Astrobiology Society of Britain

The 10th Meeting of the Astrobiology Society of Britain

University of St Andrews

UK SPACE AGENCY

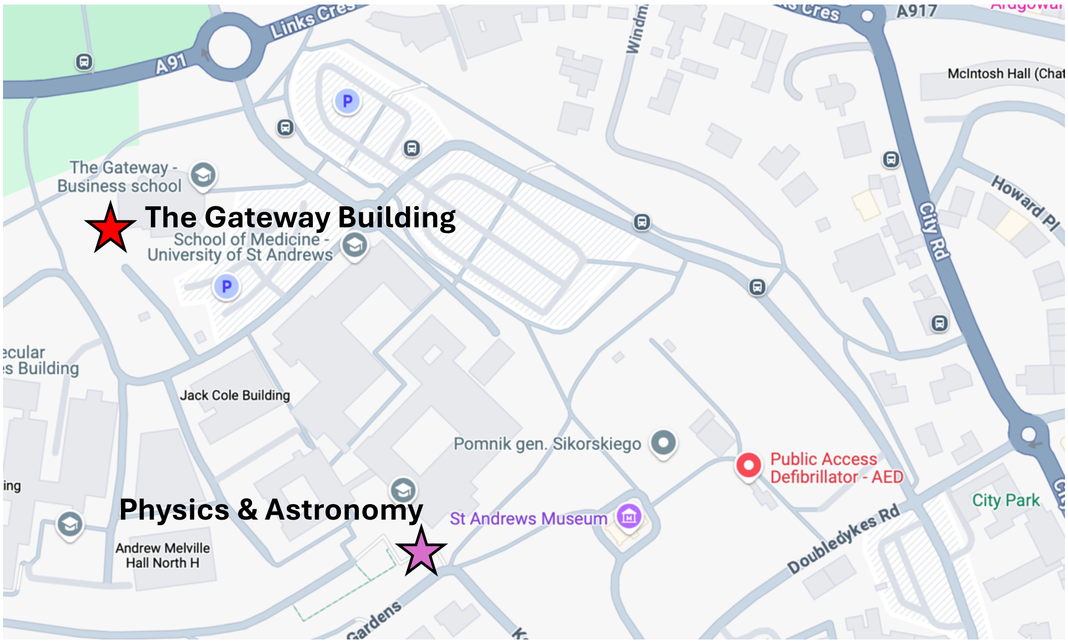
University of St Andrews

Welcome

Welcome to the University of St Andrews! Below you will find some information to help you find your way around our small town and enjoy your time here with us.

Locations

North Haugh: All talks will be held in Physics Lecture Theatre B in the **School of Physics & Astronomy**. This is in the North Haugh campus on the west side of town. The Early Career event will be held nearby at The Gateway Boardroom, in **The Gateway Building**. In town: the ice breaker will be held in the **Arts Building** foyer, which is on The Scores. The poster session will be held in **Parliament Hall**, which is accessed from South Street. Both locations can also be found using Google Maps



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Travel
Train: The closest mainline train station is Leuchars – from here there is a regular bus service to St Andrews, running approximately every 10-15 minutes.
Air: The Jet 747 is a fast bus service from Edinburgh Airport to St Andrews, or alternatively the airport tram service takes you to Edinburgh Gateway or Haymarket, with connections to Leuchars.
Town: For those staying at David Russell Apartments, it is a 20 minute walk to the School of Physics and Astronomy, or alternatively is served by the 90A, 90B, and 91A buses.
Car: For those travelling by car, there is a free public car park at Petheram Bridge close to the School of Physics and Astronomy. There is a paid public car park off Argyle Street (Argyle Street North and Argyle Street South car parks). There is also free parking along The Scores, for access to the Arts Building (ice breaker only). Parking in the town centre itself is often tricky and best avoided if possible.

Nice places nearby and in town
There are three beautiful beaches in St Andrews – Castle Sands, East Sands, and West Sands, all suitable for swimming (if you can brave the North Sea). There are also University gardens that are open for all, including St Mary's Quad and St Salvators Quad, and the Cathedral grounds. The town has a variety of options for food and drinks, many of which will be found within the town centre. Examples include:

- St Andrews Brewing Company (local ales, pub grub)
- Jahangir (Indian)
- Brew Dog (burgers)
- The Criterion (pies, pub grub)
- Janettas – superb italian gelato (if eating outside, beware of seagulls)
- Zizzi's
- Pizza Express
- Little Italy (Italian)
- Tailend (fish)
- Cromars (fish and chips)
- Thai Tanon (Thai)
- The Central (pub grub)
- Forgans (Scottish)
- Nandos
- Aikmans (pub)

Events and excursions

Ice breaker: informal welcome drinks for those arriving on Monday 16th June. These will be in the Level 1 Arts Building Foyer in town, close to nearby restaurants and pubs.

ECR evening event (Tuesday 17th June): this is an opportunity to network with your fellow ECR astrobiologists in a relaxed and informal setting! Drinks (alcoholic and nonalcoholic) will be provided. The first 30 minutes will be a Q&A panel with our three keynote speakers – you are welcome to ask questions about their research and career, either in person at the event or if you can submit questions in advance – look out for the question box at the tea and coffee breaks!

Rock and Spindle local geology excursion: please meet at 10am in the car park located behind the St Andrews Coastguard Rescue Station (accessed from Albany Park). The guided trip will take approximately 3 hours, including a 30 minute walk along the Fife Coastal Path there and back. We will see some of Fife's incredible Carboniferous volcanic and sedimentary geology! Please note it is a SSSI so hammering is not allowed, but you are welcome to collect loose samples. It may be summer, but this is still Scotland! So please wear/bring:

- Suitable clothing for possible rain and wind
- Footwear for uneven and occasionally muddy paths
- A water bottle and any food/snacks you want
- Suncream

The Rock and Spindle is just one of many wonderful geological localities along the East Neuk coastline, so please do ask for recommendations if you plan to explore elsewhere later that afternoon or are staying for the weekend.

St Andrews Botanical Garden: the garden opens at 10am and is a short walk from the town centre. Good coffee, local Luvian's ice cream/chocolate/biscuits are available at the Gatehouse. Show your conference badge and you will get free admission (note – all students get free admission anyway, so you can also just use your student ID). Take your time to enjoy the gardens which are currently engaged in a variety of ecological and environmental research projects.

RSS Discovery, Dundee: please meet outside the Gateway Building for a pre-booked taxi at 10am which will take you to Discovery Point. Your tickets will be provided at registration. You are welcome to make your own alternative way to the RSS Discovery at a different time – many buses go to Dundee from the St Andrews Bus Station.
If you wish to extend your trip, the Victoria and Albert (V&A) Museum next door is free and highly worth a visit. The Dundee Centre for Contemporary Arts (DCA) and McMannus Gallery are also excellent. The nearby Exchange Street has some lovely café's.

ASB 10 - Conference Programme

Monday 16th June	
17.00 - 18.30	**Icebreaker and site registration - Arts Building Level 1 Foyer**

Tuesday 17th June – Physics Building Foyer and Lecture Theatre B		
09.30	**Arrival, site registration + refreshments**	
10.30	Cousins	Welcome
10.40	**Keynote 1 - Inge Loes Ten Kate "Biosignatures, falses, and public perception"**	
11.10	Baidya	Magmatic reactive phosphorus on the prebiotic Earth and implications for the origin of life
11.25	Boden	Establishment of the Nitrogen Cycle on Early Earth
11.40	Holland	Igneous Rocks as a Viable Source of Fixed Nitrogen to Prebiotic Worlds
11.55	McDonald	The efficiency of delivering prebiotic feedstocks to the early Earth with cometary impacts
12.10	**Lunch (provided)**	
13.30	**Keynote 2 - Sophie Nixon "Unearthing the rules of life in microbiomes: Implications for astrobiology"**	
14.00	Cockell	Fullerenes (C60) induce a microbial metabolomic stress response under anaerobic conditions
14.15	Gault	Titan analogue tholins are biologically inaccessible
14.30	Latorre	Biogeochemical cycles in extreme volcanic environments
14.45	Ruiz-González	Snow algal plasticity and metabolic responses during a simulated Lunar light cycle
15.00	**Refreshment break**	
15.30	Olsson-Francis	A new era of planetary protection for Mars
15.45	del Moral	Insights into Europa's biological potential using high-pressure laboratory simulations
16.00	Galloway	Bioenergetic potential of Mars analogue hot spring microbial communities
16.15	Tatton	Nitrate-dependent Sulphur oxidation on Mars? Insights from a high-altitude Andean Lake
16.30	Hirsch	Preservation of iron-oxidising bacteria: an analogue for potential morphological biosignatures on Mars
17.00 - 18.30	**ECR Event - Gateway Boardroom, Gateway Building**	

Wednesday 18th June - Physics Building Foyer and Lecture Theatre B		
9.30	**Tea/coffee**	
10.00	**Keynote - Sean Jordan – "Observationally Constraining Planetary Habitability"**	
10.30	Caughtry	Mid-IR Characterisation of Salty Ice During Cooling and Exposure to Vacuum: Implications for Future Icy Moon Missions
10.45	Hogan	Size-Dependent Composition of Ice Grains Relevant to Salt-Rich Particles in the Plumes of Enceladus
11.00	Fox-Powell	What is the chemical composition of the shallowest liquid water in Europa's ice shell?
11.15	Guimond	Slightly carbon-rich rocky planets
11.30	**Refreshment break**	
11.45	Nielson	Constraining elemental enrichments linked to areas of preserved organic matter in Mars analogue sedimentary rocks
12.00	Marsh	Rover-Level Cross-Calibration of the Rosalind Franklin Rover's Enfys and PanCam Instruments
12.15	Blasciuc	Mechanochemical oxidant generation on Mars- an insight into Martian chemistry
12.30	Loron	Resolving affinities of mysterious fossils using infrared spectroscopy and machine learning
12.45	**Lunch (provided)**	
13.45	Rodgers	Can Pareto Optimality Be Evidence of Life?
14.00	Stewart	Understanding the adsorption of amino acids onto montmorillonite clays through molecular simulations
14.15	Tang	Latest Results from the JCMT-Venus Atmospheric Monitoring Project
14.30	UKSA	Community discussion/opportunities
15.00	**Posters and refreshments - Parliament Hall**	
17.00	**End**	

