# Abstracts for the 1st British Planetary Science Congress

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Space Science in Scotland – selected highlights and opportunities

Sheila Rowan\textsuperscript{1, 2, 3}

\textsuperscript{1} University of Glasgow
\textsuperscript{2} The Scottish Science Advisory Council
\textsuperscript{3} The LIGO Scientific Collaboration

Corresponding author: Sheila.Rowan@glasgow.ac.uk

Scotland has a rich tradition as a nation of innovation and innovators – a tradition that continues today. One seam of that is evident in the Scottish space sector which has a distinctive profile, covering a range of exciting developments both in the academic and industrial spheres. For example a recent briefing note\textsuperscript{1} produced by the Scottish Science Advisory Council to the Scottish Government highlights the capabilities evident in delivering leadership in microsatellites, space science and satellite applications. The SSAC note “As a measure of success, in 2016 on average six flight-ready microsatellites were manufactured each month in Scotland. There are now key opportunities for Scotland to capitalise on these strengths, develop a clear space strategy and capture a share of the rapidly growing global space economy”.

Elsewhere, activities in research are also of high interest – in studies of our cosmos that are pushing the boundaries of what we currently know.

Just over a century ago, Albert Einstein realised that in his new model for space and time in our Universe (his ‘General Theory of Relativity’), space could be stretching and squashing in response to the motion of objects. These ripples in space-time - ‘Gravitational waves’ - are produced by some of the most energetic and dramatic phenomena in our universe, including colliding black holes, spinning neutron stars and supernovae. Close to 100 years after the prediction of the existence of gravitational waves, the advanced detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) detected such signals for the first time\textsuperscript{2}, starting a new era in astronomy. This talk will explain the nature of gravitational waves, describe what sources out in the Universe can produce them, explain how they are detected and what the future of this new era in astronomy might look like.

References:
Astrobiology

Abstracts for the 1st British Planetary Science Congress
What Type Of Organic?

MJ Burchell¹, KH Harriss¹

¹Centre for Astrophysics and Planetary Science, School of Physical Science, Univ. of Kent, Canterbury, Kent CT2 7NH. UK.

Corresponding author: m.j.burchell@kent.ac.uk

Organic materials are of great interest in solar system studies. But collection methods of materials from many solar system bodies are still basic. We can wait for objects such as meteorites to come to us, or we can use space missions to visit bodies. The problem with space missions, is they are relatively few, so can cover only a small number of bodies in any depth. Further, when first visiting a body, what is often done is to fly past at speed, and not land. Indeed, if a chosen body or site was of particular astrobiological significance, planetary protection protocols may preclude a direct sampling of the site. In such cases, collecting samples via high speed fly-bys is a suitable technique. This has been done at comet 81P/Wild 2 by the NASA Stardust mission for example¹. The Cassini mission to Saturn collected data on dust grains in a chemical analyser². And is often proposed for future possible missions to Enceladus (when plumes from sub-surface oceans push material up to orbital heights).

In such cases, an interesting question is what happens to an organic material in the high speed impact by which it is collected by the spacecraft? In CDA-Cassini, explicit use was made of this violent event to vaporise the projectile and measure its elemental composition via TOF mass spectrometry. In other cases the samples residues are used for subsequent analysis. But some basic questions remain. Here we ask a very basic question: can we tell the difference between an aliphatic organic and an aromatic organic after a high speed impact?

Cryogenic silicification of microorganisms from hydrothermal fluids

Mark G. Fox-Powell¹, Alan Channing², Paul Mann³, Daniel Applin³, Ed Cloutis³ and Claire R. Cousins¹

¹School of Earth and Environmental Sciences, University of St Andrews, Irvine Building, North Street, St Andrews, Fife, UK, KY16 9AL
²School of Earth and Ocean Sciences, Cardiff University, Cardiff, Wales, UK, CF10 3AT
³Department of Geography, University of Winnipeg, Winnipeg, Canada R3B 2E9

Corresponding author: mgfp@st-andrews.ac.uk

The delivery of hydrothermal fluids into low-temperature planetary surface environments is a common process in the solar system. Once frozen, silica-rich fluids precipitate cryogenic opal-A (COA) within ice-bound brine channels. We investigated cryogenic silicification as a novel preservation pathway for chemo- and photo-lithotrophic microorganisms. We found that the co-partitioning of microbial cells and silica into brine channels causes microorganisms to become fossilised in COA. Rod- and coccoidal-form Bacteria and Archaea produce cell casts on COA particle surfaces (Fig. 1), while Chloroflexus filaments are preserved within particle interiors. Natural COA particles from Iceland have similar biomorphic casts. Biomolecules and inorganic metabolic products are also captured by COA precipitation, and detectable with reflectance, FTIR and Raman spectroscopy. Cryogenic silicification is a new mechanism by which microbial biosignatures can be generated within hydrothermal environments. This work has significant implications for life-detection on Mars and Enceladus, where opaline silica deposits indicative of hydrothermal activity have been identified, and sub-zero surface conditions predominate.

Figure 1. SEM images of COA particles. (a) experimental COA lattice. (b) COA particle from Strokkur, Iceland (c, d) experimental COA containing cell casts of *R. palustris* TIE-1 (e, f) cell casts of *M. thermophilus* on an experimental COA branch.
Exploring fluvial-lacustrine sedimentary systems on Mars with the Curiosity rover

Sanjeev Gupta¹ and the Mars Science Laboratory Science Team

¹ Department of Earth Science and Engineering, Imperial College London, London SW72AZ, UK.

Corresponding author: s.gupta@imperial.ac.uk

The search for rocks with potential to contain evidence for past life on Mars is highly dependent on reconstructing the palaeoenvironmental context of sedimentary rock strata and identifying those rocks that record ancient habitable environments. We have been using NASA’s Mars Science Laboratory rover, Curiosity, to explore the sedimentary archive preserved in the ~3.7±0.1 Ga crater, Gale, for ~5 Earth years and have documented a rich array of clastic sedimentary rocks in lower Aeolis Mons (Mt. Sharp) and Aeolis Palus (the valley between the north wall of Gale and Aeolis Mons). Aeolis Mons is a 5-km-high mountain of stratified rock. Through detailed sedimentary, stratigraphic, and geochemical investigations using the rover and its tools and instruments, we have been able to derive a robust model for sedimentary evolution of potentially habitable environments in Gale at a time chronocorrelative with Earth’s early Archean. Field observations enable us to reconstruct a first order stratigraphy for these Martian rocks and identify a variety of depositional environments that range from alluvial fan conglomerates, cross-bedded fluvial sandstones, deltaic sandstones, lacustrine mudstones and aeolian sandstones. In particular, mapping of sedimentary facies along the rover traverse enable identification of a lateral facies transition from fluvio-deltaic sedimentary rocks to a finely laminated mudstone succession deposited in an open lake system. The sedimentary rock record in Gale indicates a climate with sufficient warmth and humidity to sustain river systems and long-lived lakes in the crater. A current debate is how Mars’ climate system could have achieved these conditions early in Mars’ geological evolution.
Microstructure of carbon in impact melts from the Gardnos crater

Paula Lindgren¹, Lydia Hallis², Fredrik Hage³, John Parnell⁴, Martin Lee², Ian MacLaren⁵

¹Department of Geology, Lund University; ²School of Geographical & Earth Sciences, University of Glasgow; ³SuperSTEM, SciTech Daresbury Campus; ⁴Department of Geology & Petroleum Geology, University of Aberdeen; ⁵Department of Physics & Astronomy, University of Glasgow

Corresponding author: paula.lindgren@geol.lu.se;

The behaviour of carbonaceous matter during impacts is relevant to the detection of organic compounds on the early Earth and in planetary exploration. Suevites from the Gardnos impact structure in Norway contain melt fragments with unusually high concentrations of organic carbon (5.25 ± 2% TOC, n=23). The origin of carbon at Gardnos is thought to be from immature organic-rich shale that was included in the target at the time of impact, but is no longer preserved at the site today [1;2]. The carbon occurs as a film with a thickness of 2.4±1.2 µm (n=200) at the boundary between two silicate phases, and highlights textures of immiscibility and flow within the melt. The silicate phases are secondary but probably reflect the composition of the precursor melt phases. Microprobe analyses at the University of Aberdeen show that a stilpnomelane phase is enriched in Si and K compare to a chlorite phase. TEM imaging and analyses at the University of Glasgow show that the Gardnos carbon is nanocrystalline with diffracting areas of crystallites ~1-3 nm in size. Selected area diffraction patterns have broad diffuse rings in the positions for the three strongest reflections for graphite, with an unusually large c-parameter typical for “graphon” (a type of carbon black) [3]. Electron energy loss spectra of the C K-edge of Gardnos carbon was compared to highly ordered pyrolytic graphite (HOPG), C₆₀ fullerenes and evaporated amorphous carbon. The Gardnos carbon matched best with the graphite spectra, but with a key difference: the valley between the π* and σ* peaks in the spectra is not as deep and flat at the bottom in the Gardnos carbon. By mixing some of the amorphous carbon spectra into the graphite spectra, a shape somewhat similar to the Gardnos carbon could be generated. We conclude that the Gardnos carbon is graphitic in nature but has a nanocrystalline grain size and is less ordered than HOPG. Despite extremely high temperatures in the impact melt, Gardnos carbon may have cooled too rapidly to crystallise into highly ordered graphite.

The impact of martian brine chemistry on the growth of microorganisms

M.C. Macey, N.K. Ramkissoon, S.P. Schwenzer, V.K. Pearson and K. Olsson-Francis

Faculty of Science, Technology, Engineering and Mathematics, The Open University, Walton Hall, Milton Keynes, Buckinghamshire, UK.

Corresponding author: Michael C. Macey (Michael.macey@open.ac.uk)

There is evidence that water may currently exist on Mars as brines [1-4]. The chemistries of these brines will be greatly influenced by the local lithologies [5], which would, in turn, impact on the organisms that could potentially live within them [6]. We have previously developed four geological simulants for Mars: a global composition, an early and unaltered basaltic composition, a sulfur-rich composition, and a haematite-rich composition [7-10]. Thermochemical modelling was used to determine the composition of brines associated with the alteration of the simulants under Mars-analog conditions. In this study, we assess whether microbial life would grow in these brines under martian simulated conditions.

The organisms used in these growth experiments were selected to represent a broad range of metabolic capabilities with relevance to Mars: They include methanogenic archaea (Methanosarcina soligelidi, Methanobacterium arcticum and Methanothermococcus thermolithotrophicus), as biotic processes are a potential source of methane in the martian atmosphere [11-12]. Additional organisms were species of iron reducing bacteria (Desulfosporomusa polytropa), due to the presence of iron oxides on Mars and the high amount of Fe$^{3+}$ in haematite [10]; iron oxidising bacteria (Acidovorax sp. BoFeN1), due to the high presence of Fe$^{2+}$ [13]; and sulphate reducing bacteria (Desulfomicrobium macestii), due to the high sulfur content of Paso Robles [9]. We will present details of the impact of the martian simulants on the growth and metabolism of the selected strains, which gives insight into habitability on early Mars.

Effects of oxygen-containing salts on the detection of organic biomarkers on Mars and terrestrial analog soils

Wren Montgomery¹, Samuel H. Royle¹, Elizabeth A. Oberlin², Samuel P. Kounaves¹,², Dirk Schulze-Makuch³ and Mark A. Sephton¹

¹Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, SW7 2AZ, UK.
²Department of Chemistry, Tufts University, Medford, MA 02155, USA.
³Center of Astronomy and Astrophysics, Technical University of Berlin, 10623, Germany.

Corresponding author: w.montgomery@imperial.ac.uk

The detection of chlorinated hydrocarbons by Curiosity on Mars has been attributed to the presence of unidentified indigenous organics. Similarly, oxychlorines on Earth have been proposed to be responsible for the apparent lack of organics in the Atacama Desert, where they are abundant. The presence of perchlorate in samples collected on Mars poses a unique challenge to the measurement of organics due to the oxidizing potential of oxychlorines during commonly used pyrolysis-gas chromatography-mass spectrometry (py-GC-MS) methods. Through py-GC-MS studies of samples from the Atacama Desert, we show that perchlorates and other oxyanion salts inhibit the detection of organics, but that removing oxychlorines prior to pyrolysis using aqueous extraction enables direct analysis of organic matter present. We also discuss the minimum mass ratio of perchlorate to organics required to interfere with detection. Our results confirm that aqueous leaching of samples prior to analysis is a simple and effective method to reduce perchlorate interference prior to organic analysis by py-GC-MS, allowing for more confident identification of organics.

References:
Characterisation of two Mars-analogue geothermal environments in Iceland

Moreras Marti, A.*, Fox-Powell, M., Cousins, C., Zerkle, A., Purkamo, L.

School of Earth and Environmental Sciences, University of St Andrews, Irvine Building, North Street, Fife, UK, KY16 9AL

Corresponding author: *amm48@st-andrews.ac.uk

To better understand the requirements for detecting geochemical evidence of ancient microbial life on Mars, it is important to study analogues on Earth that host conditions of relevance to Mars. Due to their ability to support chemolithotrophic life on Earth, martian relic hydrothermal systems remain a key target for exploration. Constraining the water chemistry, sediment mineralogy, and which microbial metabolisms would be realistic in early martian hydrothermal environments will inform which biosignatures may be detected.

