-4 products [6].

Figure 1: CASP-GO [4] ASP & new (green).

Figure 2: Footprints of the ≈3,000 best quality processed iMars CTX DTMs displayed on top of a grey-scale hill-shaded MOLA DTM in the webGIS.

Figure 3: Perspective view of HRSC + CTX + HiRISE (2 strips) DTM products in Fledermaus®.

The resultant multi-resolution co-registered 3D models allows a much more comprehensive interpretation of the Martian surface, and are available to browse by the international community of planetary geo-scientists through an interactive webGIS system (http://www.i-mars.eu/web-gis) developed at the Free University Berlin [8] available at UCL-MSSL and through the ESA Guest Storage Facility (doi: 10.5270/esa-0j79yk8).

Introduction: The lunar regolith is comprised of a diverse range of lithologies, which may have been mixed vertically by local impact gardening processes or horizontally from mixing in of impact ejecta layers [1]. The lunar surface is bombarded by galactic and solar cosmic rays, and the solar wind. These interactions occur in the upper meter or so (cosmic rays) through to upper few microns (solar wind) [3-4]. Individual rock fragments within parent soil samples have unique irradiation histories, this means that individual grains derived from a given soil sample may serve as probes of multiple key geological processes and events throughout the history of the Moon [2].

The generation of cosmogenic nuclides is controlled by the target element concentration and the energy spectrum of the particle flux (as well as particle flux density, which is assumed to be constant over recent galactic history; [5]). In many cases, the calculated average shielding depths for a sample do not reflect the depth from which they were collected. Most studies of cosmic ray exposure (CRE) histories adopt a simple one-stage exposure model making the assumption that the sample existed for its entire exposure either at the surface, or at a depth defined by average shielding depth calculations [6-7]. This approach is useful for comparing regolith stratigraphic horizons and their different histories, however, for individual rock fragments it is possible to apply more complex analysis to further understand the history unique to that sample. We have devised a two-stage cosmic ray exposure model based on the Ne isotopic composition of regolith basalts that accounts for both attenuated cosmic ray exposure at depth, as well as a period of exposure on the lunar surface. We have applied this modelling approach to the Ne gases released at temperature steps of 700, 1000, 1400, 1700 °C, for several 5-15 mg basalt grains (from Apollo 12 parent soil 12003, and of known chemistry [1,8]). We present and compare the values calculated by these two methods.

Single stage shielding depth method: Using the sample bulk chemistry composition [1,8], the established approach [6] and production rates of Hohenberg et al. [4], surface exposure CRE ages range from 36.3 to 128.9 Myr for 21Ne and 21.6 to 105.3 Myr for 38Ar. These occur as a continuous spread of ages and are not clustered. Additionally, they are consistent with previously reported Apollo 12 regolith CRE ages [9,10].

Multiple stage shielding depth method: The chemistries of our samples and the Ne isotopic compositions of individual temperature steps are input to linear regression software [11]. ‘Trapped’ (solar wind and fractionated solar wind), and cosmogenic end-member compositions are then calculated for each sample. These are independent of assumed end-member compositions. The end-members, therefore, reflect the cosmogenic compositional variations that arise from target element concentration differences (i.e. [4]), and means the ‘trapped’ composition reflects the effect of sustained upper surface solar wind exposure on isotope fractionation [12].

Given our samples were collected from within ~4 cm of the lunar surface [13], it can be assumed that each sample has resided for part of its history close to, or at a shielding depth equivalent to 0 g/cm². We have developed a two-stage shielding model for each sample, by treating the cosmogenic end-member as a mix of gas produced during surface exposure and gas produced at a deeper depth (defined by the intercept of a line plotted from the surface exposure ratio, through the measured cosmogenic end-member, to its intercept point with the theoretical production rate ratio curve; Figure 1). Two P21 CRE ages are calculated that account for a surface CRE age contribution, and a ‘deep’ CRE age contribution. This method gives a range of total CRE ages from 119 to 445 Myr. These occur as three distinct clusters (122, 182, 445 Myr).

Implications: Barring variations in the cosmic ray flux, it appears that this approach leads to more precise CRE ages. Full implications and considerations will be presented.

Comparing Bulk and In-Situ Techniques to Analyse Martian Organic Material in Preparation for ExoMars, Mars 2020 and Mars Sample Return

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Introduction: A key aim in the search for martian biomarkers is the detection of organic matter (OM), since terrestrial life is carbon-based. Both NASA and ESA’s upcoming 2020 Mars rover missions include experimental suites dedicated to the detection and analysis of organic matter. So far, little OM has been found on the martian surface. It’s absence is thought to be due to the presence of perchlorates in martian soil, which oxidise OM during pyrolysis (step-heating) analyses onboard Mars rovers [1].

Inclusions of complex OM have been found in several martian meteorites, both falls and finds [2]. These inclusions primarily consist of refractory macromolecular carbon (MMC) in the form of polycyclic aromatic hydrocarbons, in addition to solvent soluble OM. The origin of martian OM has not yet been confirmed. Suggestions include that this material is indigenous to Mars, having precipitated from reduced martian magmatic fluids, or that it is exogenous and was deposited by carbonaceous chondrites. Recent analyses of OM found in martian meteorites were consistent with OM found by the Sample Analysis at Mars instrument onboard Curiosity at Gale Crater [3].

This study seeks to investigate the nature, structure and possible origin of martian carbon. We applied a suite of in-situ and bulk organic analytical techniques to OM in martian meteorites and carbonaceous chondrites to determine their structure. In addition, we compare and evaluated these techniques in order to determine the approach with the maximise scientific output in preparation for Mars Sample Return, as well as to verify future datasets from ExoMars’ MOMA (Mars Organic Molecule Analyser) and Mars 2020’s SHERLOC instruments.

Methods: In-situ Investigations: Confocal Raman spectroscopy was carried out at the Carnegie Geophysical Laboratory, Washington D.C. to locate MMC inclusions in the martian meteorite Tissint. These MMC inclusions were then extracted using a focused ion beam instrument. The 100 nm thick MMC sample was then analysed by scanning tunneling x-ray microscopy x-ray analysis near edge structures (STXM-XANES) at the Diamond Light Source.

Bulk analyses: Soluble OM was extracted from triplicate samples of Lafayette and Nakhla (martian meteorites) using hexane, dichloromethane, and methanol. Extractions will be analysed using GC-MS and LC-MS at UoG. Hydrogen-pyrolysis will be carried out on the remaining material to extract refractory insoluble OM. In addition, samples of Jbilet Winselwan (CM2 chondrite) were treated with varying concentrations of perchlorate salts, prior to the extraction protocol, to investigate how exogenous OM is affected by oxidants during MS analyses.

Preliminary Results: Raman spectra confirm MMC presence in martian meteorites. These data suggest that immature labile OM may also be present in Tissint, and may be affected by laser heating during Raman spectroscopy scanning (Fig. 1). Our STXM-XANES data confirm presence of MMC, through aromatic, aliphatic and phenolic peaks (Figure 2). Bulk OM analysis are ongoing and preliminary results will be presented at the meeting.

Introduction: In an effort to improve the characterisation of Oxia Planum, selected as the Rosalind Franklin rover’s landing site partly due to the its extensive Noachian-era clay deposits [1, 2], an analysis of 4-band VNIR, Colour and Stereo Surface Imaging System (CaSSIS) [3] imagery is currently being undertaken.

CaSSIS, including co-analysis with CRISM and HiRISE colour imagery, was used to identify and map out three spectrally and morphologically distinct units at Oxia [3]. The two stratigraphically lower members are sub-units in Oxia’s clay-bearing unit, with the lower member showing metre scale fracturing and a spectral signature indicative of Fe/Mg-rich clay minerals, while the upper member shows decametre scale fracturing and a mixed Fe/Mg-rich clay mineral/olivine signature [1]. The upper part of the stratigraphy consists of an olivine-rich unit, detected at the edges of a delta fan in the SE of the rover’s landing ellipse [1].

While these members were initially identified using HiRISE colour imagery and had their mineralogy determined using CRISM [4], the incomplete coverage of the site with these data sets limits the mapping which can be carried out using them. CaSSIS, with its high resolution (~4.5m/pixel) and ability to image in up to 4 colour’s across the full width of each image, was used to correlate with and extend the existing mapping, as well as to optimise future planning of rover traverses to high priority surface targets.

Methods: Radiometrically and geometrically corrected images are initially band ratioed and combined into an RGB image, band ratioing being where the output of one colour band is divided by the output from another on a pixel by pixel basis. This allows CaSSIS images to be used to distinguish between the presence of ferrous and ferric minerals [5] which, given that the lower clay unit has a ferric component likely due to the presence of haematite/ferric oxides [2], while the other members have a ferrous component due to containing olivine [4], should make the three members distinguishable.

The band ratios (BR’s) used were NIR/PAN, PAN/BLU and PAN/NIR, with RED replacing NIR depending on which was available from a given CaSSIS image [6]. The former two ratios are sensitive to ferrous minerals and the latter one to ferrous minerals. Dark Object Subtraction (DOS) [7] was then applied to minimize the effects of atmospheric scatter partly caused by the presence of atmospheric dust. The members identified using the HiRISE colour imagery were then mapped with CaSSIS imagery to determine whether the CaSSIS BR’s could be used to distinguish the three members.

Results: From a visual inspection of the band ratioed imagery, as well as a look at the mean I/F values of the 3 members (figure 1), it can be seen that the two clay-bearing members are distinguishable from each other within the CaSSIS imagery. The lower member appears more ferric, with the value of the 3 BR’s more closely matching the two clay candidates though appearing significantly more ferric than would be expected. The upper member appears more ferrous, having BR’s more closely matching a mix of either of the clay candidates and olivine. The olivine-rich unit is not noticeably different from the upper member, visually or based on BR values.

Discussion: As the values of the PAN/BLU and RED/BLU BR for the upper and lower clay-bearing unit members are distinct, extension of the mapping of the two sub-units into other areas is possible. The apparent inability of CaSSIS to detect the olivine-rich member, as well as the lower member being more ferric than it should be, may be due to the DOS method not completely correcting for the presence of atmospheric dust. This is thought possible due to the high dust opacity at the time of imaging skewing the apparent ferric content of the image, masking the olivine’s signature. This will be addressed via repeat imaging of such affected areas over Oxia Planum.

BEERS: BENEFITS OF THE ESA EXPLORATION ROADMAP IN SOCIOECONOMICS

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Introduction:
The socio-economic benefits of space exploration have been demonstrated over many decades as downstream applications of related technologies and innovation in environmental management, health, urban development and electric vehicles among many others.

ESA’s European Exploration Envelope Programme (E3P) Roadmap is intended to secure Europe’s central role in global space exploration and consolidates their exploration activities across four Cornerstones: utilisation of the International Space Station and low Earth orbit activities, development of human activity beyond low Earth orbit (BLEO), robotic and human lunar exploration and Mars exploration.

The Benefits of the ESA Exploration Roadmap in Socioeconomics (BEERS) research team at the Open University has pioneered in its work for ESA, evaluating the socio-economic benefits of the E3P using a novel method for socio-economic analysis and visualisation to reveal the full benefits and impact of the Roadmap.

Approach:
ESA define four benefits categories by which E3P is evaluated:
- Science.
- Economic growth and competitiveness.
- New means to address Global Challenges/ Sustainable Development Goals (SDGs)
- Inspiration.

There are a number of approaches to modelling socio-economic benefits, however this study invokes a capitals evaluation framework which combines direct and indirect benefit analysis with a set of metrics from which Value Leverage may be estimated and built upon. It can allow identification of socio-economic benefits that are not easily measured in monetary terms. In this context the following capitals are used for analysis:
- Cultural/Symbolic Capital
- Educational Capital
- Environmental Capital
- Financial Capital
- Human Capital
- Organisational Capital
- Social Capital
- Technological Capital

These capitals were defined based on [1] and used as a framework for a two-fold stakeholder analysis that was combined with input/output logic modelling.

Methodology:
Phase 1 consisted of stakeholder interviews with ESA technical officers from each Cornerstone (n=9) We also interviewed representatives from ESA’s Education, SDGs and Industrial policy and space economy offices. The focus of these interviews was on their perspectives on the strength of impact on each capital. In addition, national (member state) delegates were interviewed (n=12) to ascertain their perceptions on their state’s priorities towards each capital. Responses were rated against a Likert scale (1 to 5, disagree to strongly agree) and visualised using radar plots (e.g. Figure 1).

Figure 1 Example of radar plot that visualises stakeholder-responses to each capital (here Cornerstone 4, ExoMars programme)

Phase 2 consisted of face to face stakeholder workshops (1 per Cornerstone) with ESA staff to identify long-term benefits and the activities/outputs that facilitate these, identify data sources for quantification and investigate perceptions on E3P’s impact on SDGs. In addition, industry representatives from those companies with formal interest in E3P were interviewed (Phase 1 methodology) (n=19, 11 individual companies).

The data from Phase 1 and 2 were combined into a single database in which to identify case studies for analysis and to use for the construction of logic models to demonstrate the outputs and outcomes from each Cornerstone activity.

Summary:
We present details of the methodology used in the BEERS study, and the preliminary results from the capitals analysis.

References:
COMMONPLACE MULTIPLE VOLCANIC ERUPTIONS ON MERCURY AND THEIR IMPLICATIONS

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**Introduction:**
The MESSENGER mission imaged high albedo red spots (now referred to as faculae) on the surface of Mercury [1-3]. Faculae show little relief apart from central rimless, non-circular depressions. They are interpreted to be volcanic vents surrounded by explosive volcanic deposits [1,2,4]. The vent within Agwo Facula is comprised of several vents inside a common rim [5] making it a compound volcanic vent [6]. There are many others (e.g., Fig 1).

![Fig 1: Example of a compound vent system on Mercury. Sinusoidal projection centred on the vent.](image)

We present here a larger study of all compound vent sites on Mercury, in which their internal structures are described and analysed.