Abstracts

Magmatic reactive phosphorus on the prebiotic Earth and implications for the origin of life

Baidya, AS[1], Walton, CR[2,3], Stüeken, EE[1]

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Phosphorus (P), a critical nutrient for all living organisms on Earth, was essential for the origin and early evolution of life. However, the dominant form of P, i.e., phosphate (P(V)) is sparsely soluble in water and less efficient in making phosphorylated compounds in prebiotic settings. Reduced P species such as phosphite (P(III)) and condensed P species such as pyrophosphate (PP(V)) might have been more useful for this purpose as they are more soluble and/or reactive compared to P(V). The known pathways to supply these species on the prebiotic Earth involve dissolution of highly reduced phosphide minerals and thermal heating of phosphate salts and minerals in dry conditions, both of which could have been geologically restricted. Here, we propose that mafic and ultramafic rocks could have delivered a significant part of the prebiotic reactive and soluble P species for the origin and early evolution of life. We have extracted P species from olivine separates, peridotite, basalt, and komatiite using an alkaline solution and measured P(III), P(V), and PP(V) concentrations by IC-ICPMS. We see that, on average, 0.2%, 4.9%, 4.0%, and 9.4% of total extracted P is phosphite in basalt, olivine, komatiite, and peridotite, respectively. We further see that PP(V) is rare in olivine and peridotite but common in basalt and komatiite, with averages of 0.3% and 2.5% of total extracted P, respectively. We suggest that melting process may be key for phosphate polymerization. We inserted the data into a box model considering seafloor weathering as the major source and photochemical oxidation as the major sink of phosphite and found that the concentration of P(III) in the prebiotic deep ocean might have been in the nanomolar range but likely higher in crustal pore fluids in submarine and subaerial hydrothermal settings. Within these settings, reactive P supplied from magmatic rocks could have been an important contributor to the formation of phosphorylated biomolecules for Earth's earliest biosphere. Furthermore, in the ocean, reactive P species derived from magmatic rocks contributed some bioavailable P in the Archean.

Mechanochemical oxidant generation on Mars- an insight into Martian chemistry

Blasciuc Raluca[1], Edgar John[1], Telling Jon[1], Lu Erli[2], Kaiser Jan[3]

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Oxychlorine species (perchlorate/chlorate) are important as 1) they affect the analysis of organic molecules by *in situ* Mars rover instruments, 2) they dramatically lower the freezing point of liquid brines thus affecting Martian habitability, and 3) they can provide a source of fuel for future manned missions to Mars, as well as potential toxic effects to explorers (Hecht *et al*., 2009; Kounaves *et al*., 2012). It is still uncertain, however, as to the mode(s) of formation of oxychlorine species on Mars.

In this study we have performed new experiments to test if the mechanical abrasion of sodium chloride with a range of different silicate and metal oxide minerals (mimicking aeolian-driven abrasion on Mars) can generate oxychlorine species. Minerals of defined starting grain sizes were ground together with halite in a gastight ball mill under different atmospheres (air, and oxygen-free nitrogen), mimicking methods of Edgar *et al.* (2022). Oxychlorine species were extracted with water and analysed via ion chromatography. The absolute concentrations of oxychlorine species varied with the starting grain size of the minerals prior to milling, and the ratio of chlorite:chlorate:perchlorate with different mineral mixtures was found to vary systematically as a function of the oxygen content of the headspace during milling. Results are compared to those of past *in situ* measurements on Mars and may be useful to help interpret future samples returned from Mars to Earth.

<u>References</u>

1. Edgar, J. O., Gould, J. A., Badreshany, K., & Telling, J. (2022). Mechanochemical generation of perchlorate. Icarua, 387, 115202.
2. Hecht, M. H., Kounaves, S. P., Quinn, R. C., West, S. J., Young, S. M. M., Ming, D. W., Catling, D. C., Clark, B. C., Boynton, W. V., Hoffman, J., DeFlores, L. P., Gospodinova, K., Kapit, J., & Smith, P. H. (2009). Detection of Perchlorate and the Soluble Chemistry of Martian Soil at the Phoenix Lander Site. Science, 325(5936), 64-67.
3. Kounaves, S., Folds, K., Hansen, V., Weber, A., Carrier, B., & Chaniotakis, N. (2012). Identity of the perchlorate parent salt (s) at the Phoenix Mars Landing Site based on reanalysis of the calcium sensor response. AGU Fall Meeting Abstracts.

Establishment of the Nitrogen Cycle on Early Earth

Boden, J.S.[1], Anderson, R.E.[2], Stüeken, E.E.[1]

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Nitrogen is an essential component of living matter. Without it, the amino acids and nucleic acids that facilitate metabolism and inheritance for life as we know it would not exist. However, we do not yet understand how the nitrogen cycle began on early Earth. In this research project, we reconstruct and date the evolutionary histories of biological ammonium transporters and nitrogen fixing genes to determine whether the first ammonium on Earth was fixed by early microbial communities or abiotic geochemical processes. We examined 1,024 different genomes, representing the full diversity of bacteria, archaea and eukaryotes and found that Earth's earliest life-forms accessed ammonium and/or methylammonium from the environment (using transporters from the Amt / Mep / Rh family) several hundred million years before they evolved genes (namely *nifD, nifK*, and *nifH*) which enable them to produce ammonium themselves. More specifically, we find a 59 % to 99 % probability that ammonia transporters originated in the last universal common ancestor of all life on Earth, estimated to have existed 4.38 to 4.39 billion years ago (Ga, confidence intervals span 4.40 to 4.34 Ga). In this same lineage, the probability of genes for biological nitrogen fixation are close to zero (2 % for *nifD*, 2 - 7 % for *nifH* and 1 % for *nifK*). Instead, nitrogen fixing genes are more likely to have originated in later bacterial lineages (probabilities of 76 to 97 % for all genes) that are estimated to have existed in the Paleo- to Meso-Archean eras spanning 3.6 to 2.8 Ga. This is consistent with independent phylogenetic evidence for biological nitrogen-fixing genes originating in bacteria (Pi et al., 2022) at approximately 3.1 to 2.7 Ga (Parsons et al., 2021). It is also consistent with evidence from rock records of biological nitrogen fixation at 3.2 to 3.5 Ga (Moore et al., 2017, Stüeken et al., 2024). Furthermore, it points toward an abiotic source of ammonium during the early evolution and diversification of life in the Hadean and Eoarchean, which could include hydrothermal vents, and/or the reduction of nitrate produced via lightning. Thus, the presence of ammonium on other planetary bodies may prime those environments for the evolution of nitrogen-dependent life-forms, similar to those found on Earth.

MOORE, E. K., JELEN, B. I., GIOVANNELLI, D., RAANAN, H. & FALKOWSKI, P. G. 2017. Metal availability and the expanding network of microbial metabolisms in the Archaean eon. *Nature Geoscience,* 10**,** 629-636.
PARSONS, C., STUEKEN, E. E., ROSEN, C. J., MATEOS, K. & ANDERSON, R. E. 2021. Radiation of nitrogen-metabolizing enzymes across the tree of life tracks environmental transitions in Earth history. *Geobiology,* 19**,** 18-34.
PI, H.-W., LIN, J.-J., CHEN, C.-A., WANG, P.-H., CHIANG, Y.-R., HUANG, C.-C., YOUNG, C.-C. & LI, W.-H. 2022. Origin and Evolution of Nitrogen Fixation in Prokaryotes. *Molecular Biology and Evolution,* 39.

STÜEKEN, E. E., BOOCOCK, T., SZILAS, K., MIKHAIL, S. & GARDINER, N. J. 2021. Reconstructing Nitrogen Sources to Earth's Earliest Biosphere at 3.7 Ga. *Frontiers in Earth Science,* 9.
STÜEKEN, E. E., PELLERIN, A., THOMAZO, C., JOHNSON, B. W., DUNCANSON, S. & SCHOEPFER, S. D. 2024. Marine biogeochemical nitrogen cycling through Earth's history. *Nature Reviews Earth & Environment*.

Mid-IR Characterisation of Salty Ice During Cooling and Exposure to Vacuum: Implications for Future Icy Moon Missions

Jessica Caughtry[a]*, Louisa J. Preston[a], Emily Ingman[b], Andrew R. Thompson[c], Tom M. Mitchell[c], Anne D. Jungblut[d], and James Bradley[e]

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Many water worlds have been discovered throughout the solar system, each hiding a liquid, sub-surface ocean beneath a thick shell of ice. Jupiter's moon Europa may be the most astrobiologically promising of these; chaos terrains criss-crossing its exterior suggest communication with the subsurface ocean, enabling a potential pathway between the hydrothermal seafloor and the radiolytically processed surface, and further facilitating the formation of more complex chemical species within the ice. Identifying the chemical composition of these terrains and any potential biosignatures they may contain is therefore key to evaluating Europa as an astrobiological candidate.