We investigated two hydrothermal environments in Iceland: Kerlingarfjöll, situated to the SW of the Hofsjökull ice cap in central Iceland, with a rhyolitic composition [1]; and Kverkfjöll, a basaltic volcano on the NW of the Vatnajökull glacier [2]. In both locations, geothermally-sustained ephemeral pools host lithotrophic microorganisms adapted to anoxic, oligotrophic environments. By investigating both rhyolite- and basalt-hosted systems, differences in microbial biogeochemistry can be identified, allowing for the recognition of any signatures unique to the basaltic systems more typical of Mars. Water and sediments were collected from ice-melt pools at these sites, along with in-situ measurements of pH, temperature and Dissolved Oxygen (DO). Three pools at Kerlingarfjöll have temperatures from 20 to 60°C with circumneutral pH and 0.06 to 0.8 mg/L DO. Two Kverkfjöll pools have temperatures of 16.8 and 20°C, pH of 1.7 and 2.7, and DO of 0.26, 1.57 mg/L. These results will be coupled with bacterial 16S rRNA assays, XRD mineralogy, and dissolved water chemistry to introduce the context of these analogue environments in preparation for future detailed investigations into microbial sulfur and carbon isotope fractionation.


Biosignatures in high altitude environments

Philippe Nauny\textsuperscript{1}, Juozas Nainys\textsuperscript{2}, Karolis Simutis\textsuperscript{2}, Linas Mažutis\textsuperscript{2}, Martin R. Lee\textsuperscript{1}, Jaime L. Toney\textsuperscript{1}, Vernon R. Phoenix\textsuperscript{1,3}

\textsuperscript{1}School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK
\textsuperscript{2}Institute of Biotechnology, Vilnius University, Vilnius, Lithuania
\textsuperscript{3}School of Engineering, Strathclyde University, Glasgow, UK

Corresponding author: p.nauny.1@research.gla.ac.uk

High-altitude low-latitude environments experience intense solar irradiation, cold temperatures, extreme daily thermal fluctuations, and unstable liquid water. These arid and inhospitable environments could serve as Martian analogues when investigating for biosignatures.

Soil samples were collected on the Sairecabur — a volcano in the Chilean Altiplano — between 4300 and 5300 m, as depth profile. It was postulated that at high altitude, most of the microbiota, and the biomolecules they produce, will be found just above the subsurface ice layer, where liquid water is available. For this reason, a high-resolution depth-analysis of the soil was planned and samples were collected every 2 cm down to 21 cm deep, along with environmental parameters.

Physio-chemical properties of the soils were investigated, as well as the lipid and the DNA contents. Most of the lipids found are plant leaf waxes or short chain \( n \)-alkanes of potential microbial origin. Prior to their preparation for high-throughput sequencing, some of the total DNA extracts have been amplified by combining multiple displacement amplification with droplet microfluidics — to avoid amplification biases. Optimal sequencing conditions are currently being investigated.

Early metagenomic results will be presented along with geology and geoorganic chemistry data.
Biofilms and Bioleaching in Altered Gravity

N. Nicholson¹, C.M. Loudon¹, K. Finster², C. Cockell¹ and the BioRock Team³,⁴

¹UK Centre for Astrobiology, School of Physics and Astronomy, University of Edinburgh, UK
²Department of Bioscience – Microbiology, Aarhus University, Denmark
³Institute of Aerospace Medicine, Radiation Biology, DLR, Germany
⁴Department of Microbiology, Belgian Nuclear Research Centre, SCK-CEN, Belgium.

Corresponding author: n.e.nicholson@sms.ed.ac.uk

To investigate how communities of cooperative bacteria (biofilms) growing on rock substrates are altered by low gravity, a European Space Agency mission ‘BioRock’ is flying to the International Space Station at the end of 2018. New experimental hardware has been developed to allow the investigation of mineral release rates and the biofilm structure of three different organisms during micro- and martian-gravity. As well as informing us of the role that gravity plays in geomicrobial biofilms, it will enable further work on the application of microbes for bio-mining off-world environments.

Initial results from separate basalt leaching experiments with *Sphingomonas desiccabilis*, *Bacillus subtilis*, and *Cupriavidus metallidurans*, showed that biotic weathering does increase mineral release rates, and of the 43 elements examined post-ashing and ICP-MS, the Rare Earth Elements reflected this increase most reliably. *Cupriavidus metallidurans* caused the greatest increase in mineral release rates, followed by *Sphingomonas desiccabilis*.

Understanding the effects of higher gravity environments, which have also been shown to have an effect on the growth and behaviour of bacteria, would allow for a broader and more comprehensive understanding of the role of gravity in bacterial systems. We introduced a starting culture of our model organism, *Sphingomonas desiccabilis*, to a 10 x g environment, and found that while division rates were slowed, the population grew to within the same order of magnitude over 24 hours.

Simulating 10 x g in a centrifuge over the course of three weeks, biofilms were grown on basalt and examined using Confocal Laser Scanning Microscopy. The results showed clear differences, with hypergravity biofilms being more abundant than their 1G counterparts on both 2D and 3D substrates. ICP-MS analysis is currently underway to assess microbe-mineral leaching at hypergravity.
Fluid evolution within enceladus

Perera L.J.¹ Cockell. C.S¹

¹ UK Centre for Astrobiology, University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, EH9 3FD

Corresponding author: l.j.perera@sms.ed.ac.uk

Icy moons are some of the most promising candidates for the search for life beyond Earth. On Enceladus, a moon of Saturn, the discovery of a water vapor plume with geochemical signatures indicative of warm-water-rock interactions, along with a subsurface thermal anomaly, suggests that a liquid water ocean may exist beneath the icy surface¹⁻⁴. Water rock interactions will feed the geochemical evolution of a subsurface ocean and the presence of dissolved solutes will depress the freezing point of liquid water. On Earth, ice environments are known to host a rich diversity of microbial life within networks of fluid veins and inclusions, where high solute concentrations maintain a liquid water environment below 0°C⁵. However, a fluid can become uninhabitable as it freezes through the combined stresses of lowering water activity, increasing ionic strength, pH changes, water crystal formation and the general lowering of metabolic rates. Conditions within these microenvironments can vary on millimetre scales, so understanding the link between physiochemical evolution and habitability will be crucial to future life finding missions to icy bodies. Here we aim to model and characterise habitable microenvironments within icy environments, particularly the evolution of habitability in freezing salt systems.

Geobiological traces of nitrate-dependent ferrous iron oxidation

Price A.¹, Pearson V.K.¹, Schwenzer S.P.², Olsson-Francis K.²

¹School of Physical Sciences, Faculty of Science, Technology, Engineering & Mathematics, The Open University, Walton Hall, Milton Keynes, Buckinghamshire, UK.
²School of Environment, Earth & Ecosystem Sciences, Faculty of Science, Technology, Engineering & Mathematics, The Open University, Walton Hall, Milton Keynes, Buckinghamshire, UK.

Corresponding author: alex.price@open.ac.uk

Evidence from Gale Crater and orbital data indicate that Fe²⁺-bearing minerals are abundant in the martian crust [1] and NO₃⁻ is also present [2], providing a potential electron donor-acceptor redox couple for microbes throughout the history of Mars.

We investigated the ability of nitrate-dependent iron oxidisers (NDFOs), a metabolic group of micro-organisms able to use this redox couple, to grow in batch cultures with an olivine substrate as the sole Fe²⁺ source under conditions relevant to early Mars. Our results show the capability of some NDFOs for growth in autotrophic, nitrate-amended, anoxic media with inorganic carbon sources (CO₂ and CO₃⁻).

Known biomineralisation behaviours of some NDFOs [3, 4] under high [Fe²⁺] provide a mechanism by which morphological and geochemical biosignatures of these microbes could be produced and preserved in the sedimentary rock record on Mars. We will present SEM, EDX and Raman analyses of the mineral end-products, highlighting any changes associated with NDFO metabolism which could be differentiated from abiotic processes by future life detection missions.

References:
Hard rock life: metagenomes from deep terrestrial subsurface

Lotta Purkamo¹, Claire Cousins¹, Aubrey Zerkle¹

¹School of Earth and Environmental Sciences, University of St Andrews, UK

Corresponding author: lkp5@st-andrews.ac.uk

We have known the existence of the deep biosphere for over 20 years, but the microorganisms living in these environments still continue to puzzle us. Microbial life plays a crucial role in global elemental cycling and as a significant proportion of Earth’s biomass lies in the subsurface, understanding these cycles is vital. Only a small fraction of the microorganisms on Earth are cultivable, thus hampering the study of microbial functionality¹. The development of molecular biological tools, especially metagenomic DNA sequencing has allowed us to progress significantly in understanding the complexity and versatility of deep subsurface communities². We studied microbial communities from ancient deep crystalline bedrock from two different locations in Finland. The amplicon sequencing of the 16S rRNA gene suggested that the microbial communities in these environments express low diversity. The copy numbers of the 16S rRNA gene of bacteria and archaea varied in these samples from less than 10 copies to a few hundred copies, bacteria being more numerous than archaea. The initial analysis of metagenomic data from groundwater from 2.2 km depth revealed that ~19% of annotated protein sequences related to biological processes affiliated with metabolism, while proteins involved in transport (~10%) was the second most common group. Proteins involved in molecular functions were frequently affiliated with nucleic acid and nucleotide binding, catalytic and oxidoreductase activity and ion binding. The results of the detailed investigation of the metagenomic data is expected to provide insights into the microbial metabolism, adaptation and survival in hard rock habitats and provide constraints on life and habitability on Earth and beyond.

The development and characterisation of four new martian simulants for use in microbiological experiments


Faculty of Science, Technology, Engineering and Mathematics, The Open University, Milton Keynes, MK7 6AA, UK.

Corresponding author: nisha.ramkissoon@open.ac.uk

In this study, four new martian simulants have been developed for specific use in a series of microbiological simulation experiments. Although martian regolith simulants already exist [1-6] they do not possess all the key requirements necessary for the proposed simulation experiments, because their geochemistry is, generally, based on an ‘average’ surface composition and not on specific locations that have been analysed by spacecraft. Even more importantly, they generally have a lower abundance of iron and a higher abundance of aluminium than the martian regolith. In our simulation experiments, the oxidation of Fe$^{2+}$ to Fe$^{3+}$ is a crucial source of energy for microbial life so the ability to control/alter the Fe$^{2+}$/Fe$^{3+}$ ratio is paramount.

Using a mixture of gabbro, Fe$^{2+}$-silicate glass and various Mars-relevant minerals, we have developed simulants that represent four specific martian chemistries (including a close approximation of iron content and Fe$^{2+}$/Fe$^{3+}$-ratio): i) a global martian regolith based on Rocknest at Gale crater, ii) a sulfate-rich regolith based on Paso Robles at Columbia Hills, iii) an iron-rich regolith based on Haematite slope at Meridiani Planum and iv) an ‘unaltered’ basaltic chemistry based on a basaltic Shergottite.

These simulants will allow us to examine how differing physical and chemical conditions could affect potential microbial life on Mars and their bio-signatures. Using thermochemical modelling we have derived the potential brine chemistries for these simulants, which will enable us to simulate different martian environments for microbial growth experiments.

We will present the chemical composition of these new simulants, their associated brines chemistries and an outline of the martian simulation experiments.

Effect of hydration state of Martian perchlorate salts on their decomposition temperatures during thermal extraction

Samuel H. Royle\textsuperscript{1}, Wren Montgomery\textsuperscript{1}, Samuel P. Kounaves\textsuperscript{1,2}, Mark A. Sephton\textsuperscript{1}

\textsuperscript{a} Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, London, UK;
\textsuperscript{b} Department of Chemistry, Tufts University, Medford, Massachusetts, USA

Corresponding author: s.royle@imperial.ac.uk

A number of missions to Mars have analysed the composition of surface samples using thermal extraction techniques. The temperatures of decomposition have been used as diagnostic information for the materials present. One compound of great current interest is perchlorate, a relatively recently discovered component of Mars surface geochemistry that leads to deleterious effects on organic matter during thermal extraction. Knowledge of the thermal decomposition behaviour of perchlorate salts is essential for mineral identification and possible avoidance of confounding interactions with organic matter.

We have performed a series of stepped pyrolysis experiments on samples of magnesium perchlorate hydrate which were dehydrated to various extents – as confirmed by XRD and FTIR analysis. This revealed that the hydration state of magnesium perchlorate has a significant effect on decomposition temperature, with differing temperature releases of oxygen corresponding to different perchlorate hydration states. We find that the peak temperature of oxygen release increases from 500 to 600\textdegree C as the proportion of the tetrahydrate form in the sample increases and the hexahydrate form decreases.

Our work therefore shows that the hydration state of these salts can affect the temperature of oxygen release just as much as cation chemistry. Consequently, incorrect identification of perchlorate species may occur if hydration state is not taken into account and a mixture of metastable hydration states (of one type of perchlorate) may be mistaken for a mixture of perchlorate salts. Our findings are important for Mars as the hydration state of salts in the regolith may change throughout the Martian year due to large variations in humidity and temperature.
A lacustrine ecosystem in Gale Crater and the biosignatures left behind

Adam H. Stevens\textsuperscript{1}, Alison McDonald\textsuperscript{2}, Charles S. Cockell\textsuperscript{1}

\textsuperscript{1}UK Centre for Astrobiology, University of Edinburgh
\textsuperscript{2}Bioimaging Facility, School of Engineering, University of Edinburgh

Corresponding author: adam.stevens@ed.ac.uk

The Curiosity rover has found evidence for a long-lived habitable environment in the sedimentary record of Gale Crater on Mars. The geochemistry of the mudstones suggests that the lake filling the crater had a neutral pH, low salinity and contained all the elements required by life\textsuperscript{1}. Given the contemporary discovery of numerous sedimentary systems on Mars and their potential for preserving biomarkers\textsuperscript{2}, analogues of these sedimentary environments are of interest to prepare for future missions.