**Methods:**
We used the high resolution MDIS images from the MESSENGER mission [7] to study faculae and vents previously identified by [8-11]. Where a vent structure was clearly resolved and had two or more immediately adjacent or overlapping vents, we classified it as compound.

In a few cases, where image resolution was sufficient, we used the cross-cutting relationships and relative internal roughness of each vent to infer relative timing: smoother surfaces being assumed to be older (blanketed by a thin layer of younger volcanic ejecta, or muted by thicker regolith).

**Results:**
There are 288 vents sites on Mercury, of which ~70% are compound vents.

There is no clear pattern to the global distribution of compound vents.

**Internal features:** Within most vent sites the dominant style of volcanism is explosive excavation. This includes newly-recognised features from our study: small-scale pits on the edges of the larger vents within a compound structure.

**Discussion:**
Previous work has shown that explosive activity on Mercury occurred over a long period (and possibly as recently as the Kuiperian 280 Ma) [10-12]. It is not possible to make estimates of the length of time individual vent sites were active, their small size and their rough appearance make impact crater statistics unreliable. The large proportion of compound vents suggests that the majority of vent sites erupted more than once probably over a prolonged period of time. This prolonged activity suggests that the dyke systems that presumably fed these vents must have been recharged with volatiles.

**Conclusion:**
A large proportion of explosive volcanic vents on Mercury are compound structures indicative of multiple eruption events at that site. This suggests that magma sources were long-lived and recurrent. Volatiles were replenished over time, either through magma recharge or assimilation. This has wide implications for the internal plumbing of these sites, suggesting that, once established, they can be long-lived. Further study by BepiColombo will provide more information on these structures and their implications for Mercury’s volatile rich volcanism.

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**References:**
GEOLOGICAL MAPPING OF THE DEBUSSY QUADRANGLE (H-14) OF MERCURY

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Introduction: Geological mapping of Mercury is crucial to understand the planet and to set the context for the BepiColombo mission for when it begins science operations in 2026 [1]. Geological mapping of the Debussy quadrangle (H-14) is underway (Fig. 1) as part of a program to map the entire planet at a scale of 1:3M [2-7].

Data and Methods: Mapping uses ArcGIS software. The base map is the 166 m/pixel global mosaic from MESSENGER’s Mercury Dual Imaging System [8]. The map projection used is Lambert Conformable Conic. Mapping follows both the Planmap [9] and USGS guidelines [10]. A 5° overlap with the adjacent quadrangles will enable correlation and comparison between maps.

Mapped Units and Features: Craters larger than 5 km have been outlined and ejecta extents marked for craters larger than 20 km. Craters are classified based on crater degradation using both three class [3] and five class [11] schemes enabling comparison between historical and current maps. Additionally, the Rembrandt impact basin and surroundings are being divided into units based on morphology, in a similar way to the larger Caloris basin.

The remaining surface area is being separated into plains units, ‘Smooth’, ‘Intermediate plains’, and ‘Intercrater plains’, that probably represent different generations of lava flows.

Linework is used to represent the structural features in the quadrangle. Lobate scarps [14], dominate the tectonics of the quadrangle, and formed due to the cooling and contraction of Mercury. Grabens have been mapped within the Rembrandt basin. Wrinkle ridges are found within the more recent plains units and crater infills.

A separate map layer for superficial units has been produced that includes ejecta rays, faculae postulated to be pyroclastic deposits [16], and large collections of hollows.

The map will provide context for further studies of the processes which have shaped the planet.

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Fig. 1. In progress geological map of the Debussy Quadrangle Mercury
SEARCHING FOR BIOALTERATION IN IMPACT GLASSES

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Introduction: Hydrothermal systems are considered to have played an essential role in the origin of life on Earth and, potentially, on other planets [1–4]. These systems are known to form within hypervelocity impact structures [1,5], making them a target for astrobiology. Such environments provide heat sources on otherwise cold planetary surfaces, creating habitable environments for microorganisms [3].

However, finding direct evidence for biospheres within impact structures has proven to be both challenging and contentious [e.g., 6]. One approach is to search for evidence of biologically mediated alteration of impact-generated glasses. Such features are evidence of the past presence of chemosynthetic microorganisms that ‘bore’ into rocks and minerals in search of energy and nutrients. Bioalteration of volcanic glass is common in submarine lavas, and found in ophiolites and greenstone belts up to 3.5 Ga old [7]. There are two main textures resulting from bioalteration in volcanic glasses: “granular” and “tubular” [8]. While the tubular type is the most visually striking, it is far less common than the granular type [7].

Micro- and nano-scale tubular features have been previously reported in impact-generated glasses from the Ries impact structure, where they have been suggested to be biogenic [1, 2] and/or abiotic pyroxene microfibers/microlites [3, 4, 5]. We are examining morphologically similar tubular and granular textures in impact-generated glasses from the Dellen (~141 Ma, 19 km) and Boltysh (~66 Ma, 24 km) impact structures, in order to determine if these features are biotic or abiotic in origin. Preliminary work has focused on optical morphological characterization, with follow-up work planned using detailed geochemical analyses.

Results: Approximately 15% of the Boltysh glass shows concentrations of very thin, curving, and apparently tubular features. The tubular features are typically curvilinear, helical, or convoluted, and often segmented. They are typically ~1 µm wide and up to 200 µm long. Tubules are absent from haloes around pyroxene crystals. The presence of plagioclase crystals does not seem to have the same effect on the density of tubules in the surrounding glass. Compared to host glass, the tubules are enriched in Fe and Mg. Two size fractions of tubules can be recognized: widths of < 1 µm and 1-2 µm. Glass surrounding the larger tubules has tubule-free haloes that are similar in appearance to those around large pyroxene crystals. Most tubules appear to be randomly oriented relative to each other. The exception is where they radiate from an iron sulphide nucleus, and these tubules appear to be straighter and their walls smoother. SEM images of the larger tubules show that some of them are hollow or infilled by clays. They are commonly segmented by fractures, and they yield electron backscatter diffraction (EBSD) patterns that index as clinopyroxene. Tubular features were far less common in Dellen impact glass than in the Boltysh glass. However, the Dellen sample showed several areas of granular alteration along the edges of perlitic fractures.

Discussion: This study has been motivated by the intriguing possibility that similar features in glasses from the Ries (~15 Ma, 24 km) impact structure may be biogenic [9,10]. However, results of our work are consistent with the tubular features being pyroxene microfibers/trichites, similar to those described at the Ries impact structure [11–13] and in volcanic glasses [e.g., 14]. While the morphologies seen here (curvilinear, helical, and convoluted) are atypical growth habits of crystallites, their chemical composition and crystal structure matches clinopyroxene. The tubule-free haloes around large pyroxene crystals and the larger tubules are suggestive of a chemical gradient where the Fe and Mg necessary for pyroxene crystal growth was obtained by depletion of nearby glass. Further work is needed to determine whether the granular textures observed in the Dellen glass are the result of biotic or abiotic processes.

Future work: Further work is planned using higher resolution techniques including transmission electron microscopy and atom probe tomography. We also plan comparative studies of other impact-generated and volcanic glasses. If results of subsequent work reveals chemical/isotopic signatures of biogenicity, it will strengthen the findings of [9,10], and pave the way for further studies into which types of impactites are most likely to host signs of former or extant life.

CARBONATE PRECIPITATION AND DISSOLUTION IN LAFAYETTE AND ITS EFFECTS ON THE EVOLUTION OF THE NAKHLITE FLUID.

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Introduction: The Martian nakhlites display unique carbonate-bearing alteration assemblages and show a variation in secondary phases which correlate to their depth and distance from the fluid source [1, 2, 3]. Lafayette hosts olivine fractures filled with siderite, ferric-serpentine, ferric-oxide and amorphous gel; and mesostasis areas with siderite and ferric serpentine. We identify carbonate dissolution textures that reveal details regarding the fluid’s evolution.

Methods: Two thin sections; one, from The Smithsonian, and one from The Field Museum, Chicago, were characterised using a FEI Quanta 650 FEG-SEM. Wafers suitable for STEM imagery were extracted using a FEI Quanta 200 FIB-SEM. STEM was performed using a Deben HAADF Anular SEM STEM detector with a FEI Siron 200 FEG-SEM. Fe-K XANES analysis was carried out using the I-18 and I-14 beamlines at Diamond Light Source, UK.

Dissolution Textures: There is a large difference in alteration between the two sections. Chicago shows little alteration, <5% of section, and minor carbonate, <1%. The Smithsonian shows a higher abundance of alteration, ~15%, and the largest abundance of SNC carbonate yet reported, ~4%.

Olivine-Hosted Carbonate shows evidence for incipient dissolution and replacement by thin veining within siderite grains (Fig. 1). Other areas show where the siderite grain’s boundary is unidentifiable, evidence of more extensive dissolution that had almost reached completion. In STEM Dark Field (DF) imagery there is no discrete phase boundary between the siderite and saponite and the less dense clay (darker contrast) can be seen replacing it. Ferric oxide microparticles were observed frequently within the saponite and around the carbonate boundary.

Mesostasis-Hosted Carbonate displays similar evidence to the olivine siderite (Fig. 2). Thin irregular veining, seen in the more pristine grains, as well as large-scale replacement textures are observed. In STEM DF we see subparallel veins of serpentine that are corroding and replacing the carbonate.

Compositions and Fe-K XANES: Olivine-hosted Ca-siderite has a composition of Mg$_{28}$Si$_{46.9-53}$Rh$_{19.2-24.2}$, and mesostasis-hosted Ca-Siderite has a composition of Mg$_{28}$Si$_{41.2-44.2}$S$_{0.7-0.7}$. Both are metastable [4]. XANES analysis reveals Fe$^{3+}$/Fe$^{2+}$ of up to 0.7 in the veined siderites.

Discussion: It is evident from the textures and XANES that carbonate dissolution and replacement by ferric clays has occurred. The finding of ~4% carbonate in one section but <1% in another suggests this has been extensive, though variable.

During carbonate precipitation (Stage 1) the fluid started as a carbonic acid, pH ~4. As the bicarbonate was depleted, the buffer system weakened and the pH increased to circumneutral conditions. Metastable compositions suggest this stage occurred rapidly.

Once the bicarbonate had been exhausted, dissolution takes over with the concurrent precipitation of ferric clays (Stage 2). During this stage, bicarbonate is introduced back into the system and could absorb H$_2$O, further increasing pH, before being flushed out by the abundance of water [3]. Over pH 5-7 the dissolution mechanism changes from proton-promoted to water hydrolysis reactions and the dissolution rates reach steady state [5], therefore, as the pH increased and temperature decreased, the precipitation of clays dominated over the dissolution of carbonate.

Conclusions: Carbonates within Lafayette have been dissolved and partially replaced by ferric clays. We have identified a large variation in dissolution textures within the carbonates. Changes in pH greatly affect carbonate dissolution rates and a varying pH in different micro-environments within the rock can possibly explain the variation in textures observed.

Figure 1 - (Left) BSE image of an olivine-hosted vein, Fe oxide can be seen arrowed towards the bottom of the image. (Right) STEM image of siderite-saponite boundary.

Figure 2 - (Left) BSE image of mesostasis alteration highlighting veining, (arrows) and more extensive alteration (box). (Right) STEM image of vein of mesostasis siderite.

RESULTS FROM THE SHORT-PERIOD (SP) SEISMOMETERS ON THE MARS INSIGHT MISSION


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Introduction: The Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission landed successfully on Mars on 26 November, 2018 in Elysium Planitia. InSight’s seismic payload, SEIS, includes the short-period (SP) sensors (fig. 1) optimized to investigate the martian seismic signal above a few Hz [1]. The two horizontal SPs acquired data during the cruise to Mars in a free-fall environment allowing the performance of the sensors to be determined and validating their noise requirements. The SP sensors on board the lander have been used to make an initial assessment of site dynamics prior to the full deployment of SEIS on a levelling platform, LVL allowing operation of its very-broad-band (VBB) sensors [2].

On-deck operations: The first SP data was acquired on Sol 4, with six additional sols of on-deck observations. SEIS was deployed on to the surface of Mars on Sol 24. Further SP data was recorded on the ground, with the VBB joining SP operations after SEIS levelling on sol 35.

The SPs characterised the seismic environment of the lander [4, 5] and the dynamical environment, observing consistent patterns in the transduced atmospheric environment. As well as environmental signals across the full seismic bandwidth, the SPs also were able to determine the tilt variation of the lander by tracking the position of the sensors’ proof mass over several sols indicating a very stable attitude of InSight up to SEIS deployment.

Off-deck observations: SEIS was lifted off the deck and lowered onto the surface of Mars on sol 24 at a site chosen to minimise as far as possible the seismic noise injection from the lander [6]. The introduced response from LVL [7], as well as transmission of the lander modes were subsequently observed allowing estimation of the transmission of seismic and aseismic signals though the regolith.

The SPs have subsequently observed candidate seismic events, both codetected with the VBB and above 10 Hz. The level of seismic activity to date can be used to estimate martian seismicity, and the potential active sources on the planet.

Conclusions: The dynamic environment at the InSight landing site has been observed during the deployment of a seismic payload on to the surface of Mars. This data provides an assessment of the first on-the-ground planetary seismic installation, as well as estimates of the performance on Mars that can be expected from on-the-deck and on-the-ground deployments, with and without additional wind and thermal shielding. The SPs are contributing to InSight’s determination of the seismicity of Mars, which in turn will lead to the first seismic investigation of the internal structure of another planet.