Contemporary mission design emphasises the use of near- and far- infrared (IR) spectrometers to distinguish the spectral signatures of different elements and compounds. In contrast, the mid-IR has received comparatively less focus, despite covering fundamental vibrational modes of water, salts, and organics. Mid-IR spectroscopy thus represents a valuable but underutilized approach to detecting surface compounds. This study aims to address this gap by examining the mid-IR characteristics of two key salts frozen in ice and already identified on Europa, magnesium sulphate heptahydrate ($MgSO_4{\cdot}7H_2O$) and sodium chloride (NaCl) [1], under decreasing temperatures from -10°C to -180°C, and during vacuum exposure at -180°C for 30 minutes. Results reveal clear absorption bands which can be used to identify the presence of the $MgSO_4$, including features at 1100 and 1670 cm^{-1}, and two bands centred around 4460 and 5420 cm^{-1}. In contrast, NaCl is spectroscopically invisible until -37°C, where it restructures into a different ice phase, SCII [2], illustrated by the development of three clear peaks in the high-energy edge of the OH stretching region. This transformation can be blocked or masked when combined with $MgSO_4$, although this behaviour varies both between and within ice pellets. All samples reduced in absorption following vacuum exposure, with the greatest changes occurring within the first 10 minutes and, in some cases, revealing or eroding certain absorption peaks.

Results highlight distinct mid-IR spectral signatures that allow identification of salts under Europa-like conditions, along with their hydration responses to changing temperatures and pressures.

[1] S.K. Trumbo et al, *Sci. Adv.5(6)* (2019), [2] Journaux, B. et al., *PNAS, 120(9).* (2023)

Fullerenes (C60) induce a microbial metabolomic stress response under anaerobic conditions

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Fullerenes are allotropes of carbon whose molecules consist of carbon atoms connected by single and double bonds to form a closed or partially closed mesh, with fused rings of five to six atoms. They are found in the interstellar medium and as a minor fraction in meteoritic organic carbon. Motivated by an interest to discover if these compounds could be used as a carbon source by life, we studied their metabolism by anaerobic enrichment cultures grown on meteoritic carbon and the well-characterised organism *Escherichia coli* grown under anaerobic conditions. Although *E. coli* is not phylogenetically deep branching, its well understood metabolic pathways yield insights into the potential effects of fullerenes on microbial metabolic pathways under anaerobic conditions.

In *E. coli*, we observed large changes in membrane phospholipid composition, restructuring of amino acid pathways and suppression of nucleotide biosynthesis and the methionine synthesis pathways all indicate *E. coli* experiences oxidative stress in response to UV-C60 exposure. These data are consistent with the lack of ability of *E. coli* to use C60 as a sole carbon source under anaerobic conditions and may be related to our observation that the UV-degradation products of C60 were inhibitory to growth. The anaerobic isolate results, however, demonstrated that activation of the same metabolic pathways which are involved in the degradation of other complex aromatic organics in different bacterial species, which indicates the anaerobic isolate may use the same pathways to degrade UV-C60.

We propose that fullerenes interact with the bacterial cell membranes, potentially because of their hydrophobicity, interfering with membrane integrity and eliciting a stress response. This suggests that fullerenes on early Earth or on other young planets may be inhibitory or deleterious to hydrophobic biochemical structures unless life innovates a way to degrade or metabolise them.

*This work was funded by the Leverhulme Trust and was conducted by Elle Bethune in partial fulfilment of the Degree of PhD at the University of Edinburgh.

Insights into Europa's biological potential using high-pressure laboratory simulations

del Moral, A; Siggs, D; Macey, M.C.; Fox-Powell, M.G.; Pearson, V.K.; Olsson-Francis, K;

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Under its thick ice layer, Europa contains a liquid water ocean where habitable conditions may exist. Chemical disequilibrium may occur due to hydrothermal activity at the ocean floor and a supply of oxidants from the irradiated icy surface. On Earth, chemical disequilibrium drives microbial metabolism, and in subsurface environments, primary production depends on chemolithotrophs, which produce energy from the oxidation of inorganic compounds. To understand the habitability and biosignature formation on Europa it is important to integrate our knowledge of the moon's conditions with laboratory-based analysis. For this work, we developed a laboratory simulation experiment to study the effects of the physicochemical modelled conditions of Europa's subsurface ocean on microbial function and physiology.

A high-pressure reactor was used to simulate the pressure (between 0.2 MPa and 30 MPa) associated with the upper region of the ocean[1,2]. Ocean chemistry was simulated based on a metamorphic origin of the ocean[3]. Using this chemical composition, an analogue environment was identified, and the microbial community was used as the inoculum for the biotic experiment. For this, we used a microbial enrichment from Basque Lake, Canada; a magnesium- and sulphate-rich environment characterised by low annual temperatures (-5°C to 8°C, with -45°C peaks)[4]. To condition the microorganisms to the high-pressure conditions, cells were initially grown at ambient pressure, and the pressure was gradually increased every 14 days to a final pressure of 30 MPa.

An increase in pressure did not have a significant impact on the chemical composition of the fluid or the cell abundance. However, diversity indices demonstrated a reduction in microbial diversity with increased pressure, with the genus *Pseudodesulfovibrio* dominating the microbial community. This organism was later isolated through serial dilutions and sequenced using whole genome sequencing (WGS). Transmission electron microscopy demonstrated that the amount of organic material, potentially extracellular polymeric substances, produced by the cells increased with pressure.

Utilising this approach, we can not only grow microbial communities within a simulated Europa subsurface ocean but also isolate model organisms for future study under the conditions in Europa. This has implications for studying potential habitability and biosignature formation within this putative habitable environment.

References: 1) Olsson-Francis *et al.*, (2020) doi.org/10.1016/j.mimet.2020.105883; 2) Marion *et al.*, (2005) doi.org/10.1016/j.gca.2004.06.024; 3) Daswani *et al.,* (2021) doi.org/10.1029/2021GL094143; 4) Buffo *et al.,* (2022) 10.1089/ast.2021.0078

What is the chemical composition of the shallowest liquid water in Europa's ice shell?

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Jupiter's moon Europa possesses a geologically active ice 'shell' overlying a salty subsurface ocean that may contain the necessary conditions to support life. Chlorine salts of sodium and magnesium have been observed on Europa's surface, indicating that the ice shell contains materials from the ocean. Although the ocean itself may be locked beneath 10s of kilometres of solid ice, the presence of salts within the ice shell can keep liquid thermodynamically stable as brine at shallower depths. Even where ice shell temperatures are too low for stable liquid, dissolved salts can extend the lifetimes of gradually freezing liquids to potentially hundreds of thousands of years. Such ice shell brines could be the shallowest possible habitable environments on Europa. However, very little is known about their chemical composition, and thus their potential as habitats for life.

I used Pitzer thermodynamic models to investigate partitioning of elements between solid and liquid phases as a function of temperature and pressure in Europa's ice shell. Since the bulk composition of Europa's ice shell is unknown, I systematically considered a wide range of hypothetical compositions comprising chloride-dominated, sulfate-dominated and chloride-carbonate endmembers, in which the mole fractions of major ions were independently varied over multiple orders of magnitude. I will show how across this vast chemical parameter space, that includes current predictions of Europa's ocean chemistry, freeze-concentrated brines converge to a narrow range of compositions dominated by Mg^{2+} and Cl^{-}. Even for ice shell compositions with low relative abundances of these ions, the formation of sulfate and carbonate minerals nevertheless forces residual brines to evolve to Mg^{2+}/Cl^{-} rich fluids at relatively warm temperatures, leaving large ranges of temperature where Mg-chloride brines are stable. By comparing with predicted depth-dependent temperature profiles and lifetimes of re-freezing melt, I postulate that Mg-chloride-rich brines should be the shallowest stable ocean-derived liquids on Europa and the most long-lived fluids during re-freezing of melt in the upper ice shell. Because Mg-chloride brines are known to present severe physicochemical challenges to life, these findings have implications for the distribution of habitable conditions within Europa's ice shell.

Bioenergetic potential of Mars analogue hot spring microbial communities

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The habitability of a given environment is determined, in part, by its geochemical capability to support microbial metabolisms. Thermodynamic calculations can be used to estimate the Gibbs free energy produced by redox reactions that are feasible for the local environmental geochemistry. This allows for predictions of the dominant biological reactions within environments, such as Noachian age martian hot springs. Previous studies have used orbital data and meteorite mineralogy to model martian surface geochemistry and predict dominant biological processes in martian hydrothermal systems [1,2]. Utilising this tool in modern analogue systems on Earth tests the reliability of thermodynamic calculations to reflect biological processes on early Mars.

This work presents thermodynamic habitability estimates of Mars analogue active hot spring environments in Iceland. These provide geochemical context to detailed genomic characterisation of key chemolithoautotrophic metabolisms present within the same environments. Gibbs free energy calculations are performed using aqueous geochemical data, and these are compared to relative abundances of key metabolisms detected in metagenomic and metatranscriptomic data. We also present a model for the outflow of a theoretical martian hot spring, considering metal dissolution from basaltic minerals and equilibration with a Noachian Mars atmosphere to examine the nutrient availability and free energy available to any putative microbial communities during this period.

The thermodynamically feasible carbon, iron and sulfur metabolisms revealed by the model are consistent with results of bioinformatic analyses from these communities and agree with previous estimations of modelled martian systems [1,2]. Results further suggest a ubiquitous reliance on biological fixation of inorganic N_2 and C. Lastly, our findings suggest that minerals play an important role in the biogeochemical cycling of hot spring communities, contributing both essential metals used in catalysis and redox species for energetic metabolisms.

[1] Crandall, J. (2021). *The Planetary Science School,* **2**(4). [2] Ramkissoon, N. (2021). *Meteoritics & Planetary Science*, **56**(7).