We produced a geochemical analogue (Y-Mars) that simulates the Sheepbed mudstone of Gale Crater by mixing minerals in proportion to match XRD data from Curiosity\textsuperscript{3}. Y- Mars reproduces an XRD diffractogram qualitatively similar to that observed by Curiosity and has a spectral reflectance comparable to other Mars analogue materials in the visible to near-IR range.

Y-Mars can be used to test important astrobiological techniques and methods in material analogous to what will be explored by future Mars missions, including the ExoMars rover. For example, Raman spectroscopy will be included on both the ExoMars and NASA 2020 rovers\textsuperscript{4}, but the Y-Mars analogue material displays Raman features that would potentially interfere with organic molecule detection. Our analogue can be used in a number of experiments, some of which we will described here, but the production of Y-Mars highlights the need for a more diverse selection of Mars analogue materials.

References:
The Fate of Lipid Biomarkers in a Mars-Analogue Sulfur Stream

Jonathan Tan¹, Mark Sephton¹

¹Organic Geochemistry Laboratory, Department of Earth Science and Engineering, Imperial College London, SW7 2AZ, United Kingdom

Corresponding author: jst110@imperial.ac.uk

If past life evolved on Mars, it would have generated organic remains in the form of biomarkers preserved in present day Mars rocks [1]. Of the potential biomarkers that are accumulated, biological lipids are the most resistant to degradation and thus become concentrated in the rock record [2]. The latest period in martian geological history that supported widespread surface water was the late Noachian to early Hesperian (3.7 Ga) [3], which had the potential to sustain the most evolved and widely distributed martian life. Acidic, sulfur-rich streams can be used as geochemical analogues for this period in martian history [4], and the investigation of the preservative qualities of the iron sulfates and iron oxides in these environments can guide future missions to Mars.

This study reports the organic signal of an acidic stream containing acidophilic, iron- and sulfur-reducing organisms. The data is derived from gas chromatography-mass spectrometry (GC-MS) analysis of free fatty acid Bligh-Dyer extracts of the acid stream samples (Figure 1). Acid stream data show that a significant amount of fossilised organic material is retained in the form of a diverse suite of biological lipids, preserved in goethites that have replaced pre-existing jarosites. The data shows that these fossils can potentially survive mineralogical transformation in Mars rocks, and are concentrated in rocks that suggest persistent aqueous conditions. Due to their demonstrated preservation potential, iron oxide remnants of sulfur-rich environments are good candidates for future life detection missions on Mars.

Figure 1: Lipid distribution and diversity of the total lipid extract of a core in the sulfur stream, consisting of the overlying microbial mat, the goethite-rich stream precipitates and the underlying country rock.

Building Solar Systems

Abstracts for the 1st British Planetary Science Congress
The permeability of stagnant lids: diffusive loss of volatiles in Venus and Venusian-type exoplanets

Geoff D. Bromiley\textsuperscript{1} & Nicci J. Potts\textsuperscript{1}

\textsuperscript{1}School of GeoSciences, University of Edinburgh, Edinburgh, UK, EH9 3FE

Corresponding author: Geoffrey.bromiley@ed.ac.uk

In recent years there have been numerous reports of Earth-sized exoplanets. It is widely assumed that these planets can only support life if they lie within the habitable zone of the stars which they orbit, and exhibit plate tectonic style convection, where fractured lithosphere is recycled into a vigorously convecting mantle. However, in our solar system plate tectonics is uniquely confined to the modern Earth, with most rocky bodies displaying stagnant lid type regimes, in which thick, stable lithosphere is uncoupled from a convecting interior. Therefore, in order to identify potentially habitable Earth-like exoplanets we first need to understand the consequences and key characteristics of stagnant-lid type planets, especially in terms of distribution and mobility of volatile elements needed to sustain life.

Here we explore, for the first time, how effectively stagnant lids in Earth/Venus-like planets act as impermeable barriers to volatile loss. It is commonly assumed that mass loss in stagnant lid regimes only occurs via volcanic degassing and lid overturn/melting. Using a novel diffusion model, we determine mobility of volatile elements through stagnant lids over geological timescales. Conditions at the base of stagnant lids, constrained by mantle melting relations, and lid thickness have a defining influence on element mobility. Decrease is temperature through the lid ultimately results in stagnation of hydrous and diffusion fronts; stagnation distance is additionally dependent on surface conditions. For hot, Venus-like planets, diffusion of H into the lid over Gyr timescales can result in localised melting as H contents approach the lid’s storage capacity. However, melting can only occur at appreciably greater depths than in Earth-style plate tectonic models, implying that melting would not result in the formation of an Earth-like asthenosphere, which might promote a change in tectonic regime.
On the causes of silicate partial melting in planetesimals:
The combined influence of impact and radiogenic heating

Eleanor R. MARE\(^1\) and Andrew G. TOMKINS\(^1\)

\(^1\) School of Earth, Atmosphere \& Environment, Monash University, Clayton, VIC 3800, Australia.

Current affiliation: School of Earth and Environmental Sciences, University of St Andrews, Irvine Building, St Andrews, KY16 8HZ, United Kingdom.

Corresponding author: em227@st-andrews.ac.uk

Ordinary chondrite meteorites are classified into petrologic types from 3 to 7, representing progressive stages of thermal metamorphism. This metamorphism occurred within parent asteroids that were heated by both collisions with other bodies, and the decay of short-lived radioisotopes. Previous thermal models have shown that Types 3-6 can form at progressively increasing depths within an asteroid due to radiogenic metamorphism, but none have attempted to explain the silicate partial melting seen in Type 7 ordinary chondrites. We use thermal modeling to determine if these meteorites could have formed in the core region of an asteroid through radiogenic heating, or if impact-related heating was responsible. Our results indicate that both heat sources were involved; impact-related heating on an asteroid that was already warm due to radiogenic heating promotes partial melting in small domains at moderate depth, which equilibrate and cool slowly in insulated settings. This process can explain the textures seen in Type 7 meteorites and their low abundance relative to unmelted Type 3-6 ordinary chondrites. On the other hand, meteorite groups with high proportions of primitive achondrites, and few or no unmelted equivalents, such as the acapulcoite-lodranite group and the winonaites, are best explained statistically by partial melting primarily through radiogenic metamorphism.
A net-loss of Earth’s volatile elements as the result of impacts

Sami Mikhail\textsuperscript{1,2} and Duncan H Forgan\textsuperscript{2,3}

\textsuperscript{1} School of Earth and Environmental Sciences, The University of St. Andrews, UK
\textsuperscript{2} Centre for Exoplanet Science, The University of St. Andrews, UK
\textsuperscript{3} SUPA, The School of Physics and Astronomy, The University of St. Andrews, UK

Corresponding author: Sami Mikhail (sm342@st-andrews.ac.uk)

Stochastic events including primary accretion, the Moon-forming impact, late veneer, and late heavy-bombardment were fundamental to the origin and evolution of Earth’s atmosphere, and hydrosphere \cite{Morbidelli}. Therefore, these events must be quantitatively understood to discern how Earth became habitable, and by extension, to provide a rigid framework within which to categorize current and future exoplanet discoveries as potentially habitable exoworlds. To this end, impact events (i.e. late veneer, Late Heavy Bombardment, the rest of Solar System history) are the focus of a long-standing quandary; did they provide or remove Earth’s volatile elements? \cite{Marty}

Here we contribute to this line of inquiry using astronomical modelling to explain primordial noble gas abundance datasets. These data show that Venus, which is slightly smaller than Earth, has a more volatile-rich and massive atmosphere \cite{Porcelli}. We explain this observation using the results of a series of N-body simulations to show that Earth should have received significantly more impacts relative to Venus and Mars, respectively. These data rule out secondary accretion providing more volatiles to Venus, and thus imply that a chondritic (asteroidal) late-veneer resulted in a net-loss of Earth’s Hadean atmosphere. Importantly this model prohibits a chondritic late veneer from being the primary source of Earth’s volatile elements. We will show how this finding has important consequences for the search for life on telluric planets elsewhere in the Milky Way and beyond, because stochastic processes likely drove the post-accretion development of habitable (clement) environmental conditions on Earth.

FTIR and Raman Spectroscopy of Chemically Degraded CM2 Chondrites

Christian Potiszil\textsuperscript{1}, Wren Montgomery\textsuperscript{1} & Mark Sephton\textsuperscript{1}

\textsuperscript{1} Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, SW7 2AZ, United Kingdom.

Corresponding author: c.potiszil13@imperial.ac.uk

Carbonaceous chondrites record some of the earliest solar system processes, among their cargo are complex organic matter, consisting of both free and macromolecular organic matter (FOM and MOM) fractions\textsuperscript{1}. We have isolated the refractory organic matter (ROM) fraction from the MOM of the Murchison and Mighei CM2 chondrites, via chemical degradation, and undertaken, for the first time, 2D Raman and high-resolution synchrotron source FTIR spectroscopic mapping of this organic component. Whilst spectroscopic mapping of meteoritic organic matter has been performed previously\textsuperscript{2-4}, no study has compared the spectroscopic responses of different organic matter fractions. FTIR mapping of the undegraded meteorites revealed that organic matter is strongly associated with phyllosilicates in both Murchison and Mighei, in line with previous studies\textsuperscript{5,3}. Our measurements show that Murchison may have accreted with, or gained through synthesis, a higher overall carboxyl content than Mighei and that some oxygen containing components may be present in the ROM of these meteorites. Both FTIR and Raman data suggest that the ROM of Mighei and Murchison are statistically similar in composition, representing a universal organic precursor accreted by all primitive CM chondrites if not all carbonaceous chondrites.

References:
The Lunar Mantle as a Volatile Reservoir

Potts, N.J.¹, Bromiley, G.D.¹

¹School of GeoSciences, Grant Institute, University of Edinburgh, Edinburgh, EH9 3JG

Corresponding author: Nicola.potts@ed.ac.uk

Olivine, and its high-pressure polymorphs, are thought to be the largest reservoirs of volatile material, including water and fluorine, on Earth. Cycling of volatiles between the Earth’s interior and surface throughout geological time, however, has overprinted any primordial volatile signatures. As the Moon has no plate tectonics, it is expected that any volatile material present in the deep lunar interior would have been inherited during accretion and differentiation. Furthermore, it is now widely accepted that the Moon is mostly formed of proto-Earth material, or at the very least is geochemically indistinct from the Earth, making the Moon an appropriate analogue for the early Earth. Incorporation of trace elements into major minerals varies as a function of temperature, pressure, $f_\text{O}_2$, and bulk composition. Experiments were, therefore, performed in a primitive lunar mantle composition, intended to replicate the initial stages of LMO solidification with some combination of olivine, pyroxene, and melt present, and run at relevant temperatures, pressures, and $f_\text{O}_2$ (below the IW buffer). Mineral-melt partition coefficients ($D_x$) derived for volatile (F, Cl, S, $H_2O$) incorporation into olivine varies significantly compared to terrestrial studies. Preliminary results suggest that an order of magnitude more $H_2O$ can partition into the lunar mantle compared to the terrestrial upper mantle. While an inverse trend between $D_F$ and $D_{OH}$ hints towards de-coupled substitution mechanisms between H and F under low-$f_\text{O}_2$/lunar bulk composition. These results suggest that if volatile material was present in the lunar magma ocean a significant proportion could be partitioned into the lower lunar mantle. The implications of this are not only important for understanding the delivery and behaviour of volatiles during planetary differentiation but would impact any future seismic study of the Moon.
Planetary Atmospheres and Magnetospheres

Abstracts for the 1st British Planetary Science Congress
Development of CH$_4$ and C$_2$H$_6$ retrieval systems for ExoMars TGO

George Cann$^1$, Jan-Peter Muller$^1$, Dave Walton$^1$.

$^1$Imaging Group, Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK.

Corresponding author: george.cann.15@ucl.ac.uk

In 2003 methane, CH$_4$, was detected in the Martian atmosphere (10 ppbv)$^{[1]}$, which has, at most, a photochemical lifetime of a few hundred years.$^{[2]}$ This short lifetime of CH$_4$ in the Martian atmosphere implies that CH$_4$ should be uniformly distributed over Mars. However non-uniform distributions of CH$_4$ are observed.$^{[3]}$ This raises questions with regard to the source(s) and sink(s) of CH$_4$. Abiotic and biotic sources have been suggested to explain the detection, ranging from serpentinisation of olivine to methanogenesis$^{[4]}$ by methanogenic archaea.$^{[5]}$ ESA’s ExoMars Trace Gas Orbiter (TGO) NOMAD (Nadir and Occultation for MArs Discovery) instrument is expected to have sufficient spectroscopic sampling, resolving power and SNR to measure the isotopic ratios of carbon-based molecules in the Martian atmosphere.$^{[6]}$ On Earth, the ratios $^{13}$CH$_4$/C$_2$H$_6$ and $\delta^{13}$C and $\delta^2$H for CH$_4$, can be used to determine whether sources of CH$_4$ are biogenic or abiogenic.$^{[7]}$ Assuming similar conditions hold on Mars, such NOMAD measurements have the potential to address this question.