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TITLE: COMBINING MORPHOLOGICAL AND ORGANIC GEOCHEMICAL EVIDENCE FOR THE DETECTION OF FOSSILISED LIFE ON MARS

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Introduction: The procedures for detecting fossils on Mars can be derived from the methods that are already used in telluric paleobiology (Cady et al., 2003). In this approach, regions that are geologically conducive to the formation of fossils, are visually located, and then these sites can be inspected for morphological features that have sizes, shapes and distribution that might imply fossilised biology (Cady and Noffke, 2009; Westall et al., 2015). Morphological evidence of microfossils on its own is not a completely reliable biosignature (García Ruiz et al., 2002). However, evidence of biological activity may be implanted within the molecular and isotopic composition of organic compounds and this can also serve as a biosignature (Summons et al., 2008). Thus, combining both morphological with organo-geochemical evidence could strengthen any argument that a given geological feature could be associated with biological activity. The results from the simultaneous morphological and geochemical analysis of telluric geobiological structures on Earth could provide evidence that any comparable structures that may be observed on Mars, are potentially connected to biological activity, and therefore, may be suitable for collection for return to the Earth, for further analysis.

As a proof of concept, the distribution of the organic material that is associated with distinctive microtubules in the glassy volcaniclastic shards within tuff, that have been suggested to be putative ichnofossils (Banerjee and Muehlenbachs, 2003), were analysed by us.

X-ray photoelectron spectroscopy (XPS) of this sample indicated that the organic material was heterogeneously distributed, but the lack of spatial resolution meant that no specific correlation with the microtubular features could be ascertained, therefore a detailed distribution of mass spectral data was obtained with nanoSIMS, however, the mass fragment size of the organic compounds that could be confidently identified was limited to a maximum of 30 amu. Consequently, the Ionoptika J105 time of flight secondary ion mass spectrometer (ToFSIMS), with an argon gas cluster ion beam was used to detect and map the distribution of the higher molecular weight organic materials that are of interest as biosignatures, in the tuff sample. The large volume of data that was obtained by the J105 re-quired processing by principal component analysis, to highlight the variation between the organic compound composition in the different geological textures in the tuff. Pyrolysis Gas chromatography/mass spectrometry (py-GC/MS) data was used to obtain the identities of the molecules for some of the mass fragments that were obtained using the J105. This indicated that nitrogenous organic material occurred in regions of the sample that were rich in microtubule textures and in the surrounding microfractures (Sano et al., 2016).

These results demonstrated that the J105 ToF-SIMS combined with XPS and GC/MS analysis is able to match geomorphological features with their organic and inorganic composition at the µm scale, which may be a useful approach for the identification of fossilised life on Mars.

References:
MAPPING OF DYNAMIC CHANGE PHENOMENA ON MARS AND THEIR RELATIONSHIP TO UNDERLYING PHYSICAL CONSTRAINTS

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**Introduction:**
The Martian surface appears to be more changeable than originally perceived. Given that there is now more than forty Earth years since the first image from Mariner 4 was captured and more than 500,000 thousand images of the Martian surface\(^1\), a lot of dynamic phenomena have been observed, such as dust devils and dust devil tracks \(^2\), slope streaks\(^3\), araneiform (spiders)\(^4\), Swiss Cheese Terrain\(^5\) and at sufficiently high spatial resolution, and recurring slope lineae (RSLs)\(^6\) whose changes can only be observed in HiRISE 25-30cm images. Mapping these dynamic features globally allows us to obtain sufficient information to retrieve underlying physical constraints behind them, which can then contribute to understanding about Martian surface formation and their atmospheric interaction.

**Methods:**
With the volume of data and the small number of co-registered change datasets available, automatic or semi-automatic methods are preferred to help narrow down the number of candidates. In this research, a method based on autoencoder and anomaly detection \(^7\) had been used to narrow down putative change candidates over different Martian areas with multiple instruments. The method is applied to different Martian dynamical features and then applied to a better understanding of different science cases, such as dark slope streaks and non-seasonal polar changes. Orthorectified HRSC can be used to co-register and orthorectify CTX images \(^8\) to HRSC\(^9\) using either HRSC or CTX DTM\(^10\) if available are compared pair wise, with HRSC available from MY27 onwards and CTX from MY28 onwards available in finer resolution (until 6m/pixel) to HRSC’s finest of 12.5m/pixel.

**Results:**
Comparisons between CTX images allows us to better understand dark slope streak formation and disappearance by looking by solar longitude and season, year, and slope amongst others has been applied to areas around Nicholson Crater and Noctis Labyrinthus which has been the subject of previous research\(^11\)\(^12\).

In the dataset used in this research, no notable new impact craters over the South Pole or volcanic activities near the North Polar Layer Deposits where it has been claimed that volcanic cones may be present. Other reported changes in HiRISE are not easily observable at 6m CTX resolution. The results of this research suggest that physical constraints for appearance and disappearance of features such as slope, latitude, solar longitude, are in agreement with previous research results for slope streak research and crater counting \(^13\) and new impact crater findings \(^14\). Better resolution for an image doesn’t necessarily help in observation of Martian dynamical features, but certain changes are observable in different instrumental image due to their size and the resolution of the images.

**Summary and Conclusion:**
Mapping of dynamic change phenomena has been applied to different science cases with the help of an automatic method to reduce search time. Underlying physical constraints for different features discussed and compared to other Martian dynamic change phenomena

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**References:**

Figure 1 Green dots are the changes observed by Schreiner et al. (2017) and orange dots are the changes only observed in this research.
Numerical Simulations for Planetary Defence Missions

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Earth is continuously impacted by space debris and small asteroids, and, while large asteroid impacts are very rare, they have the potential to cause severe damage. If an asteroid of a few hundred meters is detected in advance to be on an Earth-colliding trajectory, an appropriate action can be taken to deflect its orbit. A kinetic impact [1] approach seems to be the most straightforward solution in deflecting an asteroid, however a technology demonstration has yet to be implemented. In response, the Asteroid Impact and Deflection Assesment (AIDA) collaboration [2], an international cooperation between Europe and the US, was created. NASA’s contribution, the Double Asteroid Redirection Test (DART), is set to launch in 2021 [3], and will be the first mission to test a controlled deflection of a Near-Earth binary asteroid, by impacting the spacecraft with the smaller component of the 65803 Didymos asteroid system [2, 3] and altering the binary orbit period.

In a high-velocity impact on an asteroid the change in momentum of the asteroid \( \Delta P \) can be amplified by the momentum of crater ejecta that exceeds the asteroid’s escape velocity. The total momentum change to the asteroid divided by the impactor momentum is a measure of deflection efficiency, commonly defined as \( \beta = \Delta P/(mU) \), where \( mU \) is the impactor momentum [4].

The DART mission, together with Earth-based observations, will measure the deflection of the Didymos secondary–Didymoon–and hence, \( \beta \). However, the amount by which crater ejecta enhances asteroid deflection, \( \beta - 1 \), has been found to vary significantly depending on the target asteroid’s properties and composition [e.g., 5, 6]. Without knowledge of the surface properties of the Didymos secondary, therefore, a measurement of \( \beta \) alone is not sufficient for the purpose of numerical model validation.

The European component of AIDA, Hera [7, 8], will better constrain Didymoon’s target properties. Hera will arrive at Didymoon several years after the DART impact and will enable detailed characterisation of the Didymoon volume and surface properties, as well as measure the DART impact outcome, such as the change in the binary system orbit and the size and morphology of the DART impact crater.

Here, we discuss the measurements made by Hera that should enable important asteroid surface material properties to be inferred from the DART impact crater size and morphology. We used the iSALE shock physics code [9, 10] to numerically model the DART impact and quantify the effects of the target material on the deflection. We found that impacts on targets with very different material properties (e.g. cohesive strength, porosity, internal friction) or structures (e.g. homogeneous, layered) can produce similar deflections, yet very different crater morphologies. Our results suggest that the Hera mission, which is still awaiting funding, is vital for numerical validation purposes and for creating a reproducible and well-understood planetary defence technique from the DART impact experiment.

The identification of potential martian biosignatures using a flow-through simulation chamber

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Introduction: The widespread detection of aqueously altered minerals [1,2], and Recurring Slope Lineae [3,4] suggests habitable environments may exist on Mars today, in the subsurface, or at some point during its history, either as a widespread hydrological cycle or in isolated and transient hydrothermal systems. If Mars was once capable of supporting life, these organisms may have left behind biosignatures that could be used as key indicators for life by future life detection missions, such as the European Space Agency’s (ESA) ExoMars rover. This work investigates how potential biosignatures could express themselves.

Methods: For this, abiotic and biotic experiments were conducted using a bench top flow-through reaction vessel to simulate the physical conditions that might be found in the martian subsurface. This flow-through system allows the continuous flow of fluids through the reaction chamber, which is more representative of the open systems found in nature. It also allows for the continuous sampling of fluids, meaning fluid chemistries can be monitored without affecting the water-rock ratio. A mixture of regolith simulant [5] and a modelled groundwater chemistry [6] were added to the reaction chamber to mimic the martian chemical environment. Biotic experiments were inoculated with a microbial community sub-cultured from sediments collected from the mudflats in the Colne estuary (Essex, UK) [7].

Abiotic and biotic experiments were conducted over 28 days, with fluid samples taken in intervals of one or three days for cell counts, ICP-OES and pH analysis. Silicate material was removed at the end of the experiments and dried in preparation for analysis.

FEG-SEM and Raman spectroscopy were used to identify morphological changes and secondary mineral formation in silicate samples. A combination of Raman spectroscopy, TOC, and GC-MS were used to identify organic material.

Results: Cell counts showed a clear increase in cell numbers over the duration of the biotic experiments, indicating continuous growth of the microbes within this simulated environment.

ICP-OES analysis of fluids showed no significant differences between abiotic and biotic experiments for ions at ppm concentrations (e.g. Na, Ca, K), but differences were observed for ions at ppb concentration. For example, Fe, Sn and P were only detected in biotic experiments. Sn and P are of particular interest as these trace elements we not supplied in the initial fluids, and are therefore, likely a result of microbial activity effecting the simulated environment.

SEM analysis of silicate grains from biotic experiments showed direct evidence of microbes and deposits on silicate grains (Fig. 1 and 2), which were not seen in abiotic experiments. It also showed some evidence of enhanced dissolution of grains under biotic conditions, which shows that microbial activity has affected the morphology of grain surfaces.

Summary: Initial results from these experiments show variations between abiotic and biotic experiments, indicating microbial activity has a detectable impact on the chemical environment, albeit at trace levels.

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MODELLING JUPITER’S DYNAMIC WEATHER LAYER: TURBULENCE, CLOUDS & MOIST CONVECTION

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Introduction: Jupiter’s weather layer is generally regarded as the region of the atmosphere where motions are influenced by a combination of interior heating, solar radiation and latent heat release by condensation of water. This layer is well known to be very active dynamically, with a wealth of intriguing cloud features such as the ubiquitous pattern of powerful zonal jets (including the super-rotating equatorial jet), coherent waves and vortices over a range of scales and turbulent motions on small scales. The origin of these features and their 3D structure and evolution have long been the subject of intense investigation, both in observations from Earth-based telescopes and spacecraft and through models of varying sophistication. Recent measurements from the Juno mission have significantly extended the scope of such observations, providing new insights into the weather layer in the polar regions and constraints on the likely depth to which the cloud level circulation extends into the deep interior. Such observations present some major challenges to modellers to account for the origin of various dynamical phenomena and how different scales of motion interact with each other within the weather layer.

In this presentation we will present an overview of recent results from a new and extended version of the Oxford Jupiter GCM (Young et al. 2019), which seeks to capture a reasonably complete representation of Jupiter’s weather layer circulations.

Numerical model: The current version of the model is based on the MITgem finite difference dynamical core, using a uniform latitude-longitude grid. Physical processes that are represented include solar and infrared radiative transfer (in a semi-gray formulation), interior heat sources, subgrid-scale turbulence, advective transport of condensable tracers (including H2O, NH3 and chemical conversion with H2S to NH4SH), cloud condensation (currently radiatively passive) and latent heat release, together with a simple representation of bottom “MHD” drag. The model has been run under Jovian conditions with 33 vertical levels between pressures of 10 hPa and 18 bars at horizontal resolutions ranging down to 0.7° in latitude and longitude (and down to 0.3° in a few cases). The model is typically run for up to 150,000 days to allow the deeper parts of the atmosphere to approach equilibrium.

Results: At a resolution of 0.7°, the model is able to demonstrate the development of a reasonably realistic set of almost rectilinear zonal jets, including a prograde equatorial jet. The most realistic jets in terms of amplitude and spacing are found in simulations with the highest spatial resolution and full representation of internal heating, latent heat release and a moist convection parameterization.

Fig. 1: Distribution of H2O clouds in a high resolution simulation of Jupiter’s weather layer at 0.3° resolution (Young et al. 2019).

Turbulent cascades of kinetic (KE) and potential (PE) energy result in the transfer of PE downscale and KE upscale, especially energizing the zonal jets. At the smallest scales, however, KE transfers are downscale, consistent with the conversion of PE to KE by baroclinic instability at scales comparable to the baroclinic Rossby radius of deformation. In this regard, the model simulations emulate recent observational measurements of cloud level energy exchanges (Young & Read 2017).

The simulated circulation also transports NH3 vapour in an intense upwelling at the equator, somewhat as found in recent Juno observations. Moist convection is also found to be most intense at high polar latitudes, again emulating recent findings by Juno.

Where the model is less successful is in representing the formation of compact oval eddies and coherent wave trains, although an analogue of Jupiter’s stratospheric Quasi-Quadrennial Oscillation is obtained.

These results will be presented and discussed in the light of recent and future observations and models.

References:
BURIED AND DEGRADED IMPACT CRATERS IN OXIA PLANUM, MARS

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Introduction: Oxia Planum will be the landing site of ‘Rosalind Franklin’ the ExoMars 2020 rover [1]. The region of the landing site is populated with impact craters, the distribution and degradation of which can tell us where and when burial and erosion processes have occurred. Larger craters could have hosted hydrothermal environments conducive to life [2] whilst small recent craters expose the near subsurface that can be accessed by the rover drill [3]. We created a map of all the impact craters larger than 500 meters in diameter in a 300 km by 150 km region around the landing site (Figure 1) and categorized the likelihood of different types of degradation morphologies occurring together.