Titan analogue tholins are biologically inaccessible

Gault, S[1], Maratrat L[2], Chatain A[2], Cockell, CS[1]

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Saturn's moon Titan hosts a vast inventory of organic carbon, termed tholins, produced by the irradiation of Titan's nitrogen and methane atmosphere[1].
As all life requires carbon, the presence of tholins on Titan raises the question as to whether these organic compounds are biologically accessible, and whether they could support microbial metabolism and growth.
Previous studies had suggested that tholins are metabolically available to a range of soil microorganisms[2]. However, the tholins used by Stoker et al., were produced in an atmosphere containing 2.5% H_2O, which likely resulted in a significant fraction of oxygenated species such as amino acids. As H_2O vapour is negligible within Titan's atmosphere, these results likely do not represent the metabolic availability of Titan's tholins.
To address whether Titan-analogue tholins are biologically accessible, we challenged a range of metabolically diverse microorganisms (*E. coli, C. necator, A. borkumensis, B. subtilis*, *P. simplicissimum)* with tholins produced from cold plasma discharge of a N_2:CH_4 (90%:10%) gas mixture[3].
Due to the insolubility of tholins and the dark suspension they form, optical density measurements were unreliable, and colony counts could be affected by the adherence of cells to tholins particles. To remedy this, isothermal microcalorimetry was employed as an agnostic measure of the metabolic heat produced by the assayed microorganisms. Calorimetry data revealed that the microorganisms assayed could not metabolise tholins as their sole carbon source in minimal media. Growth could be achieved in tholin containing media but only if it was supplemented with a bioavailable carbon source such as glucose or pyruvate. However, this was accompanied by a significantly longer lag phase suggesting that the presence of tholins was inducing a stress response. The cellular stress induced by tholins was further confirmed by fluorescence microscopy which revealed stressed morphologies such as cell chaining and cell lysis. Integration of the microcalorimetry heat output revealed that despite the increased lag phase and general stress, microbes were still able to utilise all the available preferred carbon source.
Our results therefore suggest that tholins made from a mixture of nitrogen and methane are biologically inaccessible. Future work will explore mechanisms to process tholin compounds to assess whether their metabolic availability can be increased.

Refs:
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Slightly carbon-rich rocky planets

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To aid the search for atmospheres on rocky exoplanets, we should know what to look for. An unofficial paradigm is to anticipate CO_2 present in these atmospheres, through analogy to the solar system and through theoretical modelling. This CO_2 would be outgassed from molten silicate rock produced in the planet's mostly-solid interior—an ongoing self-cooling mechanism that should proceed, in general, so long as the planet has sufficient internal heat to lose. Outgassing of CO_2 requires relatively oxidising conditions. Previous work has noted the importance of how oxidising the planet interior is (the oxygen fugacity), which depends on its rock composition (Guimond et al., 2021, 2023). Current models presume that redox reactions between iron species control oxygen fugacity. However, iron alone need not be the sole dictator of how oxidising a planet is. Indeed, carbon itself is a powerful redox element, with great potential to feed back upon the mantle redox state as it melts (Holloway, 1998; Stagno et al., 2013). Whilst Earth is carbon-poor, even a slightly-higher volatile endowment could trigger carbon-powered geochemistry..

We offer a new framework for how carbon is transported from solid planetary interior to atmosphere. The model incorporates realistic carbon geochemistry constrained by recent experiments on CO_2 solubility in molten silicate, as well as redox couplings between carbon and iron that have never before been applied to exoplanets. We also incorporate a coupled 1D energy- and mass-balance model to provide first-order predictions of the rate of volcanism. We show that carbon-iron redox coupling maintains interior oxygen fugacity in a narrow range: more reducing than Earth magma, but not reducing enough to destabilise CO_2 gas. We predict that most secondary atmospheres, if present, should contain CO_2, although the total pressure could be low. An atmospheric non-detection may indicate a planet either born astonishingly dry, or having shut off its internal heat engine.

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Preservation of iron-oxidising bacteria: an analogue for potential morphological biosignatures on Mars

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Introduction: In the search for life on Mars, evaluating the biogenicity of morphological structures may be important as they can provide a primary independent line of evidence for past life, and can be used to target areas to focus further analyses. However, our experience with terrestrial materials indicates that the deleterious effects of diagenetic processes regularly make the assessment, and even detection, of microfossils and other microscopic biosignatures challenging. Currently, the resolution of cameras on Martian rovers is insufficient to resolve bacterial or archaeal µm-scale fossils [1]. However, larger extracellular structures on the order of tens of micrometres in size may be possible to observe *in situ* [2]. An example of large extracellular structures found in Mars analogue terrestrial environments are the iron-bearing stalks and sheaths formed by iron-oxidising bacteria (FeOB). The preservation potential of these structures under Martian diagenetic processes is not well constrained.

Methods: We subjected samples of extracellular sheaths produced by the FeOB, *Leptothrix ochracea* to artificial maturation using hydrous pyrolysis. The structures were imaged and measured using a scanning electron microscope in order to investigate morphological changes with increasing maturation temperature. X-ray diffraction patterns were acquired to determine mineralogical changes.

Results and Discussion: Simulated diagenesis induced a phase change in the mineralogy of the structures, from ferrihydrite to crystalline iron oxides. We find that conditions associated with the onset of this phase change are correlated with the start of significant degradation of the extracellular structures. Comparison to previous studies demonstrates the importance of original morphology for the preservation potential of microbial morphological biosignatures. Our results reveal the sensitivity of remains of iron-oxidising bacteria to diagenesis, providing insights for improved targeting of astrobiological missions to areas on Mars that are most conducive to morphological biosignature preservation. Additionally, these results compel increased scrutiny of FeOB-like purported biosignatures if their mineralogy is dominated by crystalline iron oxides[3].

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Size-Dependent Composition of Ice Grains Relevant to Salt-Rich Particles in the Plumes of Enceladus

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The plumes of Saturn's moon Enceladus emit icy material from cracks in the ice shell, fed by vents that transport subsurface ocean material to the surface [1]. Among these, salt-rich "Type III" ice grains are used to infer its chemistry and habitability [2]. However, as ocean fluid ascends through steep temperature and pressure gradients, the effect on grain composition remains unclear. Size-dependent stratification is observed in the plumes, where larger grains fall back and smaller grains escape [3]. As different droplet sizes experience various cooling rates when exposed to the same thermal environment, grain composition can be affected [4]. Thus, spacecraft sampling of ice grains at altitude versus surface observations of plume fallout may yield different compositional information about the subsurface ocean.

This study investigates how droplet size affects composition and, specifically, how salts believed to be present in Enceladus' ocean [2, 5] behave during freezing. A fluid simulant containing sodium, chloride, carbonate, potassium and phosphate based on Cassini plume data [5, 6] and adjusted to pH 10 [7, 8] was flash-frozen in liquid nitrogen. This Enceladus ocean fluid simulant was frozen across a range of droplet volumes ($\leq 1\times10^{-4}$ µL, 0.5 µL, 5 µL) to simulate plausible plume-relevant freezing rates (>10 K s^{-1}).

Preliminary SEM-EDS analysis of 0.5 and 5 µL grains revealed sodium chloride, carbonate, and phosphate salts formed and were embedded in a matrix, with compositional heterogeneities visible below the 100 µm scale. Sodium carbonate/bicarbonate formed flat sheets of globular nodules, while sodium chloride appeared as striated fibres. Larger grains (5 µL) showed vesicle-like pores and compositional heterogeneity at the 10 µm scale, while smaller grains (0.5 µL) exhibited finer microstructures and distinct salt partitioning of the sodium chloride and sodium carbonates at the 5 µm scale. How compositional heterogeneity varies with grain size and whether they are associated with mineralogical differences is be addressed in current work.

Ongoing work focuses on the smallest grains ($\leq 1\times10^{-4}$ µL) and quantifying phase abundances using cryo-Raman and XRD. Future experiments will assess how organics - present in plume material [10] are incorporated, affecting ice grain composition and microstructure. These findings will help predict compositional differences between grains that fall back and those that escape.

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Igneous Rocks as a Viable Source of Fixed Nitrogen to Prebiotic Worlds

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The origin and early evolution of life on Earth and other habitable worlds requires constant supply of ammonic nitrogen (N). Previously proposed abiotic ammonium sources rely on sporadic and heterogeneously distributed high-energy processes, such as lightning, subaerial volcanic degassing, or deep-sea hydrothermal vents to generate bioavailable nitrogen from atmospheric N_2 gas. Here we explore weathering of ammonium contained in felsic igneous rocks as an alternative source. We find that this process could have supplied 10^8-10^9 $mol \cdot yr^{-1}$ of bioavailable N to surface environments in the early Archean, leading to dissolved concentrations of 0.023 ± 0.017 μM in freshwater and 0.01-0.1 μM in seawater. In terrestrial settings, evaporation paired with elevated N-supplies from locally enriched felsic bedrock may have led to concentrations approaching 1 μM. Rock weathering would thus have constituted a smaller flux than the sum of all proposed high-energy sources of fixed N, but with the major benefit that it was reliably present, especially in terrestrial settings. Weathering of differentiated igneous rocks should thus be considered in models of the emergence of life on Earth, and other rocky planets.

Biogeochemical cycle in extreme volcanic environments

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Carbon-containing trace gases, such as carbon monoxide (CO) and methane (CH_4) can serve as energy sources for many microorganisms, providing valuable insights into how life might survive in extreme environments with limited resources. Studying volcanic environments, provide a unique opportunity to explore how CO, a toxic trace gas for human, is degraded and oxidized to carbon dioxide from microbial communities offering insights into ecosystem formation and carbon cycling. Such studies are crucial in astrobiology as they mimic extreme conditions that could be present on other planets or moons, where trace gases like CO may play a similar role in supporting life. This project will examine the microbial dynamics that influence soil succession in volcanic ecosystems and enhance our comprehension of how plant-microbe interactions promote the pedogenesis process. The primary objective is to identify essential microbial species implicated in carbon turnover and their contribution to soil development in volcanic settings to contribute to our understanding of how life might thrive and the development of habitable environments in extreme conditions.