In this study, we use the HITRAN2012 database$^{[8]}$ through Hitran-on-the-Web, to simulate the spectral absorption lines, absorption coefficients and transmittance of $^{13}$CH$_4$, $^{12}$CH$_4$ and C$_2$H$_6$ in the Martian atmosphere, so as to identify the ideal wavebands to retrieve these species with NOMAD. We also comment on the development of two CH$_4$ and C$_2$H$_6$ retrieval systems, one using a variational approach and another using a statistical approach. The variational approach involves assessing an atmospheric composition-isotopologue retrieval system developed at JPL, for the OCO-2 RT Retrieval Framework.$^{[9]}$ This approach will use the retrieval system, with HITRAN2012 and the MCD V5.2,$^{[10]}$ to retrieve $^{13}$CH$_4$, $^{12}$CH$_4$ and C$_2$H$_6$ mixing ratios in the Martian atmosphere, using calibrated PSA files, generated from spectral radiance measurements by NOMAD. The statistical (machine learning) approach will use a neural network technique to empirically derive a statistical relationship between an ensemble of NOMAD measurements and an ensemble of MODTRAN®6 simulated Martian atmospheric states for $^{13}$CH$_4$, $^{12}$CH$_4$ and C$_2$H$_6$.$^{[11]}$ The results from these retrieval systems will be used to test the hypothesis that CH$_4$ and C$_2$H$_6$ in the Martian atmosphere are biogenic.

Impact of Global Model Resolution on the Representation of Martian Wind-Stress Dust Lifting

Rhian Chapman¹, Stephen Lewis¹, Matt Balme¹, Liam Steele²,¹

¹The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK
²The University of Chicago, Chicago, Illinois 60637, USA

Corresponding author: rhian.chapman@open.ac.uk

The formation of large dust storms on Mars is believed to be driven by dust lifting due to near-surface wind stress (NSWS)¹. Accurately representing this dust lifting within Mars Global Circulation Models (MGCMs) is important in order to gain a full understanding of the Martian dust storm cycle and climatology.

Model resolutions of ~ 5°x5° in latitude and longitude are often used in simulations of the Martian climate. This resolution represents large-scale weather patterns well, but small scale phenomena (e.g. near-surface winds) are not accurately depicted.

Parameterisations of dust lifting by NSWS exist within several MGCMs²,³,⁴, but few studies have explored in detail how the results of these parameterisations are affected by changing the resolution of the model. We use the LMD-UK MGCM⁵ to complete simulations across multiple model resolutions. Our experiments range from 'low' resolution ~5° lat x ~5° lon to 'high' resolution ~1° lat x ~1° lon.

In experiments with fixed lifting parameters, we find that increasing the model’s horizontal resolution results in more dust being lifted; we also find that increasing the model's number of vertical layers results in more dust being lifted. Geographical and temporal distributions of dust lifting are investigated, with the aim of developing a calibration scheme for this dust lifting across model resolutions. The scheme is verified through comparison with spacecraft observations of dust optical depths and dust storm locations.

Analysis of UV-wavelength Hubble Space Telescope (HST) images of projections of Jupiter's polar aurorae

M. N. Chowdhury\textsuperscript{1} and J. D. Nichols\textsuperscript{1}

\textsuperscript{1}Department of Physics and Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, United Kingdom

Corresponding author: mnc8@leicester.ac.uk

UV-wavelength Hubble Space Telescope (HST) images of projections of Jupiter’s polar aurorae (taken in 2016 during the Juno mission approach phase) are analysed. Emission intensities are extracted from these images and plotted as a function of time for different auroral regions. By comparing that data for various morphologies, relations between the regions are established and known phenomena, such as the main oval discontinuity, are observed. Cross-correlation techniques are also used to probe the relationship between sub-regions within the main auroral regions and determine selected statistics of features relating to the nature of temporal variations.

References:
Characterising Jupiter’s Temperatures, Aerosols and Ammonia via VLT/VISIR Spatial Mapping 2016-17

P. T. Donnelly¹, L.N. Fletcher¹, G.S. Orton², H. Melin¹

¹Dept. of Physics and Astronomy, University of Leicester, UK,
²Jet Propulsion Laboratory, California Institute of Technology, USA

Corresponding author: ptd10@le.ac.uk

The VISIR mid-IR imager (5-25 µm) on the Very Large Telescope (VLT) has been providing infrared spatial and temporal support for NASA’s Juno spacecraft, constraining atmospheric thermal conditions in the upper troposphere (100-700 mbar) and stratosphere (1-10 mbar). Our pre-Juno-arrival dataset (January-August 2016) demonstrated that Jupiter’s North Equatorial Belt (NEB) began a northward expansion in late 2015, consistent with the 3-5 year cycle of NEB activity. VISIR detected two new thermal waves during this period; an upper tropospheric wave in the mid-NEB and a stratospheric wave centred on the eastward jet at 23.9°N. The latter was quasi-stationary and both waves are morphologically similar to those observed during the 2000 expansion event by Cassini. We now extend this analysis to coincide with Juno’s perijove encounters, once every 53.5 days. We report (i) the continued existence of the mid-NEB wave; (ii) evolution of Jupiter’s North Temperate Belt (NTB) following the October 2016 outburst; and (iii) complex thermal variability associated with a mid-SEB outbreak during 2017. We discuss zonally-averaged temperatures, aerosols and ammonia distributions derived from VLT data (taking centre-to-limb variations into account), comparing the upper-tropospheric aerosols and ammonia to the findings of Juno’s near-infrared and microwave observations.

Figure 1 (above): VLT/VISIR 17.65-µm observation for 11 Jan 2017, probing upper-tropospheric (150mbar) temperatures showing persistent wave activity over the NEB region. NEB and NTB shown by yellow arrows.

Figure 2 (left): VLT/VISIR 8.6-µm observation for 10 Jan 2017, probing cloud-tops (650mbar). The NTB and the outbreak in the mid-SEB are denoted by the yellow arrows.
The Mars Modelling Information Tool for Engineering (MarMITE): A study on the Impact of Local Dust Storms

A. El-Said¹, S.R. Lewis¹, J.A. Holmes¹, M.R. Patel¹, D. Terrett², H. Morris², P.L. Read³, R.M.B. Young³, G. Parnaby⁴.

¹The Open University, ²RAL Space, ³Oxford University, ⁴Fluid Gravity Engineering.

Corresponding author: adam.el-said@open.ac.uk¹

Mars exploration is a means of understanding the wider planetary consonance of our solar system. Mars is therefore observed for scientific and engineering endeavours to further current understanding of planetary processes such as; circulation dynamics, aerosol and trace species composition and behaviours and geological composition and chronology. A Martian Global Circulation Model (MGCM) is a successful tool aiding in both scientific (processes) and engineering (entry, descent and landing systems) endeavours. However, MGCM’s require considerable expertise and time to run and therefore cannot be easily utilised by non-specialist users. The purpose of MarMITE is to enable wider-community access to MGCM data, alleviating requirements of expertise and time otherwise needed to operate a GCM. MarMITE consists of a newly developed software interface, making use of the Mars Climate Database (MCD), [1], and newly developed models. MCD data is composed of the statistical and mathematical summary of several MGCM simulations of typical Mars Years, [2].

The MarMITE project constitutes two principal elements; investigative modelling and software development. The investigative modelling element, which quantifies areas of uncertainty in MCD data, is composed of: boundary layer, detached dust layer and local dust storm impact studies, and data assimilation validation exercises.

Here we present modelling results on the impact of local dust storms, which show a succession of mechanistic effects. Our simulated storms show an impact on perturbations in the short and longwave radiative flux fields, resulting in an increased diurnal thermal tide amplitude that galvanises, sometimes quite severely, wind velocity changes throughout the atmosphere.

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References:
Saturn at Northern Summer Solstice:  
The Grand Finale of the Cassini Mission

L.N. Fletcher¹, S. Guerlet², G.S. Orton³, J.A. Sinclair³, T. Fouchet⁴, P. Irwin⁵, F.M. Flasar⁶

¹ Department of Physics and Astronomy, University of Leicester, UK; ² Laboratoire de Meteorologie Dynamique, Paris, France; ³ Jet Propulsion Laboratory, Pasadena, USA; ⁴ LESIA, Observatoire de Paris, France; ⁵ Atmospheric, Oceanic and Planetary Physics, University of Oxford, UK; ⁶ NASA Goddard Spaceflight Center, Maryland, USA.

Corresponding author: leigh.fletcher@le.ac.uk

Cassini’s orbital exploration of Saturn (2004-2017) spanned from northern winter to northern summer, providing an unprecedented database of seasonal and non-seasonal atmospheric phenomena on the gas giant planet [1]. With its 29.5-year orbital period and 26.7° axial tilt, Saturn’s atmosphere is subjected to extremes of seasonal insolation that drive complex patterns of atmospheric circulation, chemistry, and cloud formation that can be explored via thermal-infrared remote sounding. We review some of the scientific highlights of Cassini’s exploration of Saturn, and report on the completion of our long-term campaign of thermal-infrared (7-1000 μm) observations from the Composite Infrared Spectrometer (CIRS), extending previous investigations of (i) the establishment of a large, warm polar stratospheric hood (75-90°N) in the northern summer hemisphere [2]; (ii) tracking of the equatorial stratospheric quasi-periodic oscillation (QPO) and the disappearance of the strong prograde jet in the equatorial stratosphere [3]; and (iii) the aftermath of the 2010-11 storm system and ‘beacon’ at mid-latitudes [4]. CIRS observations will be compared to ground-based 7-25 μm images from the Very Large Telescope (VLT) in 2015-2017, which reveal the atmospheric conditions at Cassini’s final entry site. CIRS spectra are inverted to determine zonal-mean variability in temperatures, para-hydrogen, ethane and acetylene. The resulting distributions trace large-scale circulation patterns at the equator and poles, and disruptions of these circulations by localised dynamic phenomena.

Martian atmospheric O$_3$ retrieval development for the NOMAD-UVIS spectrometer.

W. Hewson$^1$, J.P. Mason$^1$, M. Leese$^1$, B. Hathi$^1$, J.A. Holmes$^1$, S.R. Lewis$^1$, P.G.J Irwin$^2$, and M.R. Patel$^1$.

$^1$School of Physical Sciences, Faculty of Science, Technology, Engineering and Mathematics, The Open University, Walton Hall, Milton Keynes, U.K.

$^2$Atmospheric Physics, Clarendon Laboratory, University of Oxford, Parks Road, Oxford, U.K.

Corresponding author: will.hewson@open.ac.uk

The composition of atmospheric trace gases and aerosols is a highly variable and poorly constrained component of the martian atmosphere, and by affecting martian climate and UV surface dose, represents a key parameter in the assessment of suitability for martian habitability. The ExoMars Trace Gas Orbiter (TGO) carries the Open University (OU) designed Ultraviolet and Visible Spectrometer (UVIS) instrument as part of the Belgian-led Nadir and Occultation for Mars Discovery (NOMAD) spectrometer suite. NOMAD will begin transmitting science observations of martian surface and atmosphere back-scattered UltraViolet (UV) and visible radiation in Spring 2018, which will be processed to derive spatially and temporally averaged atmospheric trace gas and aerosol concentrations, intended to provide a better understanding of martian atmospheric photo-chemistry and dynamics, and will also improve models of martian atmospheric chemistry, climate and habitability. Work presented here illustrates initial development and testing of the OU's new retrieval algorithm for determining O$_3$ and aerosol concentrations from the UVIS instrument.
Interpretation and understanding of methane plumes on Mars

J. A. Holmes\textsuperscript{1}, M. R. Patel\textsuperscript{1,2}, S. R. Lewis\textsuperscript{1}

\textsuperscript{1} School of Physical Sciences, The Open University, UK
\textsuperscript{2} Space Science and Technology Department, STFC Rutherford Appleton Laboratory, UK

Corresponding author: james.holmes@open.ac.uk

The Nadir and Occultation for Mars Discovery (NOMAD) and Atmospheric Chemistry Suite (ACS) instruments on the ExoMars Trace Gas Orbiter (TGO) spacecraft will be the first able to provide vertical profiles of multiple trace gas species, including methane. For interpretation and understanding of the retrieved methane vertical profiles, modelling studies are required to scrutinise between the different proposed mechanisms of methane release into the atmosphere, with global circulations models (GCMs) providing an invaluable tool to investigate the evolution of trace gas plumes and provide constraints on where the original source could be located, and potentially clues to its origin.

This study investigates the vertical evolution of methane from multiple different source emission scenarios, using the state-of-the-art LMD-UK Mars GCM coupled to the Analysis Correction assimilation scheme. The assimilation of temperature retrievals from the Thermal Emission Spectrometer ensures the optimal dynamical state of the atmosphere and subsequently the best constraint on the transport of tracers in the martian atmosphere.

We show that distinguishing whether the methane source is a sustained or instantaneous surface emission requires at least ten sols of tracking the emission, using methane release rates constrained by previous observations and modelling studies. A methane source must also be observed within five to ten sols of the initial emission to determine whether the emission occurs directly at the surface or within the atmosphere via destabilisation of metastable clathrates. The added constraint on global winds by the assimilation of thermal data is critical when attempting to backtrack the methane to its original source location.
Numerical Simulations of Dynamics of the Uranian Atmosphere

Chin-Min Liu¹, Peter L. Read¹, Roland M. B. Young²

¹Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford, UK
²Laboratoire de Météorologie Dynamique, Université Pierre et Marie Curie, Paris, France

Corresponding author: chin-min.liu@physics.ox.ac.uk

Uranus is one of the ice giant planets in our Solar System and has three zonal jets, namely one broad westward jet in the equatorial zone and two eastward jets at mid-latitudes. The seasonal cycle of the Uranian atmosphere is one of its dominant characteristics, which is very distinct from Jupiter and the other planets¹ due to its high obliquity and long orbital period. The pressure level of the water cloud base of Uranus is ~200 bar². In this work, a simple radiative-convective equilibrium model of Uranus has been developed as a means of obtaining the initial condition and forcing for simulations of the climate of Uranus. Subsequently, we use the MIT General Circulation Model (MITgcm) dynamical core to model the dynamics and structure of the Uranian atmosphere. Two-stream radiation and a simple cloud scheme are also included in this model. We simulate the atmosphere of Uranus using a configuration with 1.4-degree horizontal resolution and 43 vertical levels that go down to the 200-bar pressure level, which lies well below the water cloud base. The results will be compared with observations obtained from ground-based telescopes and spacecraft.