Methodology: We developed a crater degradation classification scheme based on morphologies observable in the 5–6 m/pixel CTX in ArcGis10.1 using CTX data for the majority of craters, and THEMIS data overlain by the MOLA data for the identification of topographic subtleties of “ghost craters”.

The classification was based on four aspects of post-impact burial and degradation of impact crater morphology: (1) stratigraphic relation to the contemporary surface, (2) cross-section shape, (3) rim removal and, (4) ejecta morphology (figure 2).

We performed quantitative analysis to assess the likelihood of different degradation morphologies occurring together using the open-source Anaconda Software using the Python/R data science packages.

Results and Discussion: The most commonly occurring morphologies together were morphologies associated with the freshest impact scheme: upstanding rims, continuous ejecta, and a bowl shape (the largest crater having an area of 16 km). Craters with discontinuous ejecta blankets, bowl shapes, and upstanding rims are also commonly found together which may cause traversability hazards. Craters with embayed or removed rims have a large variety of cross-sectional shapes but flat craters are more likely to have infilled floors and embayed rims. Ghost craters are commonly associated with a removed rim and are underlying the clay unit making them the oldest in the mapping area. The distribution of these craters can be seen in the sample map sheet (figure 1).

Conclusions: We found that certain types of degradation morphology are found together and that our categorisation system can be used to quantitatively to assess the likelihood of different degradation features occurring together. These trends show that some degradation processes affect crater morphology homogenously but the spread in likelihood associations indicate that a variety of processes operate to degrade crater morphology and these can act heterogeneously across the different crater morphologies. We present this data as a map and GIS-ready dataset to aid the understanding of impact crater degradation and geological process at the transition between Arabia Terra and Chryse Planitia.

URANUS AND NEPTUNE IN THE MID-INFRARED: ATMOSPHERIC TEMPERATURES AND CIRCULATION INFERRED FROM THERMAL IMAGING

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Introduction:
We present results from mid-infrared imaging of Uranus and Neptune acquired using the VISIR instrument at the Very Large Telescope (VLT) in 2008, 2009, and 2018. Using a combination of inverse and forward modeling, we analyze and compare images at wavelengths sensitive to the upper troposphere and lower stratosphere to investigate the atmospheric structure and implied circulations. Finally, by comparing images taken over a decade apart, we assess potential temporal/seasonal changes in the thermal emission from each of the solar system’s ice giants.

Background:
Due to their cold temperatures and great distances, the ice giant planets are challenging targets in the mid-infrared. Only in recent decades have spatially-resolved ground-based observations been possible. Our best constraints on upper-tropospheric temperature as a function of latitude (and the dynamical calculations these imply) still come from the Voyager 2 IRIS measurements in the late 1980s, which observed Uranus near the solstice and Neptune in southern mid-spring. These measurements suggested cold mid-latitudes (indicating upwelling) and warm equator and poles (indicating subsidence) [1]. By the late 2000’s, ground-based thermal imaging revealed that the same basic upper-tropospheric pattern had persisted, despite the passage of an entire season on Uranus and visible changes in its polar cloud cover. However, ground-based thermal imaging sensitive to stratospheric hydrocarbons have since revealed unexpectedly different patterns.

Conclusions:
Uranus: In the case of Uranus, we find the data are consistent with little change (< 0.3 K) in the upper tropospheric temperature structure, extending the previous conclusions of Orton et al., 2015 [1] well past equinox, with only a subtle increase in temperature at the emerging north pole—a region of the planet that has never before been imaged in the mid-IR.

We investigate the nature of the stratospheric emission and demonstrate that the observed distribution appears related and potentially coupled to the underlying tropospheric emission six scale heights below. The observations are consistent with either mid-latitude heating or an enhanced abundance of acetylene. Considering potential mechanisms and additional observations, we favor a model of acetylene enrichment at mid-latitudes resulting from an extension of the upper-tropospheric circulation, which appears capable of transporting methane from the troposphere, through the cold trap, and into the stratosphere for subsequent photolysis to acetylene.

Neptune: Neptune, with its greater vertical mixing and dynamical activity shows potential changes in the stratospheric emission at mid-latitudes over the past decade.

Bibliography:
THE ASYMMETRY OF NATHAIR FACULA: A VOLCANOLOGIC MYSTERY ON MERCURY

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Introduction:
Nathair Facula is the largest and most spectrally-distinct of nearly 200 ‘bright red’ spots on Mercury’s surface, most of which are accepted to be deposits from explosive volcanic eruptions. Like most of Mercury’s faculae, it hosts a central pit (in this case about 40 km wide and over 3 km deep). However the centre of this facula does not coincide with the vent, but is displaced about 20 km northwards. This poses as-yet unresolved questions about the nature of the eruption mechanism. Furthermore, the vent area is almost certainly a ‘compound vent’ (Pegg et al., 2019) within which the locus of eruption has migrated between eruptive episodes, and it is unclear how the same asymmetry could be repeatedly engendered and reinforced by a series of eruptions rather than averaging out to a symmetrical distribution.

Nathair Facula:
The bright red spot that in 2018 received the formal name of Nathair Facula was formerly known by reference to nearby named impact craters as either NE Rachmaninoff or S Copland. Its radius was estimated to be 71 km by Kerber et al. (2011) on the basis of MESSENGER flyby images, but revised to 130 km by Thomas et al. (2014) who were able to use higher resolution colour images from MESSENGER’s orbital campaign (Fig. 1). As mapped by Wright et al. (2019) its radius is about 120 km (Fig. 2). Besse et al. (2019) used MESSENGER MASCS to analyse the radial dependence of normalized VIS slope, depth of the UV downturn and the normalized NIR slope from which they determined a radius of 140 km.

Such discrepancies are not surprising given that by their very nature faculae become fainter towards their outer edge, consistent with their origin from pyroclastic ejecta that has followed parabolic trajectories from its source. However, what is surprising is that although this facula is close to circular, its midpoint is offset northwards from the central vent complex, irrespective of whether the facula is defined by visual inspection or multispectral classification. A volcanological explanation is currently lacking.

References:
Besse, S., Barraud O., Doressoundiram, A., Cornet, T., Munoz, C., 2019, Explosive volcanism on Mercury: latest results from an in-depth analysis of the MASCS visible and near infrared observations, LPSC 50 #2451.

Fig 1 Nathair Facula as seen in exaggerated colour MESSENGER MDIS imagery.

Fig 2 Nathair Facula as shown on the quadrangle map of Wright et al. (2019).
TITLE: Longitudinal Variations in the Stratosphere of Uranus from the Spitzer Infrared Spectrometer

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Introduction: NASA’s Spitzer Infrared Spectrometer (IRS) acquired mid-infrared (5-37 μm) disc-averaged spectra of Uranus very near its equinox over 21.7 hours on 16th to 17th of December 2007. A global-mean spectrum was constructed from observations of multiple longitudes, spaced equally around the planet, and have provided the opportunity for the most comprehensive globally-averaged characterisation of Uranus’ temperature and composition ever obtained (Orton et al., 2014 a, b). In this work, we analyse the disc-averaged spectra at four separate longitudes to shed light on the discovery of longitudinal variability occurring in Uranus’ stratosphere during the 2007 equinox.

The composition and temperature structure of Uranus’ stratosphere is dominated by methane photolysis in the upper stratosphere (Moses et al., 2018). The complex hydrocarbons produced in these solar-driven reactions are the main trace gases present in the stratosphere and upper troposphere. These species are observable at mid-infrared wavelengths sensitive to altitudes between around one nanobar and two bars of pressure (Orton et al., 2014a).

Due to Uranus’ extremely high obliquity we can only clearly observe its longitudinal variation close to its equinox. The northern spring equinox occurred in December 2007 with the aforementioned Spitzer observations occurring just 10 days after. Due to a lack of spatial resolution, Uranus is treated as a point source and the resulting spectra are disc-averaged. The Spitzer data has been re-analysed using the most up to date pipeline available from NASA’s Spitzer Science Centre resulting in minor changes over the previous reduction.

Longitudinal Variation: We assess the variations in discrete channels sensitive to different emission features. The radiance’s inside each interval are averaged and compared to the mean of all four longitudes. Each instrument module is exposed at a different time causing a spread of data points across the multiple longitudes displayed in Figure 1.

We detect a variability of up to 15% at stratospheric altitudes sensitive to methane, ethane, and acetylene (~ 0.1 mbar). The tropospheric hydrogen-helium continuum exhibits a negligible variation of less than 2%, constraining the phenomenon to the stratosphere.

![Figure 1: Longitudinal variability of chemical species across 360° of Uranus. Standard errors displayed. 10% amplitude wavenumber-2 sinusoid displayed for reference.](image)

Conclusion: Building on the forward-modelling analysis of the global average study, we present full optimal estimation inversions (using the NEMESIS retrieval algorithm, Irwin et al., 2008) of the low-resolution spectra at each longitude to distinguish between thermal and compositional variability. The model suggests that variations can be explained solely by changes in stratospheric temperatures. This is compounded by results from high-resolution forward models constructed using the parameters retrieved from this assumption.

Observations from Keck II NIRCII in December 2007 (Sromovsky et al., 2009; de Pater et al., 2011) and VLT/VISIR in 2009 (Roman et al. in review) suggest possible links to these variations in the form of discrete meteorological features.

The James Webb Space Telescope, when it launches in 2021, will provide much improved spectral and spatial resolution needed in the mid-infrared band to provide definitive answers to the causes of the observed variation.

Bibliography:
Roman, M.T., et al., 2019, Icarus (in review)
DETECTING PRE-BIOSIGNATURES IN THE ATMOSPHERES OF EARTH-LIKE PLANETS AROUND OTHER STARS

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Abstract:
When we observe the first terrestrial exoplanet atmospheres, we expect to find planets at a wide range of geological conditions and evolution including planets that may be in the early stages of biological development or failed biospheres that reached only a certain point of pre-biotic chemistry.

Understanding the UV environment of the host star is particularly important for contextualizing the habitability of an exoplanet. Depending on the intensity, UV radiation can be both useful and harmful to life as we know it. UV radiation from 180 - 300 nm can inhibit photosynthesis and cause damage to DNA and other macromolecule damage [1]. However, these same wavelengths also drive several reactions thought necessary for the origin of life [2,4].

Figure 1: Ratio of a star’s UV spectral irradiance to solar spectral irradiance, FUV/Fo,sun at EUV (500-1000 Å) and FUV (1000-2000 Å) wavelengths. 500-1500 Å light dissociates N2, the first step toward forming HCN photochemically. FUV photons dissociate H2O, leading to hydroxyl radicals and free oxygen atoms, which rapidly destroy HCN. The dashed red line indicates where all main-sequence stellar quiescent emission lies. Stellar flares or atmospheric absorption may cause the spectrum to deviate from this line. From [3].

Molecules such as HCN, NH3, CH4, and C2H6 would be interesting to detect in an exoplanet atmosphere since they are known to be useful for key prebiotic chemical pathways. We find that some of these molecules could be produced abiotically in a CO2/CH4/H2 rich atmosphere with lighting and photochemistry (see Fig. 1; [3]). HCN, for example, is present at each of the initial photochemical reactions that produce lipids, amino acids and nucleosides, the three building blocks of life [2]. The formation of HCN in an N2-rich atmospheres requires first that the strong triple N≡N bond is broken, and then a further reactions to form HCN. These tasks can be accomplished via photochemistry, lightning, impacts, or volcanism. As well, the C/O ratio of the planet will greatly influence the likely dominate reactions in that planet’s atmosphere. We discuss the chemical mechanisms by which HCN can be formed and destroyed on rocky exoplanets with Earth-like N2 content and surface water inventories, varying the oxidation state of the dominant carbon-containing atmospheric species.

We finally examine the plausibility of detecting prebiotically interesting molecules, such as HCN, NH3, CH4, and C2H6 in an early-Earth type atmosphere around stars with different UV environments using early Earth, a flaring M dwarf, and a quiescent M dwarf as a range of host stellar types and UV environments.

References:


EUROPEAN INVOLVEMENT IN JAXA’S MARS MOONS EXPLORATION (MMX) SAMPLE RETURN MISSION TO THE MARTIAN MOONS

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Introduction:
JAXA’s ambitious robotic MMX mission is scheduled to launch in 2024 [1]. It will orbit Mars and its moons, and will collect ≥ 10g regolith material from Phobos before returning to Earth in 2029. The moons of Mars are low density and have spectra similar to D/C type asteroids. The aims of the mission include testing whether they are captured asteroids or formed after a giant impact into Mars. This in turn will allow a better understanding of the formation and evolution of terrestrial planets and their moons. Prior to sample collection, the mission will be in quasi-stable orbit around the moons, allowing the collection of data on their global mineralogy and geology. In addition, the moons are expected to have accumulated rocky material ejected from Mars, and so the returned material may also contain martian samples.

European Involvement: The French space agency CNES will provide a Near IR Spectrometer (MacrOmega) [2]. This instrument will be used to make near infra-red measurements up to the 4μm band, to look for evidence of water and organic material.

Following the success of the MASCOT rover on Hayabusa2 [3,4], the German Aerospace Center (DLR) and CNES will also collaborate with JAXA to contribute a rover to the MMX mission. The rover will house camera systems (a stereo navigation camera and two wheel-cameras), a Raman-spectrometer (RAX) and a radiometer (miniRAD) to make in-situ measurements on the moon’s surface.