Mt. Etna is one of Europe's largest and most active volcanoes offering a natural succession gradient critical for understanding microbial colonization processes, as they are influenced by plant exudates and the organic carbon released by early colonizing plants. To address the objective of this project, soil samples were collected from various sites around Mt. Etna (Italy) in 2024, differing in altitude, temperature, pH and vegetation cover, to account spatial diversity for a succession analysis. Preliminary results from CO consumption experiments indicate that microbes from certain soil samples, from Bottoniera and Monte Intraleo, Italy consume CO (100 ppm) within 4.5 to 5 hours. Further 16S rRNA gene sequencing analysis of the extracted soil DNA showed that these soil samples share similarities in microbial community, particularly in strains of Pseudomonadota and Actinomycetota. Both these phyla are known to include CO oxidizing species which might explain the rapid consumption.

The continuation of this research will focus on elucidating the metabolic pathways involved in CO oxidation by the identified microbial communities, their role in biogeochemical cycle, and ultimately contributing to a deeper understanding of potential ecosystem dynamics in extreme analog environments.

Resolving affinities of mysterious fossils using infrared spectroscopy and machine learning

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The affinities and original composition of extinct organisms are often difficult to resolve using morphology alone. Using molecular analysis provides great complementary results. For example, using infrared spectroscopy, we can access the molecular fingerprints of various fossilization products of organic precursors. These precursors can tell us a lot about the original composition of fossil organisms and their possible biological affinities. The ca. 407 Devonian Rhynie Chert, one of the most exceptional fossil assemblages from the Palaeozoic, constitute a powerful positive control for such molecular analyses. The assemblage contains morphologically pristine remains of plants, algae, fungi, bacteria, and animals. Using a combination of infrared spectroscopy (both benchtop and synchrotron based), multivariate statistics and machine learning, we can successfully help resolve the long-debated affinities of the first terrestrial giant, *Prototaxites*, a tubular organism that could reach several meters. Recent studies converged at interpreting *Prototaxites* as a possibly extinct member of higher fungal clades but were only based on morphological similarities with modern mushroom-forming fungi. Our results, coupled with complementary analyses of extracted biomarkers, show that they were molecularly different than contemporaneous fungi in the Rhynie chert. Beyond the great interest of better understanding early terrestrial ecosystems, this global approach, validated on the Rhynie chert, can now be successfully extended further back in time for the interpretation of older ambiguous, assemblages and fossils, for example in the Precambrian.

Rover-Level Cross-Calibration of the Rosalind Franklin Rover's Enfys and PanCam Instruments.

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In late 2030, the European Space Agency's Rosalind Franklin Rover will begin its journey across the Martian surface in search of past signs of life. Onboard is a suite of instruments to examine Martian geology and geochemistry. Amongst them is Enfys - an infrared spectrometer. Infrared observations can unlock the chemical makeup of the observed geology using a method known as "Geological fingerprinting" or "Infrared fingerprinting". Absorption features, typically within the shorter wavelength range of the IR spectrum, are diagnostic of key mineral groups expected to be present at the landing site including, but not limited to, silicates, carbonates, sulphates, and phyllosilicates (all of which are indicators of different geological processes and environmental conditions). Understanding the current surface of Mars is essential to deduce the planet's previous structure and potential past habitability. The identification of key minerals can provide details on the history of aqueous alteration processes on Mars – indications that liquid water, which is thought to be essential to life, was once present there. With Enfys being one of the first steps on the rover's science pathway, it will be instrumental to the mission as a whole.

Enfys uses reflected sunlight to measure the spectrum that is a combination of all the targets within its 1-degree field of view (FOV). This spectrum will be collated with the rover's Panoramic Camera system – specifically the High-Resolution Camera (HRC) which is positioned directly above the Enfys instrument. Cross-calibration of these two instruments is essential for rover operations as HRC can provide the essential visual context to Enfys' measurements. Improper cross-calibration can lead to confusing or unusable data capture. Cross-calibration will utilise a new method known as the "Automatic Crosscalibration Technique Utilising Albedo Luminance" or ACTUAL. ACTUAL was conceptualised by the Enfys PI Matt Gunn who then entrusted the planning, testing and development of the process to the author. It utilises the difference in reflective properties between highly diffusely reflective materials such as Spectralon contrasted against a low reflectivity background. By varying viewing angle and distance between the target and the system, it is possible to locate the instruments within each other's field of view. Through testing with the Aberystwyth University PanCam Emulator (AUPE), a system was devised that minimises the number of times the rover's Pan Tilt Unit (PTU) is moved, whilst also minimising the associated errors. ACTUAL will be applied to Amalia (the ground test model of the rover) and the real Rosalind Franklin in Turin once Enfys has been delivered early next year (2026).

A brief introduction to Enfys as well as an overview of ACTUAL will be presented, including ACTUAL's evolution from concepts to practice and preliminary results - an example of the process from start to finish using AUPE and the PanCam activity planning tool known as VelociRAPDer.

The efficiency of delivering prebiotic feedstocks to the early Earth with cometary impacts

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A key challenge in elucidating the origins of life on Earth is understanding how chemical feedstocks can become concentrated in environments suitable for the onset of prebiotic chemistry. This challenge is tied to significant uncertainties surrounding the early Earth's environment, including its atmospheric conditions, subaerial landmass distribution, and chemical inventory. To mitigate some of these uncertainties, an exogenous origin for vital prebiotic chemicals has been proposed via their delivery by comets. Understanding whether organic molecules can survive the violent processes involved in passing through the atmosphere and impacting the surface is therefore crucial.

To address this question, we present a holistic picture of cometary delivery by considering their passage through the atmosphere, direct impact on the planetary surface, and the population of impactors that could have bombarded the early Earth. Our open-source atmospheric entry model (*atmosentry*) shows that the evolution of a comet's trajectory and physical structure as it passes through the atmosphere is strongly dependent on its size and density, and on the atmospheric surface density. Only the largest comets escape extensive mass loss and trajectory alteration. We then combine impact simulations of icy comets of varying sizes, velocities, and angles with a simple chemical network to model the survival of hydrogen cyanide (HCN), a particularly durable feedstock molecule widely invoked in prebiotic scenarios. The survival of HCN is highest for small comets impacting at low velocities and shallow angles.

Finally, we consider the prospects for delivering prebiotic feedstocks to Earth throughout its history by applying these models to a representative comet population to estimate HCN delivery. Although we find that idealised cometary impacts within a narrow range of parameters could deliver HCN to the early Earth, these events are rare, and rarer still in an environment where the feedstocks can be concentrated. Thus, comets may not be the most efficient way to concentrate feedstocks and initiate prebiotic chemistry, highlighting the importance in considering alternative mechanisms.

Constraining elemental enrichments linked to areas of preserved organic matter in Mars analogue sedimentary rocks for future calibration of spectroscopic instruments onboard the ExoMars Rosalind Franklin Rover

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Geological and geomorphological observations indicate that the early Martian climate was able to support a widespread and long-lived hydrosphere [1-3]. In contrast to present day Mars, this warmer and wetter Noachian and Early Hesperian climate may have been habitable, and evidence of microbial life in the form of localised geochemical enrichments may be preserved within clay bearing Martian sedimentary rocks. We will use samples from the 1.0 - 1.1 Ga fluviolacustrine and estuarine sedimentary rocks of the Clachtoll and Diabaig formations (Stoer and Torridon Groups; NW Scotland), which have preserved biosignatures on billion-year timescales, to constrain a link between areas of preserved organic matter and localised elemental enrichments associated with past life[4-11]. Other analogue samples from Markarfljótsgljúfur, Graenesvatn, and Þórisvatn (Holocene age and modern Fe/Mg smectite bearing sediments; Southwest Iceland), Fortescue Group (2.72 Ga lacustrine metasediments; Western Australia), Strathclyde Group (340 Ma high TOC sandstones and shales; Scotland), and Disko Island (65 Ma crystalline basalt with magmatic reduced carbon inclusions; Greenland) will complement the above dataset. This work will form the basis for further investigations surrounding the cross-calibration of two instruments on the ESA/NASA ExoMars Rosalind Franklin Rover set to launch in 2028 with the goal to search for evidence of past life on Mars—Enfys, a mast-mounted near infrared (900 - 3200 nm) reflectance spectrometer, and PanCam, a Panoramic Camera providing geological, mineralogical, and geomorphological context through stereo and multispectral imaging [12-15].

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A new era of planetary protection for Mars

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The primary aims of planetary protection are to ensure that: 1) Scientific investigations of possible extra-terrestrial life forms, precursors, and remnants are not jeopardised. 2) Earth is protected from the potential hazard posed by extra-terrestrial matter carried by spacecraft returning from an interplanetary mission. The concept of planetary protection has received increased attention over recent years due to the emergence of new spacefaring countries and the growing involvement of commercial actors. The international standards for planetary protection have been developed through consultation with the scientific community and the space agencies by the Committee on Space Research's Panel on Planetary Protection, which provides guidance for compliance with the Outer Space Treaty of 1967 (discussed in Coustenis et al., 2025).

To date, there are five categories of requirements, which are defined based on the mission's target, type, and scientific rationale. The categories outline the recommended measures to be applied to a mission. As the mission target increases in relevance to habitability and/or the origins of life, the stringency in hardware cleanliness requirements increases. Initial guidelines were guided by a probabilistic approach (1×10^{-4}). Post-Viking, bioburden limits/ spore counts were introduced to the policy for target bodies like Mars, as it was concluded that Mars was less hospitable than initially believed. Yet, the probabilistic approach is still applied to Category III and IV (e.g., Europa Clipper) and Category V (e.g. Mars sample return) missions. This approach uses mathematical models to calculate the probability of the initial microbial contamination from a spacecraft contaminating a target body. It could benefit more complex missions where there is a need for a more advanced approach to planetary protection.