References:
Titan's Seas and Interaction with the Atmosphere

Ralph D. Lorenz

1Johns Hopkins Applied Physics Lab, Laurel, MD 20726, USA

Corresponding author: ralph.lorenz@jhuapl.edu

The liquid hydrocarbon seas of Saturn's moon Titan, as revealed by Cassini, offer a new laboratory in which to understand air-sea interactions and the influence of seas on climate. Methane on Titan, is an analog to water in the Earth system, acting as a condensible greenhouse gas which can amplify other forcings, and which participates in a hydrological cycle forming clouds and rain. Indeed, it seems Titan is to the Earth's hydrological cycle what Venus is to its greenhouse effect – an uncomfortable and informative extreme. Titan's atmosphere, like a warmer Earth's, can hold more moisture, resulting in bigger storms spaced by longer droughts.

Global circulation models suggest greater precipitation at the highest latitudes on Titan, possibly resulting in a compositional gradient across the (connected) seas, with the northernmost Punga and Ligeia Mare 'fresher' (more methane-rich) than Kraken Mare, which sprawls to lower, warmer latitudes where evaporation may concentrate ethane and other solutes (analogous to salt in Earth's oceans).

Titan's seas are too small to effect significant global heat transport, but they may have a profound local influence on atmospheric circulation via 'sea breeze' effects, which may in fact have a sense reversed from those on Earth. Wind-generated waves have been expected as Titan moves to the windy northern summer, but only a few patches of possible roughness have been observed by Cassini, suggesting a delay in the onset of windy conditions which has yet to be fully explained.

This presentation gives a review at the end of the Cassini mission of how Titan's seas present us with a new planetary-scale laboratory in which to improve our understanding of the interaction of atmospheres with surface liquids. Proposals for future exploration have included drifting buoys and even submersibles.
TRacE Gas-mineral inteRactioNs During aeolian erosion on Mars (REGRIND)

Emmal Safi¹, Jon Telling¹*, Manish Patel², John Parnell³, Jemma Wadham⁴, Matthew Chojnacki⁵

¹School of Natural and Environmental Sciences, Drummond Building, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK.
²School of Physical Sciences, Open University, Milton Keynes, MK7 6AA, UK.
³School of GeoSciences, University of Aberdeen, Aberdeen, AB24 3UE, UK.
⁴School of Geographical Sciences, University of Bristol, Bristol, BS8 1SS, UK.
⁵Department of Planetary Sciences, University of Arizona, Tucson, AZ 85721-0063, US.

*Corresponding author: Jon.Telling@newcastle.ac.uk

Recent observations have shown surprisingly high rates of sand movement on Mars¹, with important ramifications for thermal forcing in the Martian atmosphere. Less well recognised is the potential for sand movement to directly alter trace gas fluxes to and from the atmosphere via fluid inclusion release, the reaction of fractured mineral bonds, and the build-up and release of electrostatic charge. Experiments are required to fully understand the mechanisms and likely rates of trace gas uptake and release during present day sand movement on the surface of Mars. These experiments are crucial to correctly interpret ExoMars TGO data.

REGRIND will aim to fill a critical knowledge gap by conducting a range of experiments mimicking aeolian erosion on Mars. Specifically, REGRIND aims to: 1) Use analogue laboratory experiments to quantify how sand movement impacts CH₄ and other trace gas fluxes (H₂, CH₂O, SO₂, CO, N₂O) under relevant Martian environmental conditions. 2) Investigate the link between Martian CH₄/other trace gas fluxes and sand activity by coupling ExoMars NOMAD and Mars Reconnaissance Orbiter HiRISE data.

This interdisciplinary project will aid the identification of the sources and sinks of key trace gases including CH₄ on the surface of Mars. The project is still in its early stages, and we welcome discussion and further collaborations.

Analysing martian polar dust transport using data assimilation

P. M. Streeter¹, S. R. Lewis¹, M. R. Patel¹,², J. A. Holmes¹

¹School of Physical Sciences, The Open University, UK
²Space Science and Technology Department, STFC Rutherford Appleton Laboratory, UK

Corresponding author: paul.streeter@open.ac.uk

Mars’ winter atmosphere is characterised by a polar vortex of low temperatures around the winter pole, circumscribed by a strong westerly jet. These vortices have a significant effect on the atmospheric circulation and on dust and volatile transport: modelling work has shown that increasing model dust opacity has a large effect on the northern vortex, but little effect on the southern vortex¹. Meanwhile, new MCS retrievals with updated, 2D geometry² have revealed a sharp exclusion of dust aerosol from the southern polar vortex, despite the presence of transported water ice; the northern polar vortex displays less dust exclusion and a greater water ice abundance³. This exclusion remains to be explained, as does a more general characterisation of how dust drives and is driven by Mars’ polar atmosphere.

This study uses data assimilation to integrate MCS temperature and dust profiles into a Mars Global Circulation Model. While MCS dust profiles have been assimilated before and yielded improved fit to retrievals⁴,⁵, this represents the first attempt to assimilate dust profiles for this purpose specifically using new and improved MCS 2D retrievals. By combining our best model and our most comprehensive observations, dust profile assimilation offers a uniquely powerful way to examine polar dust processes. Dust transport quantities and patterns are presented for the martian polar regions at various times of year, and compared to free-run models and retrievals.

Spectrally resolved energetics of the Martian atmosphere

A. M. Valeanu\textsuperscript{1}, P. L. Read\textsuperscript{1}, F. Tabataba-Vakili\textsuperscript{2}, S. R. Lewis\textsuperscript{3}, L. Montabone\textsuperscript{1}

\textsuperscript{1}Clarendon Laboratory, University of Oxford, UK
\textsuperscript{2}Jet Propulsion Laboratory, California Institute of Technology, USA
\textsuperscript{3}Robert Hooke, Open University, UK

Corresponding author: valeanu@atm.ox.ac.uk

The dynamics and pattern of energy distribution across scales of the atmosphere are a key component in understanding the general atmospheric circulation, in validation of atmospheric models and offers a nice extension to the work on turbulence. Recently, Tabataba-Vakili (1) produced the first Lorenz energy budget for the Martian atmosphere. This study was the first to portray the mechanisms governing the general circulation through the framework of energetics and energy reservoirs. Our plan is to complete the energy-picture through the theory of turbulence by spectrally decomposing into spherical harmonics the energy reservoirs, conversions and fluxes. The below figure is a sample of the capabilities of our method (2).

Figure 1. Plot of the vertically averaged spectral energy fluxes over 3 Martian years. The information contained is vast, so as an outline:
Total flux > 0 - dominated by downscale energy cascade, wavenumbers [1,4], [4,6], [22,31] – Hadley, Ferrel and dissipation.

References:
Measuring turbulent cascades in Jupiter's weather layer

R. M. B. Young\textsuperscript{1,2}, P. L. Read\textsuperscript{1}

\textsuperscript{1}Department of Physics, University of Oxford, \textsuperscript{2}Laboratoire de Météorologie Dynamique, Université Pierre et Marie Curie, Paris

Corresponding author: peter.read@physics.ox.ac.uk\textsuperscript{1}

Jupiter's atmosphere has often been compared with a classical quasi-two-dimensional, geostrophically turbulent fluid, in which kinetic energy is transferred upscale, with zonal jets emerging due to the spherical curvature of the planet. In a new analysis of 2D wind fields obtained from Cassini cloud images taken during closest approach to Jupiter at the time of the December 2000 fly-by [1], we have determined 2nd and 3rd order structure functions and spectral transfers of kinetic energy and enstrophy (squared vorticity) across scales ranging from ~1000 km to the scale of the planet itself. These confirm the upscale transfer of kinetic energy from eddies on scales \( \geq 3000 \) km up to the scales of the zonal jets, with \(~90\%\) of the energy being transferred into the jets themselves, accompanied by downscale transfer of enstrophy from all scales. For scales \( \leq 3000 \) km or so, however, kinetic energy is transferred downscale, indicating a strong source of kinetic energy at a scale \(~2000-3000 \) km, comparable with the internal Rossby deformation radius. This suggests an important role for baroclinic instability in energising Jupiter's turbulent atmosphere.

References:
Planetary Materials

Abstracts for the 1st British Planetary Science Congress
Clasts in NWA 11220, a recently recovered martian basaltic breccia

Almeida N.V.\textsuperscript{1}, Krzesińska A.M.\textsuperscript{1,2}, Smith C.L.\textsuperscript{1,3}

\textsuperscript{1}Department of Earth Sciences, Natural History Museum, SW7 5BD, London, UK.
\textsuperscript{2}Institute of Geological Sciences, PAS, 50-449, Wrocław, Poland.
\textsuperscript{3}Department of Geographical and Earth Sciences, University of Glasgow, G12 8QQ, U.K.

Corresponding author: n.almeida@nhm.ac.uk

Northwest Africa 11220 was recovered in Esbeta Bir Anzarane in November 2016, consisting of a single stone, 36.62 g in mass, with a complete, smooth, black fusion crust. Classification was conducted by initial high-resolution X-ray CT-scanning of the meteorite, followed by subsampling, SEM-EDX elemental imaging and EPMA analysis. NWA 11220 is a martian regolith breccia \cite{Bouvier2018}, similar in texture and mineralogy to NWA 7034, NWA 7533, and NWA 7475 \cite{Agee2013, Humayun2013, Santos2015} and likely paired with them. The most important feature of these breccias is that they contain a suite of diverse clasts, which capture information about the early martian crust \cite{Agee2013, Hewins2017}.

NWA 11220 is a polymict breccia with various lithic and igneous clasts. Protobreccia clasts are composed of fine-grained pyroxene and plagioclase with similar petrography, mineralogy and texture to the matrix, although they may contain different proportions and distributions of individual minerals. Amongst the igneous clasts, we found microbasalts and sub-ophitic andesite as well as fragments of fractionated, leucocratic rocks. Fractionated, trachyandesitic and monzonitic clasts are formed of perthitic intergrowths of potassium feldspar and anorthoclase, accompanied by augitic pyroxene. Additionally, a significant number of Fe-Ti-P-rich clasts (i.e. dominated by ilmenite, magnetite and Cl-apatite) are present in NWA 11220. Devitrified impact spherules composed of glassy material with layered textures and mantles of accreted debris are common. Additionally, we documented a large vitrophyre clast of quenched feldspathic glasses with relict grains of pyroxene.

The clasts documented in NWA 11220 are similar in mineralogy and texture to those found in other martian basaltic breccias \cite{Agee2013, Santos2015, Hewins2017}. The clasts reveal a variety of complex igneous, metamorphic and shock processes that may have repeatedly affected the martian crust and regolith.

Investigating the Effects of Heating in Primitive Asteroids

Enrica Bonato¹,², Christian Schröder³, Ashley J. King¹, Paul F. Schofield¹, Martin R. Lee², Sara S. Russell¹

¹Natural History Museum, Cromwell Road, SW7 5BD, London
²School of Geographical and Earth Sciences, University of Glasgow, Glasgow
³Biological and Environmental Sciences, University of Stirling, FK9 4LA, Stirling

Corresponding author: e.bonato@nhm.ac.uk

The CO carbonaceous chondrites are amongst the most primitive extra-terrestrial materials available for study. CO chondrites consist of chondrules and calcium-aluminium-rich inclusions (CAIs) set within a matrix of fine-grained (<1 μm) materials and an amorphous silicate groundmass [1]. Amorphous silicates could be a product of nebula condensation and processing, or result from later parent body alteration [2], and they are considered important tracers for the formation and early evolution of asteroid parent bodies. Recent studies have examined how the highly reactive amorphous silicates were affected by low temperature (<100°C) aqueous alteration [3]. In this study we investigate the effects of thermal metamorphism in asteroids by characterizing crystalline and amorphous silicates in the matrices of CO chondrites, which range in petrologic type from 3.0 – 3.6. Our aim is to better understand the initial formation condition of the crystalline and amorphous silicates, and to quantify how the degree of asteroidal heating influences their abundance, structure, chemistry and transformation behaviour.

We studied CO3 matrix both at grain scale and bulk scale. Changes at the bulk scale were determined through modal mineralogy using position-sensitive-detector X-ray diffraction (PSD-XRD) performing quantitative phase analysis (QPA) by pattern subtraction [4-6] and Mössbauer spectroscopy. Here we focus our attention on the results of PSD-XRD and Mössbauer spectroscopy concerning the bulk changes that affected DOM08006 (CO 3.0), Kainsaz (CO 3.2), Ornans (CO 3.4) and Moss (CO 3.6).

Bulk analyses show that Fe$^{3+}$/$\Sigma$Fe decreases from ~70% in DOM08006, to ~40 in Kainsaz and ~10% in Moss and it might be due to changes towards more reducing conditions in the asteroid parent body due to the presence of H and C. Goethite is present over the whole petrologic range and is probably a terrestrial weathering product. After normalising Fe$^{3+}$/$\Sigma$Fe for the presence of goethite, we are able to confirm the presence of glass in lower petrologic types: ~34 vol% in CO3.0 and ~23 vol% in CO3.2. With increasing thermal metamorphism the Fe bearing glass phases recrystallized, and their presence is also confirmed by grain scale analysis in TEM observations. Moreover, with increasing temperature olivine becomes richer in Fe due to ion exchange with the matrix. These changes are also noticeable from the shift of the position of the olivine (020) peak, which indicates a change from forsteritic to more fayalitic.