Scope for determining meteoritic analogues: Calculations have shown that delivery of meteorites to Earth from Phobos and Deimos is possible [5], leading to the interesting idea that we may already have samples of Phobos or Deimos in our meteorite collections. Indeed, some researchers have suggested that the Kaidun meteorite may come from Phobos [6]. Whether we have these meteorites or not, for sure we have our collections meteorites that are dark coloured. Phobos and Deimos have dark spectral patterns that are reminiscent of dark/black meteorites, carbonaceous chondrites and ureilite meteorites.

Material from the surface of Phobos is likely to be regolith material, and likely to contain a variety of lithologies. Shock features may be expected (such features have recently been observed on carbonaceous type meteorites [7]). Carbonaceous chondrites are prime possibilities for Phobos analogues, especially dark, water rich CM and CI chondrites. However, there are other possibilities too. Goodrich et al have pointed out the spectral similarities of C-type asteroids to ureilite meteorites [8]. The water-rich brecciated martian meteorite Black Beauty (NWA 7034) may be another possible analogue.

In this presentation we will discuss meteorites that may be analogous to Phobos material and how we can make preliminary measurements using our meteorite collections.

References:
CONSTRaining the nature of Water: Rock interaction in nakhlites using trace element signatures of alteration minerals

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Introduction: Nakhlites are pyroxenites that sample a (several) lava flow(s) from the Amazonian period, ~1.3 Ga, on Mars [1-4]. Of all Martian meteorites, nakhlites are known to have the best evidence for fluid alteration, hosting a range of alteration minerals: hydrous Fe,Mg-silicates (clay minerals), carbonates, sulphates and halides that likely formed during brief aqueous subsurface events [5-7] as recently as ~680 Ma [8]. However, the sources of the fluids and mechanisms of alteration are not fully understood. The most comprehensive model suggests that the alteration resulted from an event mediated by a low-T brine derived from an impact-triggered hydrothermal cell [9]. However, such a model struggles to fully explain the variations in alteration mineral assemblages through the nakhlite pile, or to account for the role of dissolution and replacement reactions during alteration [6].

A complete understanding of alteration history is limited as the majority of interpretations are based primarily on the observation of hydrous Fe,Mg-silicates, and limited data exist on textures and chemistry of salt minerals. Trace element composition of alteration products in nakhlites are rarely reported [7], though this information is a viable means to constrain alteration events and fluid sources. Building upon recent 2D and 3D studies of secondary minerals in nakhlites [10,11] we have undertaken a non-destructive, synchrotron-based XRF trace element mapping study of a range of alteration phase assemblages in nakhlites.

Samples and Methods: Non-destructive XRF mapping was performed on the same Nakhl and Lafayette, fragments as [10,11] using beamline I18, Diamond Light Source, UK. Areas ~250 µm in size hosting specific alteration assemblages were located in unpolished, uncoated fragments and mapped at a range of energies selected to target specific elements of interest. With a beam spot-size of ~3 µm and a step size of 3 µm, XRF maps were acquired from areas that host halite, hydrous Fe,Mg-silicates, Fe,Mg-carbonates, Mn-carbonates, and/or sulphates.

Results: Hydrous Fe,Mg-silicates in both Nakhl and Lafayette contain trace amounts of Cr, Br, K and Rb. Zr and Pb are also observed and shown to form sub-micron sized baddeleyite inclusions within the phyllosilicates. Sulphates in Nakhl show the presence of Sr, Ba, Zn and Y, with some indications of chemical zonation of these elements. Carbonates reveal the most complex trace element patterns. In Lafayette, Fe,Mn-carbonates are associated with Ca, Ba, Sr, Zn and Cu. In Nakhl, carbonates tend to form two distinct groups with varying Mn content. Fe,Mg-carbonates reveal trace amounts of Y and La, while Mn-bearing carbonates are associated with Cl and Br, and exhibit patchy zonation of Ca, Cu, Zn and Ni. Halite in Nakhl contains elevated levels of Br but no K. Occasionally As is observed in ~5 µm patches within halite.

Implications for Fluid Alteration: Several implications for water:rock interaction in nakhlites can be made from the trace element composition of alteration minerals we have imaged. Different compositional patterns of carbonates between Nakhl and Lafayette, and even more complex differences observed within Nakhl, indicate that carbonates did not form in a single fluid flow event. For instance, the association of Zn and Cu with Mn in carbonates, but not with Fe is inconsistent with crystal-chemical expectations, and strongly suggests that Mn-carbonates formed separately, after the Fe,Mg-carbonates. Similarly, the presence of REE within Fe,Mg-carbonates but not Mn-carbonates can only be explained if these phases formed independently. Furthermore, the association of Cl and Br with Mn-carbonates, but not Fe,Mg-carbonates suggests that the salinity of the brine changed significantly during the alteration event. Altogether, our results suggest that the alteration of nakhlites occurred in multiple events or at least in separate stages.

HYDROTHERMAL ALTERATION IN THE FRANKENSTEIN GABBRO MARTIAN ANALOGUE: FIRST MODELS

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Introduction: Analogue studies can improve our understanding of alteration processes on Mars where information from Martian surface missions or Martian meteorites is incomplete. This especially applies to Martian hydrothermal systems within basaltic host rocks, which are not represented in the meteorite record and thus are not available for in-detail studies in Earth-based labs, even though such systems are thought to be a common by-product of impact cratering on Mars [e.g., 1, 2] and have been observed by orbiter [3] and surface missions [4].

We present results of an ongoing petrologic and modelling study of a terrestrial analogue, the Frankenstein gabbro (Germany), to predict hydrothermal alteration in basaltic host rocks on Mars. Our aim is to constrain the likely reaction paths by which primary magmatic minerals are replaced, and to specify the expected properties of the hydrothermal fluids. Such information may be crucial in the interpretation of data gathered by Martian surface missions. In a next step, we aim to assess fluid habitability and identify mineral assemblages indicating the former presence of hydrothermal fluids suitable for potential Martian life, in order to inform the selection of sampling sites for future sample return missions.

The Frankenstein Gabbro. We use a gabbro from the Frankenstein massif in the Odenwald Mountains, Germany. This rock – chemically equivalent to basalt – formed in a magmatic arc setting at ~360 Ma BP [e.g., 5], and experienced at least three localized events of hydrothermal alteration at 170–180 Ma BP, 138 ± 8 Ma BP, and ~60 Ma BP [6, 7]. We focus on the 138 ± 8 Ma BP event, which is associated with hairline fault planes and veinlets with a complex secondary mineralogy. Our previous investigations [8] show a strong small-scale variability of mineral formation, depending on host minerals and water/rock ratio, a feature also seen in the hydrothermally-altered nakhlite group of Martian meteorites [e.g., 9].

Methods: Following our mineralogical characterization of Frankenstein gabbro samples [8], we use the CHIM-XPT thermochemical modelling software to reconstruct mineral reaction paths [10]. As input, we use previously published XRF bulk rock data [11], EMP data of single minerals, and a starting fluid based on observed mineral quantities and calculated element budgets of mineral replacement reactions.

Results: Initial results are summarized in Fig. 1, showing calculated secondary mineral assemblages for bulk rock, a pure plagioclase host, and a pure clinopyroxene host, at high and low water/rock ratios.

Discussion & Outlook: A trend seen in all models is the diminishing importance of chlorite as W/R decreases, with chlorite generally dominating at W/R > 10.000. This is consistent with observed chlorite-dominated mineral assemblages in Frankenstein gabbro fault planes, for which a high W/R is expected. The models thus show potential to match and inform petrologic observations. However, several important minerals predicted in the models (e.g., carpholite, zeolites) are not found in the Frankenstein alteration assemblage, while others are not expected to form at the modelled conditions (e.g., diopside [12]). Our next step will be to refine the models before applying them to Mars.

Biogeochemical Nutrient Dynamics and Microbial Communities in the Atacama Desert, A Mars Analog

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Abstract:

I. Nitrate is common in Mars sediments owing to long-term atmospheric photolysis, oxidation, and potentially, impact shock heating. The Atacama Desert in Chile, which is the driest region on Earth and rich in nitrate deposits, is used as a Mars analog in this study to explore the potential effects of high nitrate levels on growth of extremophilic ecosystems. Seven study sites sampled across an aridity gradient in the Atacama Desert were categorized into 3 clusters-hyperarid, middle, and arid sites-as defined by essential soil physical and chemical properties. Intriguingly, the distribution of nitrate concentrations in the shallow subsurface suggests that the buildup of nitrate is not solely controlled by precipitation. Correlations of nitrate with SiO$_2$/Al$_2$O$_3$ and grain sizes suggest that sedimentation rates may also be important in controlling nitrate distribution. At arid sites receiving more than 10 mm/yr precipitation, rainfall shows a stronger impact on biomass than nitrate does. However, high nitrate to organic carbon ratios are generally beneficial to N assimilation, as evidenced both by soil geochemistry and enriched culturing experiments. This study suggests that even in the absence of precipitation, nitrate levels on a more recent, hyperarid Mars could be sufficiently high to benefit potentially extant Martian microorganisms.

II. With annual precipitation less than 20 mm and extreme UV intensity, the Atacama Desert in Northern Chile has long been utilized as an analogue for recent Mars. In these hyperarid environments, water and biomass are extremely limited, and thus it becomes difficult to generate a full picture of biogeochemical phosphorus dynamics. To address this problem as comprehensively as possible, we sampled soils from five Atacama study sites and conducted a variety of mineralogical, meteorological, geographic, geochemical, hydrochemical, isotope, cell culture, and molecular biological analyses. We found that high sedimentation rates decrease the relative size of the organic phosphorus pool, which appears to hinder extremophiles. Phosphoenzyme and pathway prediction analyses imply that inorganic pyrophosphatase is the most likely catalytic agent to cycle P in these environments, and this process will rapidly overprint other P utilization strategies. In these soils, the biogenic $\delta^{18}$O signatures of the soil phosphate ($\delta^{18}$PO$_4^{3-}$) can slowly overprint lithogenic $\delta^{18}$PO$_4^{3-}$ values over a timescale of tens to hundreds of millions of years when annual precipitation is more than 10 mm. The $\delta^{18}$PO$_4^{3-}$ of calcium-bound phosphate minerals seems to preserve the $\delta^{18}$O signature of the water used for biogeochemical P cycling, pointing towards sporadic rainfall and gypsum minerals as key moisture sources. Where precipitation is less than 2 mm biological cycling is restricted and bedrock $\delta^{18}$PO$_4^{3-}$ values are preserved. This study demonstrates the utility of $\delta^{18}$PO$_4^{3-}$ values as indicative of biogeochemical cycling and hydrodynamics in an extremely dry Mars-analogue environment.

III. Salar de Llamara is a Mars-analogous athalassohaline endorheic basin driven by groundwater upwelling, leading to perennial saline lakes. The ecosystem in this basin undergoes extreme environmental stress resulting from high evaporation rates, hypersalinity, hyperaridity, and strong ultraviolet (UV) irradiation. Soils were removed from a water-mud interface, shore surface evaporitic crust, and shore mud of Laguna Llamara for ionic analyses, bacterial community composition, and meta-analyses of bacterial phylogenetic diversity and metabolic pathway predictions using sequence data from previous studies (Rasuk et al. 2014, 2016). Chloride, sulfate, sodium, and calcium were the most concentrated ions, indicating gypsum and halite are the primary end members of these evaporites. The predominant bacterial taxa were Gammaproteobacteria, Alphaproteobacteria, Bacteroidetes, Cyanobacteria, Planctomycetes, and Verrucomicrobia. Strikingly, Cyanobacteria were found to be significantly more abundant within communities than observed in previous studies in Salar de Llamara and other salt flats. Identified bacteria were predominantly halophilic and known to be resistant to high osmotic stress. Anaerobic pathways, photoregulatory bioreaction, hydrocarbon oxidation and assimilation, and sulfate/nitrate reduction and assimilation pathways were predicted to be abundant in the identified microbial communities. This study provides insights into microbial compositions and functions of different microniches in terrestrial hypersaline environments and on Mars.
Methane production by *Methanoculleus marisnigri* in a simulated martian subsurface environment


**Introduction:**

Methane has been detected in the atmosphere of Mars by a suite of instruments including Earth-based telescopes [1, 2], orbiters in martian orbit [3] and *in situ* by the surface rover Curiosity (MSL, NASA) [4, 5]. However, recent non-detections reported by the Trace Gas Orbiter (TGO) suggest the gas may only be present at extremely low concentrations (<0.05 ppb) [6], if at all. The average abundance reported, when detected, is extremely low (~10 ppb) compared to methane in the Earth’s atmosphere (~1800 ppb). Most methane present in the atmosphere of Earth is produced by methanogenic archaea located in oxygen-free environments (e.g. the subsurface) [7, 8]. The potential sources of methane in the martian atmosphere are unknown but could include volcanism, meteoritic infall, degradation of surface organics, serpentinitisation and subsurface microbiology. However, volcanism, meteorites and organic degradation have been all but ruled out as potential sources as they don’t reconcile the variability in the data [5, 9, 10]. This project aims to quantify methane production in a simulated martian subsurface environment to determine if methane production by microbial sources can reconcile with reported abundances. Subsurface microbiology is a processes which would occur in the near-surface subsurface of Mars, between ~10 and ~600 m. At these depths temperatures could vary between 160 K to 350 K (~110 to 80°C) [11], with temperature increasing as a function of depth and rock type. Temperatures would also be much more stable at any given depth. Pressure would also increase as a function of depth and in the upper kilometre could range from 1 bar to 100 bar [11]. Described here is a novel system and methodology designed to operate in the temperature and pressure ranges of near-surface subsurface Mars continuously and allow for the growth of methanogens in these conditions. This unique approach to anaerobic microbiology allows for methanogenic archaea, which produce methane, to be grown and for headspace gases to be continuously sampled without altering the experimental conditions of the growing chamber.