For this to be reliable, further scientific knowledge is required, e.g., our understanding of cleanroom contaminants and the biocidal impact of the mission environment, and the constraints of the mathematical models (Olsson-Francis et al., 2023; Spry et al., 2024). As part of an interdisciplinary project, we are applying a relatively deep technical mathematical/statistical approach to the planetary protection process for Mars. In this presentation, we will consider the first step in the process: estimation of bioburden. This includes a two-pronged approach: characterisation and quantification of microbial contamination in a clean room environment using molecular techniques and studying their survivability in simulated Mars conditions. This work has implications for developing a risk-informed decision approach to assess the survivability of problematic microorganisms for planetary protection.

Reference: Coustenis et al., 2025, *Acta Astronautica*, *210*. Olsson-Francis et al., 2023, *Life Sciences in Space Research 36*, 27–35. Spry et al., 2024, *Astrobiology*, *24*(3), 230–274

Can Pareto Optimality Be Evidence of Life?

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Biological evolution confronts situations in which the modification of a trait to improve the performance of one function may diminish the performance of another. Similar trade-offs occur in economics and engineering, where they are evaluated using the concept of Pareto optimality. “Pareto optimal” solutions are solutions such that performance can not be improved at any task without sacrificing performance in another. Solutions outside the “Pareto optimal” set are likely to be uncompetitive as they could be improved without negative consequences. Biologists have argued that optimisation for multiple biological functions restricts the variety of evolutionarily stable phenotypes to a Pareto set within trait-space, while promoting diversity within this set. Here, we ask whether evidence for such optimality could serve as evidence of life in astrobiology. We propose that objects whose properties lie demonstrably within a region constrained by trade-offs between biologically relevant functions are more likely to be biogenic; examples discussed here include bacterial morphology, mycelial networks and the selection of molecules. Conversely, objects with comparable characteristics to known forms of life however outside the relevant Pareto set are less likely to be biological. We conclude that the detection of Pareto optimality may disclose functionality and hence biogenicity in unfamiliar materials.

Snow algal plasticity and metabolic responses during a simulated Lunar light cycle.

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Snow algae are a group of photosynthetic extremophiles that thrive in extreme environments such as Antarctica. Some species belonging to this group can bloom under specific conditions such as high light irradiance, low nutrient availability, and during snowmelt periods (freeze-thaw cycles). These psychrophiles poses remarkable plasticity, remaining dormant in a cyst stage when conditions are unfavourable, and accumulating high value compounds such as carotenoids. The same adaptations and metabolites that give these organisms their distinctive profile might also allow them to grow on space stations and in Lunar or Martian conditions. Their ability to photosynthesize nutritious biomass whilst consuming carbon dioxide and generating oxygen make them ideal candidates for supporting extra-terrestrial human exploration. With longer-term missions, new developments like Biological Control and Life Support Systems (BCLSS)- simplistically representing a closed loop involving microalgae as the main component to provide oxygen, food, and medicine to the crew- are being investigated. To date, only model species belonging mainly to *Chlorella, Chlamydomonas* and *Limnospira* genera have been investigated for space biotechnological applications, but less research has been done using extremophilic species. An important aspect being considered for applying microalgae in space research are their long-term cultivation stability in xenic (non-axenic) or axenic conditions. Axenic cultures are completely free of any living organisms except for the microorganisms intentionally introduced in the culture whereas xenic cultures could contain a consortium of microorganisms. Maintaining axenic cultures for long-term periods is challenging and would require complex procedures in space. However, xenic cultures could be necessary for some algal species to prosper, as mutualistic interactions with bacteria and fungi have been reported for some species. Even so, xenic cultures are also susceptible to suffering bacterial blooms and pathogens that can be harmful to humans. In this study we investigate whether two snow algae isolates, a psychrophilic isolate *Limnomonas sp* 9-1A and a psychrotolerant isolate *Chloromonas sp* 34-1A could successfully adapt to a lunar cycle (~14 Earth days darkness: 14 Earth days light) to gain insight into their potential cultivation in a Moon base station. We also investigate the growth performance of the two isolates during the simulated lunar cycle cultured in axenic and xenic conditions to answer the following: Do axenic isolates grow best than the xenic isolates? Are axenic isolates susceptible to being contaminated by other organisms? Do xenic cultures get outcompeted by other cell types? Furthermore, we analysed the key metabolic shifts during the simulated lunar cycle and xenic and axenic conditions to elucidate their physiological adaptative strategies and understand which culturing conditions are more feasible to prosper in space.

Understanding the adsorption of amino acids onto montmorillonite clays through molecular simulations

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Clay minerals have a track record of long-term preservation of organics, making clay-rich soils of interest to Martian missions.[1] Amino acids are among the building blocks of life, easily synthesised, and commonly found in space.[2] However, their ubiquity means that, even preserved on extraterrestrial rocky bodies, amino acids alone do not constitute a biosignature. Clay minerals are not only capable of adsorbing amino acids, but also polymerizing them into a peptide,[3] which makes the identification of a true biosignature even more difficult.

In this case, one must find routes to distinguish these pseudo-biosignatures from true ones, that would have emerged and functioned elsewhere and only later preserved by the clay. In view of sample return missions, one must find a route to discard the samples containing pseudo-biosignatures.[4] Ideally, we must do so by only knowing the retained amino acid distribution and the mineral structure, as this is the data we realistically could obtain.[5]

To this end, we have studied the adsorption of 20 proteinogenic amino acids onto montmorillonite clay (SWy1) in the presence of 4 cations. The knowledge of the selectivity of the mineral toward adsorbed species allows us to suggest the composition of a polymer generated by this mineral surface. Anything matching the predicted composition can be confidently discarded as a pseudo-biosignature. On the other hand, the presence of amino acids that are unlikely to be adsorbed by this mineral under the given conditions will suggest the sample should be investigated further and potentially returned to Earth for in-depth studies. [4]

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Latest Results from the JCMT-Venus Atmospheric Monitoring Project

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Venus' cloud deck has long been debated as a potential habitat, owing to a temperate layer with Earth-like temperatures and pressures. Greaves et al. (2021) reignited the debate by detecting phosphine (PH_3)—a potential biomarker on terrestrial planets (Sousa-Silva et al., 2020)—in that layer. Extensive follow-up studies have yet to identify any chemical or geological pathway capable of producing the observed abundance, leaving biological production as the only plausible explanation to date (Bains et al., 2021).

To explore this mystery, we performed the large JCMT–Venus project, conducting four multi-week observing campaigns in February 2022, July 2023, September 2023, and April 2025. These observations targeted PH_3 alongside other key atmospheric species, including H_2O (via HDO) and SO_2, with the goal of constraining potential phosphine-generating mechanisms and refining our understanding of Venus' atmospheric chemistry. Here, we present our latest results on the variability of these gases over both short-term (daily) and long-term (yearly) timescales.

Nitrate-dependent Sulphur oxidation on Mars? Insights from a high-altitude Andean Lake.

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Evidence for hydrological activity on the martian surface during the Noachian (4.1 – 3.7 Gya) and Hesperian (3.7 – 3.0 Gya) is extensive, with low-energy lacustrine environments posited as ideal for the preservation of biosignatures within sedimentary material[1,2]. The detection of phyllosilicates and hydrated secondary minerals in Gale crater by the Curiosity Rover confirmed the presence of a long-standing liquid body of water, raising questions about habitability and the potential for an endemic microbiome.
High-altitude Andean lakes (HAALs) within the Central Andean dry Puna are subject to poly-extreme conditions, with elevated ultraviolet radiation (UV) levels, large diurnal temperature fluctuations, negative water balances, and seasonal ice cover. These environments present an opportunity to study microbial communities that are subject to geo and physicochemical conditions analogous to those within crater lakes, such as the lacustrine system within Gale Crater, during the Noachian-Hesperian transition[3].
Water and 30 cm sediment core samples were collected from five points around a previously uncharacterised HAAL, Laguna de Antofagasta (LDA; -26.111148, -67.407338) located in the Catamarca province of Argentina. Samples were transported to the Open University, UK, at 4 °C. DNA was extracted using the XS buffer method[4] and sequenced using a metagenome shotgun sequencing approach. The taxonomic composition and functional potential of water and lake sediment sample microbiomes were assessed using genome-resolved metagenomic approaches.
A non-redundant set of 19 metagenome-assembled genomes (MAGs) was produced. Genes associated with the oxidation of inorganic sulfur compounds, nitrate reduction, and dissimilatory nitrate reduction to ammonia (DNRA) were identified in all sediment cores. This result highlights sulphur oxidation and denitrification as key metabolic strategies within LDA lake water and sediments. These findings support previous studies[3,5,6], suggesting sulfur oxidation and nitrate reduction may have been viable metabolic strategies in martian paleolakes.

Thank you to Research England Expanding Excellence in England fund [grant code 124.18] and Europlanet (21-EPN-FT1-026) for funding this research.

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Bubbles are rockets for microbes: predicting microbial dispersion in the plumes of Enceladus based on bubbling in Iceland's geothermal springs.