Making Earth – Constraints from meteorites

A. Bouvier\(^1\), M. Boyet\(^2\), T. Hammouda\(^2\), P. Frossard\(^2\) and A. El Goresy\(^3\)

\(^1\)Department of Earth Sciences, Centre for Planetary Science and Exploration, University of Western Ontario, London, Canada
\(^2\)Laboratoire Magmas et Volcans, Clermont Université, Aubière, France
\(^3\)Bayerisches Geoinstitut, Universität Bayreuth, Bayreuth, Germany

Corresponding author: audrey.bouvier@uwo.ca

The existence and distribution of nucleosynthetic anomalies in planetary materials depict the origin of elements in the Solar System and provide constraints to the formation of the protoplanetary disc and planets (e.g., [1-5]). These isotopic fingerprints can be further integrated into dynamical accretion models for the terrestrial planets. To understand the formation and evolution of the Earth, we can compare the composition of terrestrial rocks with those of planetary materials. Amongst meteorites, many groups, ungrouped meteorites or components such as the calcium-aluminium-rich inclusions (e.g., [2, 6]) or chondrules (e.g., [7]) preserve isotopic heterogeneities in refractory elements. The closest match of meteorite groups are so far the enstatite chondrites within 5 ppm on average from the Earth’s mantle composition. The offset of \(^{142}\)Nd abundance between the Earth and chondrites may either have been produced by early silicate differentiation from chondritic materials or were already present within the disc [2, 3]. This relationship suggests that enstatite-rich chondrites were potentially major contributors to the Earth and Moon [4]. Such building materials would nevertheless challenge our knowledge of the elemental composition of the lower mantle [8]. We carried out \(^{147,146}\)Sm-\(^{143,142}\)Nd, \(^{176}\)Lu-\(^{176}\)Hf stable and radiogenic isotopic analyses on several enstatite-rich achondrites and achondrites and will present results and their implications for the Earth-Moon system.

Impact ejecta from the Australasian microtektite layer: implications for the impact scenario

Campanale Fabrizio\textsuperscript{1}, Folco Luigi\textsuperscript{1}, Glass B.P.\textsuperscript{2}

\textsuperscript{1}Dipartimento di Scienze della Terra, Università di Pisa
\textsuperscript{2}Department of Geosciences, University of Delaware, Newark, DE, USA

Corresponding author: fabrizio.campanale2@gmail.com

The impact scenario that generated the Australasian tektite/microtektite strewn field is an outstanding issue due to the lack of its source crater. The Australasian tektite/microtektite strewn field is also the largest (\textasciitilde15\% of Earth's surface) and the youngest (\textasciitilde0.8 Myr old) on Earth. In this work, we studied a number of impact ejecta particles (i.e. mineral grains, rock fragments, and partly to totally melted particles) found in the Australasian microtektite layer from two deep-sea sediment cores, namely ODP-1144A and SO95-17957-2, from within 2000 km from the hypothetical impact location in Indochina\textsuperscript{1}. These particles bear evidence of shock metamorphism, i.e. coesite, quartz with PDFs, and TiO$_2$II, in support of the impact cratering scenario. The rock fragments and the glass in partly and totally melted particles have the composition as the normal-type Australasian microtektites and tektites, except for more volatile elements. Based on the petrographic and geochemical data, rock fragments may represent the target material that generated the Australasian microtektite, indicating silt- to fine sand-sized sedimentary target rock\textsuperscript{2} probably composed of more than one source rock, i.e. micaceous shale and siltstone, such as loess, and less amount of a low-grade metamorphic rock. Evidence of late accretion observed in some impact ejecta particles constrains the nature and composition of the microscopic fraction of the impact plume associated to the impact. Enrichments in Ni, Co and Cr relative to crustal values in one impact ejecta particle supports previous identification of a projectile chondritic in composition, most likely LL chondrite. The evidence of late accretion and the projectile contamination are typical of proximal ejecta, supporting an impact location close to Indochina.

Did the R chondrite parent body experience onion-shell cooling?

Cohen B.E.\textsuperscript{1,2}, Mark D.F.\textsuperscript{1}, Lee M.R.\textsuperscript{2}, Smith C.L.\textsuperscript{3}

\textsuperscript{1}Scottish Universities Environmental Research Centre, East Kilbride, G75 0QF, UK.  
\textsuperscript{2}School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, UK.  
\textsuperscript{3}Department of Earth Sciences, The Natural History Museum, London SW7 5BD, UK.

Corresponding author: ben.cohen@glasgow.ac.uk

The R chondrites are a rare group of meteorites, currently comprising 184 known examples, not accounting for pairing – of which only one (Rumuruti) is a fall. These meteorites notably contain biotite and amphibole, indicating the presence of water-bearing fluids during their evolution\textsuperscript{1}. Like the more abundant ordinary chondrites (H, L, and LL), the R chondrites have undergone varying degrees of thermal metamorphism in the early solar system\textsuperscript{1}. Previous chronologic analyses of H-chondrites have shown that their metamorphic grade corresponds to cooling age, with the least metamorphosed samples (H4) yielding the oldest ages, and the most metamorphosed (H6) yielding the youngest ages\textsuperscript{2}. This pattern was interpreted in terms of an ‘onion-shell’ model of cooling, whereby the lowest-grade meteorites were from the outer portions of the parent body, and the highest-grade meteorites were from deeper in the interior of the parent asteroid. Such geochronologic analyses have not yet been undertaken for the R-chondrites, therefore in this study, we have applied high-precision \(^{40}\text{Ar}/^{39}\text{Ar}\) geochronology to examine if the R-chondrites show a similar cooling history. If an onion-shell structure were found for the R chondrites, it would be consistent with internal heating of the R-chondrite parent body in the early solar system, and would provide evidence that all R chondrites are likely sourced from a single parent body. We will also use the chronologic results to: (1) undertake thermal modelling to constrain parent body size and (2) test if the chondritic parent bodies were broken up at 4505 Ma, as proposed for the H and L chondrites\textsuperscript{3}, which would have disturbed parent body cooling.

I-Xe Ages of Igneous Inclusions in Ordinary Chondrites

S.A. Crowther¹, M.J. Filtness¹, R.H. Jones¹, A.M. Ruzicka², J.D. Gilmour¹

¹School of Earth and Environmental Sciences, The University of Manchester.
²Cascadia Meteorite Laboratory, Portland State University, Department of Geology.

Corresponding author: sarah.crowther@manchester.ac.uk

Large inclusions consisting of either clasts or macrochondrules are found in around 4% of ordinary chondrite meteorites [1]. Many of these have igneous textures, but their origins are unclear. The oxygen isotopic compositions and major element compositions of most inclusions are broadly similar to ordinary chondrites and chondrules, although not necessarily the same as that of the host meteorite [e.g. 2], but some inclusions have distinctly different compositions [3]. Some may have formed on early, differentiated parent bodies which were disrupted and fragments subsequently incorporated into the chondrite parent bodies [e.g. 1-4], whereas others show no direct evidence that they necessarily derived from a partially differentiated body, only that they were derived from cooling of a silicate melt [5].

The I-Xe chronometer [6] enables us to examine the timing and sequence of events that occurred in the first few million years of the Solar System with high resolution. Three clasts and a sample of host chondrite material from Barwell give old ages ≥4565 Ma [7], which represent their formation at a time contemporaneous with CAI formation. These ages indicate that processes akin to chondrule formation, in that they involve rapid cooling of a silicate melt, were ongoing at the same time as CAI formation. This lends support to the suggestion that Al-Mg chondrule ages might indicate either heterogeneous distribution of 26Al or resetting of the Al-Mg system after chondrule formation [e.g. 8]. We are also examining the I-Xe ages of a new suite of large inclusions from ordinary chondrite meteorites [9,10]. Analyses of these inclusions are currently in progress, and preliminary data will be presented.

Evidence for flow and gravity settling in the parent lavas of the nakhlite (Martian) meteorites from crystal textures and fabrics.

Daly L\textsuperscript{1}, Piazolo S\textsuperscript{2}, Trimby PW\textsuperscript{3}, Lee MR\textsuperscript{1}, Baumgartner RJ\textsuperscript{4}, Cohen BE\textsuperscript{1}, Forman LV\textsuperscript{5}

\textsuperscript{1}School of Geographical and Earth Science, University of Glasgow, Glasgow, G12 8QQ, UK.
\textsuperscript{2}School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.
\textsuperscript{3}Oxford Instruments Nanoanalysis, High Wycombe, HP12 3SE, UK.
\textsuperscript{4}School of Earth Sciences, University of Western Australia, Perth, WA, 6009, Australia.
\textsuperscript{5}Department of Applied Geology, Curtin University, Perth, WA, 6845, Australia.

Corresponding author: luke.daly@glasgow.ac.uk

The nakhlite meteorites are Martian igneous rocks that sample at least four lava flows erupted between \(~1,416 and 1,332 Ma\). They contain phenocrysts of augite and olivine, between which is a finely crystalline mesostasis. The augite phenocrysts are coarse and prismatic, and so may be ideal for recording processes that operated during emplacement. Here we evaluated the evidence for flow and gravitational settling by quantifying the crystallographic preferred orientations of phenocrysts via large area electron backscatter diffraction (LA-EBSD) mapping of thin sections of three nakhlites: Nakhla, Governador Valadares and Miller Range (MIL) 03346.

LA-EBSD analyses reveal a moderate alignment of the long axis (<c>) of augite phenocrysts in a plane forming a magmatic foliation in all samples, as well as a moderate linear alignment with maxima of the <a>, <b> and <c> axes in the general foliation plane. The linear alignment is most pronounced in those meteorites with a low ratio of mesostasis to phenocrysts: alignment increases from MIL 03346 to Grosvenor Valadares to Nakhla. Lineations defined by elongate minerals in lavas can be generated by shear stresses associated with flow\textsuperscript{2}, while foliations are attributed to gravity settling\textsuperscript{3} and compaction. Here we have observed good evidence for both processes, thus confirming that the nakhlites do represent lava flows, with an associated gravitational component.

References:
Mössbauer analysis of Alkaline Igneous Systems – Tracking redox within the Norra Kärr Lanthanoid resource

Dobrzanski, A. 1, Schröder, C. 2, Walcott, R. 3, Butler, I. 1, Kirstein, L. 1, Ngwenya, B. 1

1 School of Geosciences, The Grant Institute, Kings Buildings, Edinburgh, UK, EH9 3FE
2 Biological and Environmental Sciences, University of Stirling, Stirling FK9 4LA, UK
3 Department of Natural Sciences, National Museums Scotland, Edinburgh, UK, EH1 1JF

Corresponding author: a.j.dobrzanski@ed.ac.uk

Alkaline systems can display varying redox trends [1] in their mineralogy and Mössbauer analysis provides a straightforward method of analysing Fe$^{2+}$/Fe$^{3+}$ ratios which allow magmatic fractionation or immiscibility trends to be identified. In this study bulk-rock powders were analysed from Norra Kärr - a Mesoproterozoic alkaline igneous body that hosts mainland Europe’s largest lanthanoid element resource. The whole-rock and Fe$^{2+}$/Fe$^{3+}$ ratios for the Fe-bearing minerals present in each sample were calculated. These ratios have shown that the first magma intruded at Norra Kärr – the ore bearing magma - was oxidised and rich in Fe$^{3+}$. The second magmatic phase was more reduced with minerals from enclaves sourced from depth being the richest in Fe$^{2+}$. These results may have important implications for modelling the enrichment of lanthanoids within alkaline systems. This is due to differences in partition-coefficients between two alkaline magmas of differing redox and the redox sensitive nature of Ce and Eu. However, the use of Mössbauer data to extrapolate these trends across a whole-rock mining dataset must be done with caution as there may be significant petrological variation within homogenised drill-core used for industrial XRF assay. Further, the Fe$^{2+}$/Fe$^{3+}$ in eudialyte (an uncommon lanthanoid-bearing ore mineral) can be modelled using the Mössbauer spectrum of more common amphibole. Therefore, additional chemical and petrological data are always required when using this technique to determine the correct mineralogy especially if using remote sampling methods such as rovers. Though alkaline igneous rocks are unusual on Earth (comprising around 4% of the crust) they are thought to be more common in settings such as Mars [2] and understanding the issues involved with analysing alkaline lithologies on Earth can help support future missions.

Volatile Components and Impact Melt Processing in the Early Inner Solar System

B.E. Farrant¹, R.H. Jones¹, G. Holland¹.

¹School of Earth and Environmental Sciences, University of Manchester, Manchester, M13 9PL, UK.

Corresponding author: benjamin.farrant@manchester.ac.uk

Ordinary Chondrites (OCs) record the environment, conditions and processes that were active in the early Solar System. Impact was an important process on OC parent bodies and many OCs are shocked due to impact events [1]. During impacts of high shock pressures impact melt (IM) can be produced in veins, pockets and dykes or as whole rock melting [1]. Melting is associated with volatile evolution and loss and the amount to which impact melting has altered the volatile budget of the early Solar System is currently unclear [2].