**Microbial methods:**

*Methanoculleus marisnigri*, a methanogenic archaea, was selected as the organism to be grown during this experiment. 1 ml of cell stock at a concentration of ~10^9 or 10^9 cells per ml was added to 9 ml of fresh media, which is dispensed into the growth chamber of the manifold. An anaerobic chamber is used to ensure media and cells remain oxygen-free. *M. marisnigri* is a hydrogenotrophic methanogen which utilises hydrogen as an electron donor and carbon dioxide as an electron acceptor. Sources of both have been hypothesised to be present within the subsurface of Mars [12, 13], along with water [14] and other key nutrients [13]. Temperatures of 15, 25 and 35°C were selected as the growth temperatures because 25°C is optimum for *M. marisnigri*. Pressures of 1, 10, 30 and 60 bar were chosen to represent the depths of approximately 10, 100, 300 and 600 m. Pressures are achieved using 1 bar of CO2:H2 (20:80 v/v), with overpressure provided by N2.

Methane concentration is measured from headspace gases separated from the growth chamber, and then analysed using gas chromatography. Gas standards will be used to determine concentrations.

**Simulation:**

The temperature and pressure combinations of the near-surface of subsurface Mars have been simulated using a stainless steel manifold (Swagelok, UK). A double-ended stainless steel sample container with a stainless steel quarter turn valve at each end acts as the growth chamber of the manifold. Multiple growth chambers are aligned and attached at one end along a stainless steel gas inlet arm in two groups of three. A small length of stainless steel tubing (3/8 inch inner diameter) is attached to the other end of each growth chamber followed by another quarter turn valve, which acts as the gas sampling section of the manifold. Dedicated gas inlet and gas outlet valves allow for controlled addition and removal of gases within the manifold ensuring that the correct gas compositions can be achieved. The manifold was built in duplicate. The manifold is small enough to be placed into an incubator set to one of the experimental temperatures.

**Results:**

Preliminary results show that the attenuation time of the stainless steel, the least thermally conductive component of the entire system, was approximately half an hour, suggesting that the system will reach the desired temperature in only a small fraction of time compared to the length of the experiment. Initial growth curves, in ideal conditions including glass
serum vials, suggest a lag phase of approximately 10 days, followed by two weeks of exponential growth before stationary phase is entered. Therefore, experiments are run for four weeks at each temperature and pressure combination. Additional results on preliminary experiments, such as the effect of pressure on the pH of the media, will be presented along with initial results of the first few experimental runs in the manifold.

References:
FORMATION CONDITIONS OF SILICA-RICH IGNEOUS RIMS AROUND CHONDRULES IN CR CHONDrites: AN EXPERIMENTAL APPROACH.

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Introduction: The CR (Renazzo-like) carbonaceous chondrites have remained relatively unaltered since their formation (~4.6 Byrs ago) and therefore contain evidence of protoplanetary disk processes [1]. Many type I (FeO-poor) porphyritic chondrules in CR chondrites are surrounded by igneous rims, typically consisting of low-Ca and high-Ca pyroxene, ± Fe,Ni metal, ± plagioclase ± olivine ± glass, and primary silica [1]. Igneous rims provide insight into chondrule formation mechanisms through indicating that chondrules experienced multiple heating episodes [3]. Previous studies of igneous rims from ordinary (O) and C chondrites [2-6, 7] have suggested they formed as a result of dust particles accreting onto the surface of solidified chondrules followed by melting (Fig.1a). However, for silica-rich rims around CR chondrules, the mechanism proposed is not so clear. Various formation mechanisms have been proposed for silica-rich rim formation, including direct condensation of SiO-rich gas onto the outer zones of molten chondrules (Fig.1b)[8].

![Figure 1: Accretion versus condensation origin for igneous rims. (a) The generally accepted accretion formation model for igneous rims. (b) Gas-melt condensation into chondrule melt followed by cooling, as proposed by [8] for silica-rich rim formation.](image)

Overall, little is known and agreed upon about the origin and formation of silica-rich rims (e.g., accretion vs condensation formation mechanisms). In the accretion model, rim accretion, is suggested to occur at high temperature but no exact values have been suggested. We aim to define the formation conditions of silica-rich rims by reproducing the texture, mineral compositions, and silica polymorphs present in natural rims using experimental analogues. Peak temperature (T) information can be determined using silica, as several stable polymorphs exist below 1700°C. The presence of particular polymorphs within a rim can therefore inform on the rim’s thermal history thus giving quantitative constraints on its formation.

Methods: We are studying silica-rich rims in 6 CR chondrites (QUE 99177, MET 00426, EET 92062, LAP 04516, GRA 95229 and EET 92042).

Experiments use a Deltech one-atmosphere furnace. Starting materials are prepared from a dry powder mix of oxides (SiO₂, MgO, TiO₂, Al₂O₃, Na₂O, and CaO) as outlined by [9]. The bulk composition of the starting material to produce an analogous composition of silica-rich rims in CR chondrites was obtained from [8].

Both natural and experimental samples are analysed using the JEOL JSM-6400 SEM and the JEOL JXA-8530F electron microprobe. Silica polymorphs are identified using a Horiba XploRA.

Preliminary results: Experiments conducted at a peak T of 1360°C with cooling rates between 30-90°C/hr exhibit a similar mineralogy and texture to natural silica-rich rims. These cooling rates are similar to those predicted in the shock wave and impact jetting models of chondrule formation [10-11].

Cristobalite is the dominant polymorph in both natural and experimental samples. This is unexpected because the silica phase diagram [12] shows that tridymite (stable from ~857-1470°C), not cristobalite (>1470°C) should be present at this peak T. This suggests either that the tridymite/cristobalite phase boundary on the silica phase diagram [12] is not accurate, or cristobalite is forming metastably. In either case, previous studies have assumed that the presence of cristobalite indicates a peak T ≥1470°C. Our experiments indicate that lower peak T’s are permissible.

Magmatic segregation and volcanism on Io

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**Introduction:** Within our solar system, tidal heating powers Enceladus’ cryovolcanic faults, sustains Europa's potentially life-harbouring sub-surface ocean, and drives Io’s volcanism. How tidal heating leads to such diverse features that are so different to those of terrestrial planets is unclear. Mantle convection dominates heat transport in the terrestrial planets but, in the case of Io, is inconsistent with the observed surface heat flux [1]. This surface heat flux is emitted by Io’s globally distributed volcanos, a process referred to as ‘heat-piping’ [2]. This observable process makes Io an ideal case study for investigating how tidal heating controls interior structure and dynamics.

**Observational constraints:** Io has a global average eruption rate of 0.5–1.5 cm/yr [vol/area/time] [3]. Electromagnetic induction models indicate the presence of a ~20% melt fraction layer within Io over a 50 km thickness [4] — a layer that would be unable to support elastic stress. Considering this together with the abundant volcanism, we might expect Io’s near surface to be weak. However, Io’s mountains, up to 17.5 km tall, require the support of a thick, elastic layer [5], estimated to be at least 50 km thick [6]. Any model of Io’s interior must reconcile these apparently contradictory observations [2, 7].

![Figure 1: Schematic of the model for Io.](image1)

**Model description:** Our model is based on conservation equations for mass and energy. In the mantle, temperature is at the melting point and heat transport occurs solely by magmatic transport of latent heat, with downward flow of solid balancing upward flow of magma (fig.1). In the crust, a volcanic plumbing system continues to transport magma and latent heat upwards. The temperature drop to the surface also drives a conductive heat flux, while the downwelling solid crust transports the cold surface temperature inwards [7]. Emplacement (solidification) of magma from the plumbing system heats the crust, promoting conduction at the expense of volcanic heat loss.

**Results:** Heat transport by magmatism is efficient: the full tidal heating input of ~10^14W [8] can be removed at steady state with relatively low melt fractions (fig.2). Magmatic emplacement into Io’s crust controls crustal thickness: high emplacement rates produce thin conducting crusts, and low emplacement rates produce extremely thick crusts. Inferred observations of a high melt fraction region beneath the crust can be explained as a decompacting boundary layer.

Hematite through the eyes of the ExoMars 2020 Rover Rosalind Franklin: Simulating mineral identification with the PanCam WAC multispectral filters

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**Introduction:** We present a pipeline for evaluating the ability of PanCam to discriminate one particular mineral species against a defined set of background materials. We demonstrate the pipeline for the mineral hematite, an iron oxide indicative of changes in oxidation conditions, with implications for past habitability, and which has been one of the targets of interest for the Curiosity rover at Vera Rubin Ridge [1,2].

**PanCam:** PanCam [3] is the mast-mounted colour-stereo panoramic camera system for the ExoMars 2020 Rosalind Franklin rover [4], with an objective of visual geological characterisation, focusing in particular on signatures of ancient habitats. PanCam will measure the VNIR (visible/near-infrared, 380nm - 1100nm) spectral reflectance of surfaces with a multispectral suite of 12 narrowband filters [5]. The VNIR features of the expected surface mineralogy are mostly attributed to the oxidation state of iron, as the dominant transition metal [6]. The transmission profiles of the PanCam filter set were optimized for identifying a broad selection of minerals, expected to be encountered by Rosalind Franklin, as detailed by Cousins et al. [5]. This process considered the ability of a candidate set of filter profiles to reconstruct each of a set of mineral reflectance spectrum by linear interpolation, and also to distinguish one group of minerals against another, such as the set of phyllosilicates against the set of sulfates, via a set of 5 spectral parameters (algebraic operations between spectral bands).

**Problem Statement:** Now that the design and manufacture of PanCam is complete, there is an opportunity to further explore the spectral capabilities of the complete system. The next step is to consider the discrimination of a specific mineral species, as opposed to an entire set, against arbitrary collections of other species, as opposed to all other species, across a broad space of spectral parameters. In this study, we consider the identification of the specific mineral hematite, in contrast to the set of Fe/Mg phyllosilicate minerals expected at the selected Oxia Planum landing site [8,9], and models of martian dust [10].

**Method:** To perform this study, a pipeline has been developed with the intention of building a reproducible and distributable method, for studying arbitrary imaging systems, target mineral species, and background material sets. To this end, the pipeline consists of the following components:

1. **Mineral Database:** the Western Washington Vis-NIR Database [11] has been used as an interface to a collection of spectral libraries, including the USGS speclib06 [12], and the Uni. Winnipeg HOSERlab databases [13]. The extraction pipeline involves choosing a species from a mineral group, importing the multiple samples available per species, and interpolation and truncation to the range 380 nm – 1100 nm, Δλ=1 nm.

2. **Instrument Model:** the sampling of the reflectance spectra of PanCam, including instrument noise, is simulated under typical Mars illumination conditions, computed using a comprehensive software simulator developed by [14], with the current status of the software also reported here.

3. **Spectral Parameters:** are calculated according to the methods developed for the CRISM orbital hyperspectral imager, presented by [15,16]. Where the central wavelengths of the PanCam filter suite do not match those available for CRISM, substitutes are explored.

4. **Visualization:** in addition to plotting the computed spectral parameters, to evaluate the quantitative discrimination of hematite against a background, the success of the spectral parameter as a qualitative tool can also investigated, in terms of the target-background the contrast achieved in a 2D image. This is achieved by synthesizing spatial scenes of the target and background, via the spectral simulation software [14], and by processing the resultant images through the ExoSpec toolkit, a multispectral image analysis software package for ENVI, developed by the PanCam science team [17].

**Summary and Future Work:** In this work we demonstrate the ability of PanCam to discriminate hematite against a background set of materials representative of Oxia Planum, by simulating the multispectral response of the instrument, and exploring spectral parameter combinations. The method can be extended to investigate the response of comparative instruments, such as Mastcam and Mastcam-Z, and of the Aberystwyth University PanCam Emulator, AUPE, and to explore any target mineral against any background set for which data is available.

Chondrule formation and mixing in the early Solar System: insights from Ni isotope compositions of chondrules

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Chondrules are melt droplets which cooled in space to form spheroids. They are abundant, averaging 65% by volume in chondritic meteorites, and give chondrites their name. They also formed very early, within the first few million years of Solar System evolution [1]. Yet despite their clear significance and 200 years of study [e.g. 2,3], their origins remain speculative.

Since chondrules were first identified as having high temperature origins in space [3] several mechanisms have been proposed to explain their formation including: models which form chondrules in planetesimal collisions [4], melting due to proximity to the young Sun [5], and, melting of dust ball precursors by nebula shock waves [6], possibly forming self-gravitating clouds as an initial stage planetesimal accretion [7,8]. Chondrules represent a molten mass of material greater than that of Mars, thus, a process releasing considerable energy is required. Therefore, their formation mechanism must have been a significant early Solar System process. In addition, the relationship between chondrules and their host meteorites is not always clear and some chondrules may have been redistributed after their formation [e.g. 9]. As such, chondrules represent an important and potentially useful tool for investigating not only the conditions of the early Solar System during their formation, but also mixing between different regions of the Solar System. However, their formation, and subsequent redistribution, remains unresolved and highly debated.

The composition of Ni isotopes in chondrules offers an attractive possibility for study. Nickel is a moderately volatile, moderately siderophile element and is abundant most meteorites [10]. Nickel is also abundant in many chondrules which allows for high precision isotope compositions to be collected. In addition, the Ni isotope composition of meteorites is variable due to the incorporation different proportions of carrier phases of nucleosynthetic anomalies [e.g. 11]. Therefore, different regions of the early Solar System have characteristic Ni isotope compositions which allows for mixing of material to be traced. Importantly, the Ni isotope anomalies of bulk meteorites are correlated with other Fe-peak elements for example, Cr and Ti [e.g. 11,12,13]. Previous studies have documented the distribution of Ni isotope anomalies in meteorites [11,14,15,16,17]. Therefore, measurement of Ni isotope compositions of chondrules will allow for relationships between host meteorites and chondrules to be examined.

Preliminary Ni isotope data for chondrules will be presented. These compositions will offer insight into the mechanism of chondrule formation and the extent of mixing between different regions of the early Solar System.