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The Cassini mission confirmed Saturn's moon Enceladus has a sub-surface ocean, that is hydrothermally active and contains the ingredients for life[1]. The moon also produces supersonic plumes that eject aerosolised droplets of ocean water into space, likely formed by vigorous bubbling of hydrothermal gases[2-3]. Dependent on these bubbling mechanics, and if life is present in the ocean, long distance microbial dispersion may occur via the plumes, allowing for sample collection by spacecraft. Despite this theory, it is unknown how, or what, evidence of microbial life might be transferred into the plumes. Here results of *in situ* sampling and aerosol monitoring at the Ölkelduháls geothermal field in Iceland, utilising hot springs as analogue sites for Enceladus plume formation, are discussed. Iceland was selected as its geothermal springs, and the ocean of Enceladus, both share aerosolization driven by bubbling of hydrothermal gases and host niches for chemotrophic microbial communities[4]. Data indicate that these springs produce, and eject, orders of magnitude more aerosol compared to the background environment. Spring-generated downwind aerosol is dominated by large droplets (~2.5-10 μm diameter); this trend is not observed in the background environment, where particulate size ranges were of roughly equal proportion. Aerosol abundance also sharply decreases with distance, but the high proportion of larger droplets is maintained until interrupted by changes in local topography. Flow Cytometry indicates a range of particulates present in all samples, including potential microbial cells; ongoing Florescence Microscopy seeks to verify this. Spring samples contained comparably varied particulate populations compared to the downwind aerosol samples, suggesting these are a limited representation of their source fluid. Ongoing DNA sequencing seeks to classify the microbial composition of the springs, the generated downwind aerosol, and the upwind background environment to validate this observation. Overall, by understanding the ejection and dispersal of aerosol from Earth hydrothermal systems, this work can help inform sampling strategies for future life detection missions at icy moons with plumes.

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The Effects of Continental Configuration on the Climates and Habitability of Tidally Locked Exoplanets: An Exploration in Exo-Ecology

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Climatology of tidally locked exoplanets has grown substantially in recent years, with particular focus on the TRAPPIST-1 planetary system, advancing our understanding of the habitability of these planets. Studies have investigated the effects of various rotation rates, surface material, albedos, and atmospheric compositions on surface climate, atmospheric dynamics, and habitability, although few have explored the effects of land distribution. This study evaluates the effects of continental configurations on the surface climate, atmospheric circulation, and habitability of TRAPPIST-1e.

Six distinct continental alignments based on three timesteps from Earth's geological history were applied as plausible unknown configurations. TRAPPIST-1e was simulated under a Nitrogen-dominated atmosphere using ROCKE-3D, examining surface temperature, precipitation, sea-ice extent, cloud cover, and wind patterns. Surface habitability was evaluated using a novel metric developed by Woodward et al. (2024) which constrains complex and microbial habitability within temperature and precipitation limits. Complex habitability distributions were further subdivided into terrestrial vegetative ecological biomes based on their Earth-based limits of temperature and precipitation for clear comparison to familiar ecosystems. This informed an investigation of exo-ecology (the ecology of exoplanets), including evidence-based speculation of sub- and antistellar ecosystems.

Results indicate where land/ocean fractions are near even and evenly distributed, precipitation is widespread with a strong equatorial heat band allowing for wide areas of complex habitability in the substellar hemisphere. With large substellar oceans, mean global temperatures are higher, although available substellar habitable land is reduced due to an antistellar concentration of land. With a large contiguous substellar continent, substellar temperatures are highest and evaporation is greatly reduced, limiting precipitation and habitability to coastlines and high latitudes. This study suggests TRAPPIST-1e could remain habitable regardless of continental configuration, underscoring the need for characterisation of this exoplanet using advanced instrumentation such as JWST to determine its atmospheric composition and surface features.

Woodward, H. L., Rushby, A. J., & Mayne, N. J. (2024). *A novel metric for assessing climatological surface habitability*. http://arxiv.org/abs/2407.05838

Characterising the Behaviour of Self-Organising Silica Biomorphs Resembling Mycelial Networks

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As the search for both evidence of the earliest Earth lifeforms and signs of extraterrestrial life intensifies, the ability to identify true markers of life, from their false, abiotic mimics is becoming increasingly crucial. 'Silica biomorphs', formed abiotically through the co-precipitation of barium carbonate and silica, self-assemble into complex, sinuous microstructures distinct from their underlying atomic structure. An array of architectures has been observed whose curvilinear nature is suggestive of biogenicity, thereby presenting a challenge for distinguishing life based on morphology. While some biomorph architectures have been well documented, such as those resembling leaves, corals and double helices, this research investigates a novel morphology in which anastomosing branches form interconnected networks with a striking resemblance to fungal mycelia. In initial experiments, networks precipitated during the diffusion of carbon dioxide into a solution of sodium metasilicate and barium chloride have shown a strong dependence of network density on initial concentrations of barium chloride. Building on this, ongoing work will focus on characterising additional network features, such as branching rate and connectivity, and how these are influenced by initial conditions including pH and barium chloride concentration. With recent uncertainty around suspected fossils resembling mycelial networks, this research will establish a more comprehensive abiotic baseline of mineral morphologies. It is this baseline which will provide critical reference point against which to look for anomalies suggestive of life.

Microbial Utilisation of Tholins and its Industrial Applications

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The bioavailability and toxicity of tholins, present on celestial bodies such as moons, exoplanets, comets, and the early Earth[1], were tested using various bacterial species. Biofabrication, using tholins as a carbon source, was further evaluated through polyhydroxybutyrate (PHB) production by *Cupriavidus necator*[2]. This gave insight into future industrial capabilities for astronauts on tholin-rich planetary bodies and the potential for life to emerge and thrive using these compounds on the early Earth and elsewhere. Analogues of Titan's tholins were created by the scientists of LATMOS at IPSL by employing the PAMPRE method[3], simulating cosmic rays and magnetospheric particles through radio frequency coupled cold plasma discharge. Growth curve analysis in aerobic and anaerobic environments indicated that although tholins are toxic to most species, some can persist in their presence, though it remains unclear whether the cells metabolize them. FTIR and Raman spectroscopy were utilised to test for PHB production in *C. necator*[4,5], but none was directly observed. The variability in tholin structure may have compromised the spectra's intricacies, making it difficult to discern the true samples' content. This study shows that tholin toxicity can be overcome by continuous cell division with another accessible carbon source. The research sheds light on the potential use of tholin and tholin-like compounds in future space settlement.

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Enfys: A Near-Infrared Spectrometer for the ExoMars Rosalind Franklin Rover

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The main goal of the ESA ExoMars Rosalind Franklin (EMRF) rover mission is to search for past and present life on Mars [1]. Enfys is a new near-infrared spectrometer, added to the mission in 2023, currently under development, before Flight Model (FM) delivery in 2026 and launch in 2028 [2]. The EMRF rover will land in Oxia Planum in 2030, and Enfys will form part of the suite of remote sensing instruments used for geological context, identification of mineralogy, and target selection. Enfys will play a major role not only in mission operations, but also in helping to link orbital and in situ observations and interpretations. Enfys instrument design is based around utilizing two near-infrared Linear Variable Filters (LVTs), each with a dedicated detector. An uncooled InGaAs photodiode is paired with a LVF covering the wavelength range 0.9 – 1.7 μm. A cooled InAs photodiode is paired with a LVF covering the wavelength range 1.6 – 3.1 μm. Both LVFs are translated simultaneously on a mechanical stage.

We are carrying out concurrent and complementary projects to ensure rigorous calibration [3], and to maximize the scientific return from Enfys through preparative data modelling and simulation [4; 5] and field-testing Enfys on analogue geological targets. Our recent field-tests have focused on 1 billion year, unmetamorphosed mudstones and sandstones within the Clachtoll and Diabaig Formations, NW Scotland [6], with upcoming field tests focusing on younger, mafic lake mudstones and siltstones in Iceland this summer. These analogue field-tests will be used to explore (a) IR reflectance signatures of multiphase phyllosilicates and poorly-crystalline alteration phases in natural samples, and (b) the IR reflectance signatures that capture mineralogical and geochemical changes that are associated with preserved microbially-derived organic carbon [7].

Acknowledgements: We are grateful for support from the UK Space Agency (grants ST/Z510427/1, ST/Z510415/1, ST/Y005996/1, ST/Y005287/1).

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Mechanochemical oxidant production in the deep biosphere and its importance for early life.

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Most microorganisms on Earth live below the surface, physically separated from photosynthetically produced oxygen and organic carbon[1]. Many of these ecosystems rely directly on the geosphere for energy[2], through reactions such as serpentinization that consume water and release utilisable H_2 gas. Mechanochemical reactions, where the fresh surfaces of mechanically fractured silicate rocks react with water, also generate H_2 gas[3] in quantities capable of sustaining entire ecosystems[4]. Unlike in serpentinization, where the oxidising products of the splitting of water (e.g. $^{\bullet/-}OH$) are 'locked away' in minerals such as brucite, the fate of the oxidising products of mechanochemical reactions are poorly understood.

Our group has recently shown that at higher temperatures (> 80 °C) and over timescales of ~ 1 week, the yield of oxidants such as H_2O_2 formed mechanochemically increases, correlating with a drop off in H_2 generation[5]. If microorganisms living around subsurface fault zones could utilize these oxidants, then this could greatly expand the energy available for growth.

Our project, CERBERUS, will determine the whether the temperature dependent reaction of mechanochemically activated minerals with water can be an important element of the overall energy metabolism of the subsurface biosphere, and its significance for the development of life early in the history of the Earth and potentially other planets and moons.

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Chiral sugar utilization by Icelandic hot spring microbial communities: Implications for habitability beyond Earth

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Understanding the metabolic capabilities of microbial communities in extreme environments is essential for assessing the potential for life beyond Earth [1–4]. In particular, the utilization of rare chiral compounds such as sugars - compounds delivered to planetary surfaces via meteorites - may hold the key to understanding how life could survive in environments beyond Earth such as Mars or icy moons like Europa [5–7].

This study investigates the ability of microbial communities from Icelandic hot springs – analogues for extraterrestrial hydrothermal systems [8–12] - to use common and rare chiral sugars (D-, L-, and DL- forms of glucose, mannose, xylose, arabinose, ribose, and lyxose) as sole carbon and energy sources. Conducted under anaerobic conditions at elevated temperatures, the research employs a multi-parametric approach to track microbial growth. Metagenomic analysis complements these eTorts by providing insights into the genomic basis of metabolic pathways involved in sugar utilization.