We are undertaking a project to examine the volatile content of both IM and the OC material from which it is derived to quantify the effect impact melting has had. Abundance and isotopic ratios of noble gases and halogens will be determined in both materials as these are important volatiles and tracers of volatile behaviour [3]. Noble gases will be examined using high resolution noble gas mass spectrometry while the halogens will be investigated using the neutron induced noble gas mass spectrometric technique [4]. Prior to volatile analysis the OC and IM portions will be fully characterised by utilising Scanning Electron Microscopy and Electron Microprobe Analysis. Initial characterisation of the IM from the meteorite Chico shows compositional and textural variations. At the mm scale variable grain size, vesicle abundance and distribution, FeNi grain abundance and major element and phase distributions are all evident. These variations occur in parallel zones implying that melt was not completely mixed during cooling.

Exploring the effects of crystallographic orientation on the generation of shock deformation features in a Martian Shergottite

L. V. Forman¹, G. K. Benedix¹, P. A. Bland¹ & N. E. Timms¹.

¹School of Applied Geology, Curtin University, GPO Box U1987, WA, 6845, Australia

Corresponding author: lucy.forman@curtin.edu.au

Introduction: Shock features within Martian samples are thought to result from the impact that launched them from the surface of Mars [1], and so exploring the material response can help constrain shock parameters, related impact processes and locate candidate launch craters on the Martian surface [2]. Different minerals have varied material responses to stress and more specifically in this case, the stress applied by a propagating shockwave. Slip systems must be activated in each grain so that the crystal lattice can be deformed. However, often the dominant activated slip system is dependent upon the orientation the stress is applied in, with relation to the crystallographic orientation of the grain, and the physical conditions of the material at the time of impact [3]. Here we explore the effect of crystallographic orientation on the quantifiable amount of crystal deformation that is generated in an impact scenario on the Martian surface.

Sample & Methods: The focus of this study is the lherzolitic Shergottite Roberts Massif (RBT) 04262 specific thin section (, 24), which comprises poikilitic pyroxenes along with more normal lherzolitic texture and mineralogy [4,5]. We examined a select area (10 x 7 mm) of the section in this initial study, which contains a large poikilitic, twinned pyroxene grain. At the macro scale, shock is heterogeneous but no phase changes have been observed, therefore overall shock is limited. Electron backscatter diffraction (EBSD) techniques were initially used to determine pigeonite orientation to constrain spectral characteristics [6]. The data comprise crystallographic information from all mineral phases at a step size of 12.2 µm.

Results: The twinned pigeonite grain was divide into twins A & B. Twin A shows very little internal deformation in the pigeonite region (<2 º), but a consistently greater amount of misorientation in the augite rim present. However, twin B, which is twinned on the [001] plane with twin A, shows a variable amount of misorientation throughout the crystal, which appears to undulate in contrast to the radial trend in deformation in twin A.

Discussion & Preliminary Conclusions: This sample has a very low porosity, which would have also been true at the time of impact, and therefore heterogeneities in shock are not due to shockwave interactions arising from interaction with pores. We subsequently infer the crystallographic orientation of each grain dictated the degree of crystal-plastic deformation generated by the shock wave. Further EBSD microstructural analysis will be used to constrain the slip systems that have been activated in the pigeonite, and subsequently constrain the physical conditions at the time of impact. This approach may also allow determination of the shockwave propagation direction with respect to the plane of the sample. Examination of the remainder of the thin section will enable a comprehensive investigation into the relationship between crystallographic orientation and deformation.

Understanding the significance of slope 1 variation in early Solar System solids: Oxygen isotope studies of CO and CR chondrites

Richard C. Greenwood¹, Ian A. Franchi¹ and Conel M. O’D. Alexander

¹Planetary and Space Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, ²DTM, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington DC 20015, USA. Corresponding author: r.c.greenwood@open.ac.uk

Primitive chondritic meteorites, particularly carbonaceous chondrites, are capable of yielding unique insights into the conditions that prevailed during the early stages of Solar System formation¹. However, truly pristine chondrites are rare, with most samples showing evidence for secondary, probably parent body, alteration². In addition, terrestrial weathering is a further complicating factor for meteorites recovered from hot and cold desert regions¹. In attempting to assess the relationships, both within and between various groups of carbonaceous chondrites, bulk oxygen isotope analysis has proved to be a highly effective technique³,⁴,⁵. Here we discuss the results of oxygen isotope analysis we have been undertaking recently on two important groups of primitive meteorites, the CO and CR chondrites.

Based on a range of parameters, including: presolar silicate contents, bulk H, C and N abundances, carbon and hydrogen isotopic compositions, a small group of Antarctic CO3s have been identified as amongst the most primitive meteorites yet recognized¹,⁶. In particular, DOM 08006 has the highest matrix-normalized presolar silicate abundance of any chondrite so far studied⁹. However, Antarctic meteorites have experienced variable degrees of terrestrial weathering⁷ and CO3 samples are no exception¹. Antarctic COs are displaced from the CCAM line due to exchange with Antarctic precipitation. The effects of this alteration can be mitigated using a leaching treatment. Following leaching, these Antarctic COs define an array along the CCAM line, but displaced to more ¹⁶O-rich compositions relative to CO falls. This relationship provides additional support for the primitive nature of these Antarctic samples¹.

SIMS analysis of chondrules from primitive CR and related chondrites define a distinct slope I line, known as the Primitive Chondrule Minerals (PCM) line⁸,⁹. Laser fluorination analysis of separated chondrules from the CR chondrite LAP 02342 also fall on this trend, providing additional support for its primary significance. In contrast, whole rock analysis from some of these samples are displaced away from this line¹⁰. Current studies are focused on trying to unravel this variation, which may reflect either terrestrial or asteroidal alteration processes, or more likely a combination of both.

Our oxygen isotope studies provide strong evidence that both the PCM and CCAM lines may be of primary significance in the evolution of early Solar System solids, in particular chondrules. However, corundum and hibonite-bearing CAIs in a number of relatively pristine chondrites do not appear to show slope 1 variation, but instead have relatively invariant ¹⁶O-rich compositions¹¹. Slope 1 variation in both CO and CR chondrites therefore appears to postdate formation of at least some CAIs. Our current research is focused on trying to understand the likely setting of this slope 1 variation which may be either nebular or asteroidal in origin.

Reassessing the geochemical evolution of the nakhlite meteorites as multiple martian lava flows.

S. Griffin\textsuperscript{1}, B.E. Cohen\textsuperscript{1,2}, M.R. Lee\textsuperscript{1}, S. Kirby\textsuperscript{1}

\textsuperscript{1}School of Geographical and Earth Sciences, University of Glasgow, Glasgow G12 8QQ, UK
\textsuperscript{2}Isotope Geoscience Unit, Scottish Universities Environmental Research Centre (SUERC), Rankine Avenue, East Kilbride G75 0QF, UK

Corresponding author: s.griffin.3@research.gla.ac.uk

The nakhlites comprise 19 of the 107 currently identified martian meteorites. These igneous rocks provide important information regarding the mantle and atmospheric composition, surficial materials, as well as former active processes on Mars. Exhibiting low degrees of shock metamorphism (5-20 GPa, \~5-40 °C), the nakhlites consist of varying proportions of augite, olivine and mesostasis, and originated from a depleted mantle source\textsuperscript{1}. The minor geochemical variations within this meteorite group have previously been explained in terms of contrasting crystallization depths within a thick igneous unit\textsuperscript{2} or different magma reservoirs\textsuperscript{3}. However, recent geochronological \textsuperscript{40}Ar/\textsuperscript{39}Ar data\textsuperscript{4} has shown that the nakhlites differ in age, spanning at least four eruption events from 1416 ± 7 to 1322 ± 10 Ma (2\textsigma). This age data demonstrates that the nakhlites must represent a series of discrete magmatic events\textsuperscript{5}, and cannot be from a single unit. Here we have collated previously published analytical data with a focus on discerning how the different eruptive events vary geochemically. Preliminary investigations show variation within the nakhlites that can only be explained by different magma batches, e.g., differences in the slope of rare earth element data and analytically distinct isotopic compositions.

References:


Volatile element activity in ordinary chondrite parent bodies

Rhian Jones\textsuperscript{1}, Jonathan Lewis\textsuperscript{2}, Tom Ormerod\textsuperscript{3}

\textsuperscript{1}School of Earth and Environmental Sciences, University of Manchester; \textsuperscript{2}Department of Earth and Planetary Sciences, University of New Mexico; \textsuperscript{3}School of Earth and Environment, University of Leeds

Corresponding author: Rhian.jones-2@manchester.ac.uk

The asteroid parent bodies of ordinary chondrites (OCs) are not usually considered to be the sites of volatile activity. However, there is undeniable evidence for the presence of metasomatic fluids during metamorphic heating, which clearly involves movement and redistribution of volatile species, including water\textsuperscript{[1-3]}. Our recent studies of feldspar and phosphate minerals in OCs have shown that chemical transport occurs throughout the range of metamorphism, from petrologic type 3 to 6\textsuperscript{[4-6]}. It is important to recognize these effects, for correct interpretation of ages determined using chronometers such as Al-Mg, I-Xe and Pb-Pb. The ratio of Cl/F in the phosphate mineral apatite records heterogeneity among different chondrites that appears to post-date thermal equilibration, and which implies the presence of late-stage, dry and halogen-rich fluids that might have arisen either from impact processing or degassing of the asteroid's interior\textsuperscript{[4-7]}. In addition, we have observed that the Cl/F ratio of apatite in two regolith breccias, Zag (H3-6)\textsuperscript{[5]} and Kendleton (L3-5)\textsuperscript{[6]}, is extremely variable, from Cl/(Cl+F) values of around 0.55 to 0.95, compared with mean values of 0.75 to 0.90 in unbrecciated OCs. This heterogeneity appears to be associated with regolith processing, which implies that fluid activity could have persisted long after thermal metamorphism ceased. In order to investigate this process further, we are currently carry out a detailed study of apatite abundance, grain size distribution and compositional characteristics, in several brecciated H chondrites. Our goal is to understand processes affecting volatile behaviour and distribution in chondritic asteroids, and hence to determine the nature of primitive material that could have contributed to the composition of the terrestrial planets.

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Hydrothermal alteration record in Chassigny

Krzesińska A.M.1,2, Schofield P.F.1, Smith C.L.1,3, Michalski J.R.4

1Department of Earth Sciences, Natural History Museum, SW7 5BD London, UK.
2Institute of Geological Sciences PAS, Podwale 75, Wrocław, Poland.
3School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK.
4Department of Earth Sciences, University of Hong Kong, China.

Corresponding author: a.krzesinska@nhm.ac.uk

Chassigny is a martian dunite hosting limited secondary carbonates and sulphates [1,2]. To try to resolve the debate regarding the petrogenesis and alteration of the meteorite [1-4] we present a mineralogical and textural study (X-ray CT and SEM-EDX) at 100 nm resolution of twelve fragments of Chassigny. Olivine and chromite are the predominant igneous minerals in Chassigny although cumulus pigeonite is also present in some of the examined fragments. Associated with pyroxene are the minerals cassiterite, galena, argentite, cinnabar, and K-bearing cottunite. These minerals form aggregates and in most cases co-occur with micron-sized Ca-carbonate and/or Ca-sulphate. In some cases Ba,Ca-sulphate and Mg-carbonates also accompany the pyroxene, while pyroxene-free lithologies of Chassigny typically contain only Ca-carbonates and Ca-sulphates.

Enrichment in Pb and Ba in Chassigny was noticed by [1], and was considered to represent terrestrial contamination. However, our study suggests this is unlikely as Pb is accompanied by Hg, Ag and Sn, all of which form characteristic sulphides, oxides and chlorides. In our samples the minerals occur in clear association with pigeonite, which in Chassigny might only have formed when the parent magma chamber was metasomatised by infiltrating Cl and LREE-rich fluid [4]. We propose that the volatile-metal-bearing sulphides, cassiterite and cottunite also originated from this fluid. Such minerals are typical products of volcanogenic hydrothermal alteration [5, 6], as are barite, gypsum/anhydrite and calcite, albeit from lower temperature fluids [5]. We suggest that hydrothermal fluid infiltrated the Chassigny parent magma during the post-cumulus stage, depositing sulphides, cassiterite and cottunite. Subsequent cooling enabled the precipitation of barite, gypsum/anhydrite and calcite.

Inferring mantle potential temperature from olivine P-zoning in a Martian lava

N. Mari¹, L. J. Hallis¹, A. J. V. Riches², M. R. Lee¹

¹School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK.
²Department of Earth Sciences, Durham University, Durham, UK.

Corresponding author: n.mari.1@research.gla.ac.uk

Geochemical and geophysical data suggest that the martian mantle retained heat from Mars formation, and that it could still be actively convecting [e.g., 1]. Here we try to infer thermodynamical information related to martian mantle activity via mineralogical data acquired from olivine and pyroxene in the Tissint martian meteorite, with a crystallization age is ~574 ± 20 Ma [2]. We here report major element core-to-rim evolution of clinopyroxene and P-zoning in olivine megacrysts and phenocrysts in Tissint in order to provide new insights into the dynamics of its parental magma chamber. The largest olivine grains (~2 mm) have very low (~0.02 wt.%) or absent P in their cores but P₂O₅ concentrations increase toward their rims (~0.20 wt.%). The smallest olivine grains (~100 µm) have higher concentrations of P₂O₅ independently of their cores and rims (ranging from ~0.05 to 0.25 wt.%). The average equilibration temperature calculated in these olivine grains is ~1577° C.