References
Investigating the isotopic data reveal a clear link between these four hydrated chondrite groups (CO-CM-CY) and enigmatic Fe-bearing periclase [(Mg/Fe)O] and a range of magnetite morphologies (Ikeda, 1992; King et al., 2019). Their reconstructed geological history records an initial period of intense (CM-like) aqueous alteration, resulting in the secondary replacement of (almost) the entire anhydrous silicate content and thus the formation of pseudomorphic chondrules under low-temperature (<150°C) alteration. This was followed by, or transitioned into, a short period of thermal metamorphism at temperatures >500°C (Akai, 1992; Ikeda, 1992; King et al., 2019). Isotopically, the CY chondrites form an extension of the CO-CM mixing line (Fig.1), plotting with the same slope (and δ18O intercept) but at heavier, 18O-enriched compositions – potentially implying the CYs accreted more water than the CMs, whilst forming from the same or a nearby region of the disk. Alternatively, their 18O enriched compositions could reflect the action of thermal metamorphism which appears to result in a preferential loss of isotopically light water and the formation of heavy solids (Valley et al., 1986; Clayton and Mayeda, 1999).

18O-poor micrometeorites:
Finally, among the micrometeorite flux an enigmatic group of cosmic spherules with an anomalous 18O-poor isotopic composition were previously identified (Yada et al., 2005; Suavet et al., 2010; van Ginneken et al., 2017). However, their parent body petrographic properties remained unknown. New analyses on unmelted micrometeorites resolved their pre-atmospheric parent body texture, demonstrating a connection to matrix-rich pseudomorphic chondrule-bearing hydrated meteorites (Suttle and Folco, 2019). Furthermore, the O-isotopic composition of these unmelted micrometeorites demonstrated that they form a further heavy extension to the growing CO-CM-CY oxygen isotopic mixing line (Fig.1). While previous studies (Suavet et al., 2010) have shown that atmospheric entry can affect the isotopic composition of heavily altered cosmic spherules, unmelted micrometeorites are unaffected.

Conclusions:
Petrographic and isotopic data reveal a clear link between these four hydrated chondrite groups (CO-CM-CY-18O-poor micrometeorites). They are closely related containing progressively heavier 18O-enriched compositions, tracing proportionally higher initial accreted water contents and/or more advanced thermal metamorphic histories.

Introduction:
The CO chondrites share a close petrographic relationship with the CM chondrites forming a clan united by similar chondrule properties, isotopic signatures and volatile element abundances (Kallmeyn and Wasson, 1981; Schrader and Davidson, 2017; Alexander et al., 2018). Their O-isotopic signatures (Fig.1) define a single trendline with a slope of ~0.7 (and a δ18O intercept of -4.23‰, Clayton and Mayeda, 1999; Greenwood et al., 2019). While the CO chondrites are anhydrous containing variable proportions of crystalline and amorphous silicate within their fine-grained matrix (Alexander et al., 2018), the CM chondrites are hydrated and contain high phyllosilicate contents (60-90 vol%, Howard et al., 2015). The two groups thus differ primarily in their accreted water content (minimal vs. significant) and this subsequently controlled their later parent body alteration environments (Marrocchi et al., 2018; Howard and Zanda, 2019).

From an isotopic perspective, the shared CO-CM trendline reflects a close genetic relationship potentially representing formation within the same region of the protoplanetary disk (Schrader and Davidson, 2017). Furthermore, their accretion histories may be best explained by a simple two-part mixing between isotopic reservoirs with an inner 18O-rich solar-like silicate reservoir upon which additions from a cold outer 18O-rich volatile water-ice component were added (Clayton and Mayeda, 1999; Schrader and Davidson, 2017; Alexander et al., 2018). This could reflect an inward migrating snowline moving through the CM chondrule forming region after the CO parent body had accreted (Chaumard et al., 2018).

A new hydrated chondrite group (CYs):
Building upon this evolving picture of planetesimal formation, a new chondrite group appear to be related to the CO-CM clan. Recently King et al., (2019) re-examined the CY chondrite group, previously proposed by Ikeda (1992). Most of these meteorites lack chondrules and are thus derived from intensely altered asteroids. They are dominated by dehydrated phyllosilicate (partially recrystallized as olivine) after the thermal decomposition of Fe/Mg-serpentines. However, they retain a minor coarse-grained phyllosilicate component as well as high sulphide contents (15–20 vol%, Ikeda, 1992; King et al., 2015), large phosphate minerals, Na-bearing talc, Fe-bearing periclase [(Mg/Fe)O] and a range of magnetite morphologies (Ikeda, 1992; King et al., 2019). Their reconstructed geological history records an initial period of intense (CM-like) aqueous alteration, resulting in the secondary replacement of (almost) the entire anhydrous silicate content and thus the formation of pseudomorphic chondrules under low-temperature (<150°C) alteration. This was followed by, or transitioned into, a short period of thermal metamorphism at temperatures >500°C (Akai, 1992; Ikeda, 1992; King et al., 2019). Isotopically, the CY chondrites form an extension of the CO-CM mixing line (Fig.1), plotting with the same slope (and δ18O intercept) but at heavier, 18O-enriched compositions – potentially implying the CYs accreted more water than the CMs, whilst forming from the same or a nearby region of the disk. Alternatively, their 18O enriched compositions could reflect the action of thermal metamorphism which appears to result in a preferential loss of isotopically light water and the formation of heavy solids (Valley et al., 1986; Clayton and Mayeda, 1999).

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This work has large-scale astrophysical implications relating to the formation of planetesimals during the early Solar System and the interaction between from isotopic and geochemical reservoirs within the protoplanetary disk.

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Fig.1. The CO-CM-CY mixing line – δ18O/δ17O isotope space plotting meteorite data from Clayton and Mayeda (1999) with the addition of newly described 16O-poor micrometeorites from Suttle and Folco (2019).
EXPERIMENTAL INVESTIGATION OF THE ACTION OF CO₂
SUBLIMATION IN MARTIAN LANDSCAPE EVOLUTION

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Introduction: Mars is a cold, dry planet whose seasonal cycle is similar to Earth’s, although dominated by the advance and retreat of CO₂ ice, rather than water ice [1]. The seasonal, sublimation-driven retreat of CO₂ ice in Spring creates intriguing patterns observed in images of the surface, including spots, fans and polygonal fracture networks [e.g., 2,3]. Although none of these surface phenomena result in detectable changes of surface elevation, recent, repeat-imaging of the martian surface by the High Resolution Imaging Science Experiment (HiRISE [4]) at better than 50 cm/pix has revealed volumetric changes in the surface, most often associated with kilometre-scale gullies – alcove-channel-fan systems. These changes manifest as erosional scars with downslope depositional lobes, measuring hundreds of metres cubed [e.g., 5–7]. Occurring in winter and spring, when CO₂ ice is present, the mechanism by which these movements are triggered remains unclear [5]. Our initial work revealed that CO₂ ice, condensed directly into the regolith pores, can trigger mass movements [8,9]. Here, we present the results of further, ongoing laboratory work which aims to constrain the effect of the substrate properties on triggering mass movements.

Approach: The substrate is placed inside the Mars Simulation chamber at the OU, in a liquid-nitrogen-cooled, copper test section – 20 cm wide, 20 cm deep and 30 cm long. Each experiment proceeds via four steps: i) establishment of a non-condensing nitrogen atmosphere (duration 1hr), ii) cooling of the regolith to CO₂ condensation temperature (~6 hrs), iii) condensation of CO₂ into the substrate by introducing cooled CO₂ gas at ~300 mbar (~2 hr), and iv) decrease of pressure to 6 mbar, insolation of the upper 25 cm of the test section and data collection (~2 hrs). We monitor the substrate temperature and atmospheric pressure and use videos to record surface changes. An array of six pi-cameras is used to produce elevation models at regular time intervals (~10-15 mins). For this series of experiments, we used the same JSC Mars-1 regolith simulant used in [8,9], as well as MGS-1, with varying dust content.

Results: We hypothesise that slope failures are triggered due to ice sublimating in the pore-space, which produces excess pore-pressure, leading to a decrease of internal friction angle, ultimately triggering mass-failure. This model requires a substrate that allows diffusion of the CO₂ gas into the pore space and condense as ice, while also being sufficiently gas-impermeable to allow a build-up of excess pore pressure during the sublimation phase. Our experiments show that JSC Mars-1 seems to meet these requirements, while MGS-1 with dust contents of 0.5-10% are notably less active, with lower displaced volumes. Conclusion: Mass failures by triggered by CO₂ sublimation are sensitive to substrate type. Through on-going investigations, we aim to understand where on Mars these movements can take place, by defining the limits of substrate properties required for this effect.


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Figure 1 (a) An example of gullies on Mars. b & c) Appearance of a new gully channel and deposits (Mars Year 30 and 31). High Resolution Imaging Science Experiment (HiRISE) images ESP_020051_1420 and ESP_032011_1425. Right, the simulation chamber and a top-down view of a mass movement in MGS-1.
3D multi-resolution mapping of Valles Marineris for improved understanding of RSL formation mechanisms

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Introduction: Recurring Slope Lineae (RSLs) are metre- to decametre-wide dark streaks found on steep slopes, which enlarge during the warmest times of the year, fading during the cooler periods and reappearing again in the next Martian year. A better understanding of the formation mechanisms of RSLs are fundamental to constraining Mars’ water budget and habitability. The Valles Marineris (VM) area has the highest concentration of RSLs found on Mars as well as being the sole location where the triple point of water can be reached during the Martian summertime.

In this research, we demonstrate techniques and results of multi-resolution 3D mapping of the whole of the VM area of Mars using stereo images from the Mars Express High-Resolution Stereo Camera (HRSC), Mars Reconnaissance Orbiter (MRO) Context Camera (CTX), and High Resolution Imaging Science Experiment (HiRISE). Following this, we show the methods employed for co-alignment of single strip DTMs with MOLA and mosaicing.

Methods: Previously, within the EU FP-7 iMars (http://www.i-mars.eu) project, a fully automated multi-resolution Digital Terrain Model (DTM) processing chain was developed at UCL for HiRISE, CTX, and HRSC stereo-pairs, called the Co-registration ASP with Gotcha and Optimisations (CASP-GO) [1]. The CASP-GO system guarantees global geo-referencing congruence with respect to the aerographic coordinate system defined by HRSC, level-4 products and thence to the MOLA, providing much higher resolution stereo derived DTMs.

Results: In this study, we refine and improve CASP-GO to process mosaicked 3D and imaging products from HRSC and around 1,000 CTX stereo-pairs to cover the whole of the VM area. These CTX stereo pairs are processed and mosaiced to create a 3D model at 18m (see Figure 1). In addition, 11 of HRSC level 2 stereo images were processed using CASP-GO to merge with the pre-existing 71 DLR HRSC level 4 DTMs to create a mosaiced base map at 50m resolution of the VM area (see Figure 2). This mosaicing process included the development and application of a joint image co-registration and DTM point cloud alignment method to ensure the HRSC single strip DTMs are co-aligned with each other as well as MOLA. The final mosaiced products are shown along with their initial assessment. Three areas have been chosen initially to look at RSLs and results will be shown of TGO CaSSIS images added to the dataset.

Future Work: In the short-term, we plan to build a HRSC Orthorectified image (ORI) colour combined with a CTX ORI greyscale mosaic using the HRSC colour bands after phase angle correction by colleagues in Berlin [2]. We plan to publish the VM datasets (HRSC and CTX mosaics) through the ESAC GSF site by early 2020, see (https://www.cosmos.esa.int/web/psa/UCL-MSSL_iMars_CTX_v1.0) as well as iMars webGIS (http://www.i-mars.eu/web-gis).

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Introduction:

HARMONI is the work-horse visible and near-infrared integral field spectrograph for the European Extremely Large Telescope (ELT), with planned first light in late 2025. ELT will be the world’s largest optical/near-IR telescope, with a primary mirror 39 metres in diameter. It is an adaptive telescope, achieving unprecedented resolution of 10 milli-arcseconds! HARMONI spectra span a wavelength range of 470 nm - 2450 nm, with three different spectral resolving powers of 3000, 7000 and 17000.

Planetary Science:

The exquisite combination of high spatial resolution (fed by adaptive optics), huge light gathering power, and integral field spectroscopy (150 x 200 x 4000 pixel data cubes) will allow HARMONI to make unique observations of solar system objects. With spatial resolution similar to that achieved by spacecraft, HARMONI is uniquely suited to study the composition of the volcanic ejecta on Io, and the morphology, composition of asteroids, comets and TNOs – thus providing clues to their origin and morphology. In this talk, we will showcase some of HARMONI’s scientific potential, backed up by detailed simulations.

Figure 1: Spatial resolution at different plate scales achieved with HARMONI@ELT
PRIMARY AND SECONDARY FEATURES OF CHONDRULES AND REFRACTORY INCLUSIONS IN THE ANOMALOUS CM CHONDRITE NWA11346: INSIGHTS INTO EARLY SOLAR SYSTEM ALTERATION OF CM C-CHONDRITE ASTEROIDS

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Carbonaceous chondrites (CC) are a group of primitive meteorites that have remained nearly unchanged since the Solar System’s formation [1]. As such, CCs are extensively studied for the insights that they give into the earliest time of solar system history [2]. CM chondrites typically have abundant matrix, small chondrules of various types, and refractory inclusions including calcium-aluminum rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs) [3]. The CM chondrite group is primarily characterized by having experienced extensive aqueous alteration and different degrees of brecciation. Some CMs have undergone thermal metamorphism as well [4].