The study explores whether microbial communities exhibit enantioselective preferences for these sugars (as they do for chiral amino acids[13]) and whether evolutionary biases influence their ability to integrate these compounds into metabolic processes. Given the rarity of certain sugars on Earth, this work also examines the implications of their bioavailability and the adaptability of microbial life to extraterrestrial carbon sources. These findings can provide valuable insights into the fundamental bioavailability of rare organics found in extraterrestrial rocks, oTering a deeper understanding habitability for life elsewhere in our Solar System.

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Using Spectral Libraries to optimise spectral analysis with Enfys and Pancam

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The Rosalind Franklin ExoMars Rover (EMRF) is set to launch in 2028, with the primary goal of finding Martian biosignatures at the landing site, Oxia Planum, in 2030. The infrared spectrometer on the mast of the EMRF rover, Enfys, has a wavelength range of 0.9 - 3.1 μm to overlap with the PanCam instrument [2] for multispectral imaging to identify key mineralogical features [1]. Enfys will play an important role in identifying drilling sites for in-situ analysis by the suite of analytical instruments onboard the rover [2-5].

Before launch it is necessary to know how effective Enfys and PanCam are at identifying the mineralogical compositions of martian surface materials. The 12 PanCam filters covering a range of 0.44 -1 μm were specifically chosen to be sensitive to minerals formed in the presence of liquid water e.g. ferric minerals and clays [1]. While Enfys covers a wavelength range of 0.9 - 3.1 μm, overlapping with Pancam's spectral range, to identify the features of key target minerals such as phyllosilicates, sulfates, carbonates, and other hydrated phases (e.g. borates, nitrates, ammonium-bearing minerals).

To evaluate Enfys' detection capabilities, high-resolution laboratory spectra from RELAB [6], MICA [7], VISOR [8] , and USGS [9] libraries have been resampled by convolving the spectra with Lorentzian transmission profiles that represent the spectral response function of Enfys' channels [10]. To provide a representative assessment of how Enfys will perform under realistic surface conditions, the resampling process included a wide range of grain sizes and mineral mixtures drawn from the spectral libraries and analogue samples. In line with ExoMars mission objectives, the developed methods must be able to characterize potential drilling targets by detecting minerals associated with past water activity. To assess the performance of Enfys after spectral resampling, a variety of error metrics have been devised, that can be split into categories depending on whether they measure overall numerical deviation or spectral feature preservation.
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Aberystwyth University Low Pressure Wind Tunnel.

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Aberystwyth University has produced a versatile planetary environment chamber to investigate planetary processes and test space hardware. The apparatus has two configurations: a wind tunnel to simulate atmospheric processes and aeolian transport of other planets (e.g. Mars), and a vacuum chamber to simulate the space environment.

The test section contains a 45cm by 60cm optical breadboard for test sample mounting. There are plenty of electrical and optical feed-throughs to allow for different experimental configurations. Illumination of the test section is achieved with a AAA-class solar simulator that produces an output up to 1 kW/m^2. The humidity and temperature can be tracked. The temperature of samples or regions in the test section can be cooled with liquid nitrogen or CO_2 ice. The system's humidity can be increased with water being injected as a liquid or vapour.

In the wind tunnel configuration, the test section is 52 cm long with a 15 cm diameter with a stable and uniform wind speed up to 12m/s at Earth's atmospheric pressure. The wind tunnel can be operated at pressures between 1 bar to less than 1 mbar (<1% of Earth's atmosphere). Gases in the wind tunnel can be replaced by a custom composition to mimic other planets' atmospheres. The velocity of the wind is measured with a laser Doppler anemometer, which is a non-invasive velocimetry device. While wind is being simulated, dust can be injected with a cold gas thrust.

The system can be operated as a vacuum chamber, with a working area of 81cm long by 48 cm wide and 70 cm high, that can reach high vacuum pressures. This allows simulation of the space environment with the sample temperature, electrical and optical feed-throughs, and illumination of the system remain identical to when used as a wind tunnel.

The wind tunnel will simulate aeolian dust in the Martian atmosphere to study the transport and deposition of dust onto the PanCam Calibration Target and other rover surfaces, including solar cells. The solar cells and Calibration Target are observable surfaces by Enfys on the Rosalind Franklin rover, providing surfaces for the study of the dust's composition and reflection spectrum. This work will allow the in-flight reflectance calibration of Enfys with dust obscuring the calibration target.

There are many possible experiments that the chamber can achieve with its wind simulation, large test section, low pressures, humidity control, temperature control, and illumination. We await future ideas and collaboration.

Metasomatism is a Source of Methane on Mars

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The abundance of inactive Martian volcanic centres suggests that early Mars was more volcanically active than today. On Earth, volcanic degassing releases climate-forcing gases such as H_2O, SO_2, and CO_2 into the atmosphere. On Mars, the volcanic carbon is likely to be more methane-rich than on Earth because the interior is, and was, more reducing than the present-day Terrestrial upper mantle. The reports of reduced carbon associated with high-temperature minerals in Martian igneous meteorites back up this assertion. I will present the results of irreversible reaction path models of the fluid-rock interaction to predict carbon speciation in magmatic fluids at the Martian crust-mantle boundary (Rinaldi et al., 2024). We find methane is a major carbon species between 300 and 800 ºC where log$f$$O_2$ is set at the Fayalite = Magnetite + Quartz redox buffer reaction (FMQ). When log$f$$O_2$ is below FMQ, methane is dominant across all temperatures investigated (300-800 ºC). Moreover, ultramafic rocks produce more methane than mafic lithologies. The cooling of magmatic bodies leads to the release of a fluid phase, which serves as a medium within which methane is formed at high temperatures and transported. Metasomatic methane is, therefore, a source of reduced carbonaceous gases to the early Martian atmosphere and, fundamentally, for all telluric planets, moons, and exoplanets with Mars-like low log$f$$O_2$ interiors.

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The 1977 Wow! Signal: A Systems-Level Environmental Framework for Transient Radio Phenomena

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The 1977 Wow! Signal remains one of the most enigmatic transient radio phenomena ever recorded. While its origin remains unknown, traditional approaches have largely focused on narrow-band radio analysis and assumed extraterrestrial intelligence as the primary explanatory model. This paper proposes a novel systems-level environmental framework, analyzing the Wow! Signal within the broader context of Earth's magnetosphere, ionospheric conditions, and potential signal mimicry across electromagnetic domains. By integrating data from archival X-ray sources (e.g., Nova Ophiuchi 1977), geomagnetic indices, and solar activity, the study reveals a convergence of anomalies during the August 1977 window that suggests the signal may have emerged through complex atmospheric or magnetospheric interactions, or served as a cross-domain communication artifact. This hypothesis repositions the Wow! Signal within astrobiological discourse not merely as an isolated beacon, but as part of a dynamic environmental system — with implications for future SETI detection protocols and signal verification methodology.

A reactor to investigate the mechanisms for the emergence of life.

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Sub-oceanic hydrothermal systems are candidates for incubators for the emergence of life on Earth[1,2]. Of particular interest are alkaline hydrothermal vents, often called white smokers, of which the 'Lost City' hydrothermal field is the best-known example. In contrast to volcanically driven hydrothermal systems, alkaline vents are hosted exothermic serpentinisation reactions[3] and as such are characterised by comparatively moderate temperatures and vent fluids with high pH levels and H_2 concentrations. On the Hadean era Earth, these fluids would have been exhaled through minerals rich in iron and other transition elements into the anoxic ocean containing high concentrations of dissolved inorganic carbon[4]. Here we describe new experimental apparatus to mimic these processes. This flexible apparatus can use different initial liquid or gas reactants over mineral substrates at elevated pressures and temperatures up to 150 °C. Targeted analysis of any organic molecules generated in the liquid, gas and solid phases can be used to identify potential precursors of biologically relevant molecules. While current research is focused on mimicking the chemistry of hydrothermal systems on the early Earth, future research can focus on investigating whether the chemistry of the oceans and hydrothermal systems beneath the ice of Europa and Enceladus and their potential to form organic molecules particularly those that are the precursors to life[5].

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Cracking Europa's Chemical Code: Simulating the Subsurface Environment

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Jupiter's moon Europa harbours a subsurface liquid ocean beneath its icy crust, but the ice obscures any direct observations of the subsurface environment. The composition of this ice, however, may contain a compositional record of the subsurface ocean, with the presence of salts (e.g., sodium and magnesium chlorides and sulfates) demonstrating that the ocean interacts with the rocky interior [1–3]. These reactions would liberate essential ions, potentially leading to conditions conducive to life.

To fully assess whether Europa is habitable, we first need to develop a better understanding of these reactions within the subsurface environment. This can be achieved through laboratory experiments under elevated pressures and temperature, in which mineral reaction pathways can be explored (e.g. [4, 5]), and estimates of energy availability can be made. This requires the definition of plausible compositional analogues representative of the rocky interior of Europa and its ocean.

Studies suggest that Europa could have accreted from material akin to either ordinary or carbonaceous chondrites (inner and outer solar system, respectively) [6, 7], with estimates of Europa's density, moment of inertia, and Fe/Si ratio, indicating the rocky interior could be compositionally similar to L, LL, or CV chondrites [8, 9]. We will present the definition of compositional analogues based on proposed chondritic starting materials.

To obtain a plausible ocean composition, thermochemical modelling of water-rock reactions within the europan interior has been performed using CHIM-XPT [10], using the chondritic starting compositions proposed and fluids derived from plausible accreted volatiles (specifically, pure H_2O and a fluid based on cometary ices). The fluids were evolved at varying water-rock ratios, from conditions at depth through their ascent to the ocean floor [11] and were shown to carry the bioessential and redox elements needed for life. We will present a definition of the starting and evolved fluids, and their preparation for use in experimental simulations.

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Thank you to the UK Space Agency and the Geochemistry Group for their kind support of ASB10.