NWA11346 is an anomalous CM CC that was previously found to have no hydrous minerals or phyllosilicates that are characteristic of the CM chondrite group [5]. Preliminary research on NWA11346 suggests it may be an extremely thermally metamorphosed CM group chondrite. This study will investigate NWA11346 primarily using a scanning electron microprobe (SEM) and an electron probe micro-analyser (EPMA) to look at the primary and secondary features of its chondrules, CAIs and AOAAs. We will identify chondrules and refractory inclusions of interest for further SEM investigation from an x-ray map and BSE images. Thereafter, the EPMA will be used to determine their mineral compositions. The purpose of characterizing primary and secondary features is to gain insight into how NWA11346 has been processed and why it is anomalous. For example, it has chondrules with features that are typically found in CV chondrites; one main objective is learning why such features are present in NWA11346.

More than 20 CMs are known to have undergone thermal metamorphism. There have been many investigations that examine the effects of heating on CM chondrites. Nakamura et al (2005) generated a heating classification scheme that is widely used by researchers studying metamorphosed CM chondrites. It consists of stages I–IV, which describe the mineralogical changes that can be expected with increasing metamorphic grade. It goes from Stage I (<300°C), which is characterized by serpentine as the primary phase in the matrix and the presence of altered Fe-sulfides; to stage IV (>750°C), which is defined by having exclusively anhydrous minerals [6].

Additional studies have yielded similar results and have found further characteristics of heating on CMs. For example, mild to intermediate heating causes phyllosilicates to become amorphous phases, which recrystallize to dehydrated phyllosilicates and fine-grained olivine, in chondrites heated to >500°C [7]. The most heavily altered CMs can have water concentrations as low as 3wt%, as opposed to the typical abundance of 9wt% [7]. Common components of CMs such as tochilinite, carbon and volatiles decrease in abundance with increased heating [8]. The most heavily altered CMs have affinities to anomalous CM chondrites [1]. Similarly, Ryugu’s bulk composition is CM/CI-like. Its surface seems to be partially dehydrated and shows spectroscopic features consistent with thermally metamorphosed CC’s [1]. Seeing as NWA11346 is a potential analogue for the returned samples, understanding its origin and evolution is of particular importance.

References
TITLE: From spacecraft data to rover measurements – Martian atmospheric modelling and observations

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Introduction:
The circulation at Gale crater is studied from the comparison between model and in situ observations from the REMS instrument on-board the NASA’s Curiosity rover. As the site has a highly interesting topography, we opted to embed the Laboratoire de Météorologie Dynamique (LMD) Mars Mesoscale Model (or MMM throughout this abstract) into the fields of the UK version of the LMD Mars GCM (or MGCM throughout the abstract) to reach 5 km grid-boxes in resolution. The novelty of this work is the first involvement of data assimilation within such a configuration of models. Essentially, data from the Mars Climate Sounder (MCS) instrument on-board the Mars Reconnaissance Orbiter spacecraft was assimilated in the MGCM to produce a T170L25 reanalysis. Subsequently, the reanalysis forced the MMM, and its output was compared with REMS measurements. The Singular Spectrum Analysis (SSA) decomposition was used for the comparison.

Motivation:
The landing site of Curiosity, unlike the Viking landing sites, is not ideal at studying baroclinic waves due to its proximity to the equator, however it is excellent at analysing atmospheric tides [1]. The diurnal variability is altered by the rich and tight topography of Gale Crater, making REMS valuable for studying the effects of topography on the regional atmospheric circulation, and for studying the smaller scale meteorological effects, such as orographic gravity waves, small scale convection, effects on the planetary boundary layer (PBL) and many others ([2][3][4] and more).

Methodology:
The highly computationally expensive configuration forced us to only look at short periods of 5-10 sols at the start of each season. 7x7x25 points from the T170 MGCM reanalysis (less than a degree in resolution) were provided to the MMM as boundary conditions, which were downscaled to 80x80x60 grid-boxes, covering a 400(km)x400(km) region surrounding the crater. The results were extrapolated to REMS’ position and both the time-series from the reanalysis and the rebinned observations were decomposed into their SSA eigenvectors and principal components. The boundary conditions were infused at a 2-hourly frequency to capture the diurnal variability of the environment.

Results:
The reanalysis and REMS eigenvectors show an almost perfect agreement between the first two signals (diurnal and semidiurnal); an expected feature provided that a reanalysis is driving the mesoscale fields. The (noncorrelative) principal components show a larger amplitude for the REMS observations in comparison to the model predictions. Both the eigenvectors and principal components can be used to reconstruct the signals, essentially filtering out anything else. The results are presented in Figure 1.

![Figure 1: The SSA decomposition of temperatures from the MMM and Curiosity-REMS from the start of northern spring. The first two colour maps are MMM velocities (top left plot) and temperatures (top right) taken from the terrain-following interpolated layer, which is 5m above the local topography. The following 4 plots are the SSA reconstructions of REMS observations (black lines) and MMM values (red lines). The blue vertical line shows the frame from which the two maps are extracted](image)

A definitive merger-AGN connection at $z \sim 0$ with CFIS: mergers have an excess of AGN and AGN hosts are more frequently disturbed.

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**Introduction:**

The question of whether galaxy mergers are linked to the triggering of active galactic nuclei (AGN) continues to be a topic of considerable debate. The issue can be broken down into two distinct questions: 1) Can galaxy mergers trigger AGN? 2) Are galaxy mergers the dominant AGN triggering mechanism? A complete picture of the AGN-merger connection requires that both of these questions are addressed with the same dataset. In previous work, we have shown that galaxy mergers selected from the Sloan Digital Sky Survey (SDSS) show an excess of both optically-selected, and mid-IR colour-selected AGN, demonstrating that the answer to the first of the above questions is affirmative. Here, we use the same optical and mid-IR AGN selection to address the second question, by quantifying the frequency of morphological disturbances in low surface brightness r-band images from the Canada France Imaging Survey (CFIS). Only $\sim 30$ per cent of optical AGN host galaxies are morphologically disturbed, indicating that recent interactions are not the dominant trigger. However, almost 60 per cent of mid-IR AGN hosts show signs of visual disturbance, indicating that interactions play a more significant role in nuclear feeding. Both mid-IR and optically selected AGN have interacting fractions that are a factor of two greater than a mass and redshift matched non-AGN control sample, an excess that increases with both AGN luminosity and host galaxy stellar mass.

**Figures, tables and bibliography:**

Fig.1: CFIS r-band images at 0.1 arcsec pixel scale. Bottom: CFIS DIR 1 band images at 0.1 arcsec pixel scale

Fig.2: Stellar mass and redshift distribution of optical AGN (left) and mid-IR AGN (right) sample with stellar mass coded by MBH (SMBH) luminosity and MBH mass.
TEMPORAL AND SPECTRAL STUDIES OF JUPITER’S X-RAY AURORAE WITH XMM-NEWTON DURING A COMPRESSION EVENT


Abstract:
It is now 40 years since Jupiter’s X-ray aurorae were first detected by the Einstein Observatory (Metzger et al., 1983). Since then, the aurorae have been reported to pulsate with periods of tens of minutes (Gladstone et al., 2002, Dunn et al., 2016, 2017). However, other authors found that the aurorae did not exhibit any quasi-periodic behaviours (Branduardi-Raymont et al., 2007, Elsner et al., 2005). We now also know that there are two constituents to these emissions. Soft X-rays with energies lower than 2 keV occur at high latitudes close to the poles and are due to charge exchange processes between precipitating ions and neutrals in the jovian atmosphere (e.g. Waite et al., 1994, Branduardi-Raymont et al., 2007, Houston et al., 2018). However, it is still unclear whether these ions originate from the solar wind or Io’s volcanoes. Higher energy X-rays appear at lower latitudes and mostly coincide with the location of the main UV auroral oval. These transient emissions are produced by precipitating electrons (Branduardi-Raymont et al., 2008).

XMM-Newton observed Jupiter on 19th June 2017 over several rotations of the planet, and this marked the first time that XMM-Newton was observing Jupiter during a definite magnetospheric compression event. This was confirmed by the Tao solar wind propagation model (Tao et al., 2005), by data from the JADE instrument on Juno and HST observations of the jovian UV aurora.

We ran wavelet and Fast Fourier transforms on the entire auroral lightcurve to reveal that the northern aurora pulsated with periods of ~23 - 28 minutes which slowed down and stopped part way through the second planetary rotation which we observed. The southern aurora had a weak pulse of ~23 - 35 minutes in the second rotation which then increased in intensity in the third rotation.

Spectra of the northern and southern X-ray aurorae were extracted and fitted in XSPEC using the Atomic Charge Exchange (ACX) package.

Three different ion populations were used for the ACX model. The first was iogenic in nature and consisted of sulfur and oxygen ions. The second and third comprised the ion abundances from the slow and fast solar wind respectively as measured by the Ulysses spacecraft (von Steiger et al., 2000). We conclude that for this observation, the precipitating ions are from Io’s volcanoes as the iogenic model gave best fits for all of the spectra from both poles.

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SEISMIC MOMENT AND EFFICIENCY OF SMALL IMPACTS ON MARS

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Introduction: InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) is a NASA mission whose primary seismological goals are to infer the internal structure of Mars and to constrain impact rate on the surface, using seismic data recorded by the lander [1]. These seismic signals are most likely to be generated by quakes or meteorite impacts. It is therefore crucial to be able to distinguish the two possible sources as well as infer source properties from recorded seismograms. So far, the seismic signature of impacts has not been characterised in detail, primarily due to lack of observational and experimental data. Here, we use a forward modelling approach to quantify the scalar seismic moment and efficiency of small impacts onto Martian regolith, and express these quantities as a function of impact properties.

Theory: The seismic moment tensor, $\mathbf{M}$, is a 3-dimensional tensor used to describe the geometry and magnitude of a seismic source. Here, we assume that $\mathbf{M}$ of an impact is a diagonal tensor with equal non-zero elements, equivalent to an isotropic source [2]. Magnitude of $\mathbf{M}$ (scalar seismic moment, $M_0$) is related to seismic magnitude of an impact and is important in distinguishing Marsquakes from impacts. We calculate the scalar seismic moment using a method derived by J.D. Walker [3]:

$$M_0 = \sqrt{\frac{3}{2}} \frac{1}{2^t} \int \rho v_r r dV$$

(1)

where $t$ is time after impact, $\rho$ is density of the target, $v_r$ is horizontal velocity of the material at horizontal distance $r$ from impact location.

Seismic efficiency, $k_s$, is defined as the portion of initial kinetic energy of the impactor that is converted into elastic (seismic) wave energy. It is a key component in calculating detectability of impacts at InSight, as well as inferring impact properties from recorded seismograms. Previous studies, including laboratory experiments and numerical investigations, produced $k_s$ values spanning four orders of magnitude ($10^{-6} - 10^{-2}$) [4]. Hence, $k_s$ is the largest contributor of error in impact detection rate predictions for InSight. Here we use a method for calculating kinetic energy of the wave, first derived by J. Rinehart [5]:

$$k_s = \frac{E_s}{E_i} = \frac{1}{2E_i} \int \rho v_i^2 dV$$

(2)

where $\rho$ is the density of the target material and $v_i$ is the radial velocity of the material.

Modelling: We simulated a series of idealised impacts using shock physics code iSALE [6–8]. Both impactor and target were modelled by Tillotson equation of state for basalt (reference density of 2860 kg/m$^3$) and Lundborg strength model with a cohesion of 5 kPa and a friction coefficient of 0.6 for the target. In addition, 50% porosity was included in the target to resemble Martian regolith. Impact velocity was varied between 1.5 and 6 km/s, and impactor radius was varied between 3.5 and 20 cm. The propagation of stress wave generated by the impact was simulated from the impact point until it reached the mesh boundary.

Results and Conclusions: Scalar seismic moment values calculated using eq. 1 fall in the range $10^5 - 10^{13}$ Nm and suggest that $M_0$ is directly proportional to impactor momentum, $p_i$. This is consistent with previous theoretical models of impact-generated seismic waves [4]. Seismic efficiencies obtained using eq. 2 fall in the range $1 - 2.5 \times 10^{-4}$. These values are consistent with previous experiments, but are lower than predictions used to estimate impact detection rates at InSight ($5 \times 10^{-4}$; impact rate $\sim 1$–30 per year) [9].

In the future we will expand simulation domain to include different impactor properties and target material parameters, for example porosity.

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GEOLoGICAL MAPPING OF MAWRTH VALLIS, MARS: FIRST LOOK

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Introduction: Mawrth Vallis (Figure 1) is generally understood to be unusual among Mars’ giant outflow channels. It is incised into Noachian (> 3.7 Ga) terrain and is associated with thick (> 150 m) clay-bearing deposits [1]. This clay mineralogy is well-documented [e.g. 1–3] and has made Mawrth Vallis a candidate landing site for several rover missions. However, the atypical geomorphology of the channel is less well-studied. In the PLANMAP project, we will produce a geological map of Mawrth Vallis to establish its history of erosion and deposition and relationship with the clay-bearing deposits.

PLANMAP: PLANMAP aims to provide standards for planetary geological map production to aid the dissemination of European maps, and is producing exemplar maps [e.g. 4] where various data (visual images, elevation models, spectra, crater size-frequency distributions) will be fused to make more fully integrated geological maps.

The abundance and diversity of data types at Mawrth Vallis, and its scientific interest, make this region particularly suitable for PLANMAP.

Data and Methods: The basemap will be a CTX (6 m/pixel) mosaic, with CTX digital elevation models (DEMs; ~20 m/pixel) to assess stratigraphic relationships, and HiRISE (25–50 cm/pixel) images for unit definition. Mapping will focus on channel geomorphology. Linework will be drawn at ~1:200,000. Our map will undergo compositional analysis integration with other PLANMAP partners.

Results: We have mapped several smaller channel-types associated with Mawrth Vallis, including inverted channels [5] on its floor, indicating a rich history of sedimentation and erosion.

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Figure 1. Mawrth Vallis, western Arabia Terra, Mars. MOLA topography is shown overlain on a MOLA hillshade. Smaller channels were digitised during early reconnaissance mapping of the region.