Oscillatory P-zoning in olivine can be a product of open-system processes [3]. We tested and excluded this possibility for the Tissint magmatic system by using information on pyroxene zoning and pyroxene/olivine equilibration temperatures. In light of this, we linked the marked differences in P-zoning between large and small olivine grains to vigorous convective activity in the Tissint magma chamber [4]. Equilibration temperatures from olivine that were in equilibrium with the liquid were then used to infer a mantle potential temperature of ~1720° C for the parcel of mantle that erupted the Tissint lava at ~570 Ma, suggesting an active martian mantle was still in place until at least the late Amazonian.

Cooling rates and vesiculation of shock melt pockets in shergottites

Morland Z.\textsuperscript{1}, Krzesińska A.M.\textsuperscript{2,3}

\textsuperscript{1}SEES, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK.
\textsuperscript{2}Dept. Earth Sciences, Natural History Museum, Cromwell Road, SW7 5DB, London, UK.
\textsuperscript{3}Institute of Geological Sciences PAS, Wroclaw, Poland.

Corresponding author: zoe.morland@hotmail.co.uk

Shergottites, young subsurface Martian basalts [1], record intensive shock metamorphism [2]. Melt pockets, products of shock, are highly vesiculated reflecting the entrapment of volatiles [3] and/or atmospheric gas [4]. However, vesicle origin is not fully recognised [5]. Here we interpret the formation of vesicles in a fragment of olivine-phyric shergottite SaU005 (BM.2000,M40, 0.95g). Using X-ray CT a 3D map of shock products and enclosed vesicles was generated. Additionally, we studied textures and compositions of quenched melt pocket material in two sections, using SEM-EDX and correlated this with analysis of vesicle volume and distribution.

Shock melt pockets in SaU005 are sub-rounded objects (up to 1-2 mm) obscuring original grain boundaries. Large pockets have a basaltic bulk composition, lack high-pressure polymorphs and are depleted in volatiles: S, P and Cl compared to the bulk host composition. Texturally, the pockets are composed of glass and quenched olivine and pyroxene crystallites. Smaller crystallites populate pocket boundaries, whereas larger swallowtail dendritic crystallites dominate the centre. Glassy pocket boundaries accommodate abundant small (20-40 µm) vesicles, whereas inside vesicles are rarer, but larger (200-500 µm).

Lack of high pressure polymorphs indicate that quenching occurred during the decompression stage only. This relatively long quench time enabled volatile release from the shock melt, accounting for the vesiculation. Textural changes of crystallites in melt pockets reflect heterogeneous cooling rates. A slower cooling rate in the pocket interior allowed volatiles to migrate and coalesce into larger vesicles towards the centre. Therefore, there is a distinct correlation between cooling rates and vesicle size and distribution.

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Behaviour of organic carbon during impact immiscibility

John Parnell¹ & Paula Lindgren²

¹University of Aberdeen, UK
²Lund University, Sweden

Corresponding author: J.Parnell@abdn.ac.uk

Impacts are a fundamental means of processing planetary materials. The heat and shock of impact cause localized melting of rock, which typically results in immiscibility between different melt fractions. Upon solidification, immiscibility textures are preserved in impact crater melt rocks, and comparable textures occur in the melted fusion crusts of meteorites. The behaviour of organic carbon during impacts is important as it controls the bioavailability of the carbon, in terms of both molecular complexity and accessibility in the environment.

Melt fragments from the Gardnos impact crater, Norway, illustrate the behaviour of organic carbon in a moderate-sized (5 km) crater¹. Carbon is concentrated as films at the interface between immiscible silicate melt phases, preserved post-alteration as stilpnomelane and chlorite. This database can be understood by the study of man-made analogues, in which carbon is admixed with polymer melts to make low-cost filler materials with good electrical conductivity. The analogues show comparable carbon films, of a few microns thickness, at the interface of immiscible polymers. The formation and location of the carbon films is controlled by surface tension and wettability between the phases.

The observation of comparable carbon films in natural impact melts and man-made polymer melts suggest that they are a predictable consequence of melting assemblages that include organic carbon. Any organic carbon on the impacted surfaces of planetary bodies is likely to have been processed in this way. Hopefully this conjecture can be tested.

References:
Impacts in space at a glimpse: Nanoscale orientation mapping and neutron diffraction analysis reveals extreme deformation in diamond

S. Piazolo a,*, M.A.G. Andreoli b, V. Luzi c, P. Trimby d, e, J. Westraad f, A. Venter g

a School of Earth and Environment, University of Leeds, UK
b School of Geosciences, University of the Witwatersrand, PO Box 3, Wits 2050, South Africa
Bragg Institute, ANSTO, Lucas Heights, Australia
d Australian Centre for Microscopy and Microanalysis, University of Sydney, Australia
e Oxford Instruments Nanoanalysis, High Wycombe, HP12 3SE, UK
f Department of Physics, Nelson Mandela Metropolitan University, South Africa
g South African Nuclear Energy Corporation, PO Box 582, Pretoria, 0001, South Africa

*Corresponding Author: s.piazolo@leeds.ac.uk

The shock transformation of graphite to diamond is generally linked to the high pressures produced during meteorite impacts on Earth. However, what happens when asteroids impact each other? Small, polycrystalline diamond occurring in the controversial, carbonaceous, diamond-rich extraterrestrial pebble “Hypatia” from the SW Egyptian desert shows remarkable deformation features. This offers an unprecedented glimpse into the deformation associated with impacts occurring in space. Neutron Diffraction analyses suggest the presence of highly deformed twins and, potentially, Lonsdaleite-structured diamond at the scale of individual 30g “stones”. Dark field high resolution TEM analysis shows that this stone is polycrystalline at the nanometre to micrometre scale. In-depth crystallographic orientation analysis using Transmission Kikuchi Diffraction in the SEM reveals grain sizes in the order of several hundred micrometres. Individual grains are extremely crystal-plastically deformed, exhibiting up to 10° orientation change over a distance of 100 nm. Minimum dislocation densities are in the order of $10^{19}-10^{20}$ m$^{-2}$ suggesting stresses of up to 130 GPa. Short term shock heating up to 2000 °C allowed some recovery, resulting in the development of well-defined subgrain boundaries. Our study shows that before impact this extraterrestrial diamond was a twinned grain similar to those recently discovered in ureilites. The original growth related twins with a 60° rotation around <111> have been modified during subsequent shock-related deformation and now display grain boundary structures with misorientations in the range of 50-70°. We demonstrate how crystallographic analysis on the nanometre scale can assist in the interpretation of complex deformation structures in these intriguing diamonds.
Shock metamorphism in feldspar from the Chicxulub impact structure

A. E. Pickersgill\textsuperscript{1,2}, M. R. Lee\textsuperscript{1}, L. Daly\textsuperscript{1}, D. F. Mark\textsuperscript{2}

\textsuperscript{1}School of Geographical & Earth Sciences, University of Glasgow, Gregory, Lilybank Gardens, Glasgow, G12 8QQ, UK, \textsuperscript{2}Argon Isotope Facility, Scottish Universities Environmental Research Centre (SUERC), Rankine Avenue, East Kilbride G75 0QF, UK. (*)

Corresponding author: a.pickersgill.1@research.gla.ac.uk

Planar microstructures are a pre-shock characteristic of most feldspar group minerals, therefore great care must be taken to distinguish shock-related microstructures from those formed prior to impact such as exsolution lamellae, veins, cleavages, and twin planes [e.g. 2]. We investigated the microstructures of Or-rich alkali feldspar phenocrysts from granitoid rocks recovered from the peak ring of the Chicxulub impact structure during IODP-ICDP Expedition 364 [3].

Phenocrysts display microtextures that are characteristic of Or-rich alkali feldspars from undeformed igneous rocks (i.e., albite exsolution lamellae, veins of patch perthite) [4]. Also present are semi-planar microstructures, sub-micrometer in width and frequently developed in more than one orientation. Optically, the two main sets appear to be parallel to exsolution and twin lamellae in some grains, and sub-parallel to cleavage planes in others. TEM work revealed that planar microstructures comprise sub-micrometer wide subgrains with low angle semicoherent boundaries that are parallel to the trace of \{110\}. Subgrains are absent from veins of patch perthite, which may mean that the fluid-mineral interaction that was responsible for forming the patch perthite postdated shock metamorphism.

The planar microstructures resemble strain-induced semicoherent twins, but they are too closely spaced and too narrow to be twins. They likewise show no chemical variation and are therefore not exsolution lamellae. As they appear to be different to microstructures that characterise unshocked feldspars, we suggest that these very narrow subgrains were likely generated by the impact event, but are distinctive from PDFs as they are not straight and preserve no evidence of amorphous material. Work is continuing to determine the microstructure and crystallographic orientation of the other sets of planar elements within these samples.


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Carbonates in Lafayette: Implications for Fluids in the Martian Crust

J. D. Piercy, J. C. Bridges and L. J. Hicks.

Space Research Centre, Leicester Institute of Space and Earth Observation, University of Leicester, UK, LE1 7RH. Email: jdp32@leicester.ac.uk

The nakhlite ol-clinopyroxenites display unique martian alteration assemblages; the main assemblage, shown in Lafayette, contains hydrothermal veins consisting of Ca-Fe carbonate, ferric phyllosilicates, and amorphous silicate gel, with traces of Fe oxide [1]. Studying the physical and chemical properties of these minerals can inform us about the nature of hydrous activity and past atmospheric conditions on Mars, as well as help characterise carbonate-bearing Mars 2020 landing sites. We present new SEM, TEM, XANES and XRD studies of two Lafayette sections to understand the formation of its carbonate. These analyses were performed using the University of Leicester’s Advanced Microscopy Centre and the Diamond synchrotron.

Carbonates within Lafayette come in two forms, those that are hosted within mesostasis fractures, 3.2 vol.% of one studied section; and those within olivine fractures (figure), 0.8 vol.% of the same section. Each set of carbonates shows signs of partial dissolution by ferric phyllosilicate. SEM-EDS analysis shows compositions of pure carbonates within Lafayette as: mesostasis (Cc$_{26.42}$Sd$_{58.74}$Rh$_{0.4}$), olivine (Cc$_{27.29}$Sd$_{47.53}$Rh$_{19.24}$). The vol.% and range of siderite compositions within the mesostasis indicates a relatively dynamic system where cations could be exchanged more readily than in olivine fractures. Fe-K XANES and TEM analysis reveals the ferric nature of the trioctahedral and dioctahedral clays that partially dissolved the Fe-Ca carbonate [2] as the hydrothermal fluid migrated through the nakhlite parent rocks. In another studied Lafayette section, nearly all of the carbonate has been dissolved by more extensive localized fluid activity.

The halogen composition of Shergottite meteorites

L. Ruzié-Hamilton, P.L. Clay and R. Burgess

School of Earth and Environmental Sciences, University of Manchester, Oxford Rd, Manchester, M13 9PL

Corresponding author: lorraine.ruzie@manchester.ac.uk

Martian meteorites provide important clues for understanding Mars’ mantle evolution and its volatile budget. Based on volatile/non-volatile element ratios and cosmochemical constraints, the martian interior is considered to be 2-3 times more enriched in chlorine relative to the terrestrial mantle [1, 2]. However, reported abundances of Cl in shergottites are relatively low and within the range determined for MORB [3]. The abundances of heavier halogens Br and I in shergottites are less certain, however the large range in volatility and incompatibility of halogens in silicates means that ratios of Br/Cl and I/Cl may be good indicators both of primary accretionary materials and secondary processes (e.g. melting/fractional crystallisation, degassing and crustal contamination). Based on the few analyses available [3, this study], there is a factor 1000 variation in I/Cl values, extending from \( \sim 10^5 \), similar to the comparatively uniform I/Cl of the Earth’s mantle, to \( >10^2 \) far in excess of chondritic values. The origin of this variation is unknown, possible causes may include heterogeneous halogen distribution in the Martian mantle, core-mantle fractionation of iodine, preferential outgassing of chlorine, shock processes or contamination with Martian and/or terrestrial alteration products. To gain further insight into the reasons for these variations, and increase the database of heavy halogen measurements, we are analysing the whole rock and separated minerals in several shergottites using the noble gas neutron irradiation mass spectrometry technique [4].

Zinc isotope clues on the source of Earth’s moderately volatile elements

Paul S. Savage\textsuperscript{1,2} and Frédéric Moynier\textsuperscript{3}

\textsuperscript{1}School of Earth and Environmental Science, University of St Andrews, UK
\textsuperscript{2}St Andrews Centre for Exoplanet Science, UK
\textsuperscript{3}Institut de Physique du Globe de Paris, France

Corresponding author: pss3@st-andrews.ac.uk

The measurement of mass-independent isotope anomalies in chondrites relative to Earth can provide important constraints on the chemistries and proportions of the various primitive materials that accreted to form our planet. Recent modelling has shown that a mixture dominated by enstatite chondrites, with a minor ordinary and carbonaceous component, best matches the composition of Earth \cite{Dauphas2017}. There is much debate centred on the source of Earth’s volatile elements \cite[e.g.][]{Marty2016}; however, all isotopic anomalies used in \cite{Dauphas2017} are measured in refractory elements, thus any inferences on source drawn from these anomalies may not apply to Earth’s volatiles.

Here we present the first bulk meteorite isotope anomalies found in the nominally moderately volatile element Zn. We show that carbonaceous chondrites have resolvable positive $^{66}$Zn and $^{68}$Zn excesses compared to terrestrial; crucially, we also find that enstatite chondrites have small $^{66}$Zn deficits, consistent with the small $^{48}$Ca and $^{50}$Ti deficits observed in such samples \cite{Schiller2015, Zhang2012}.

Modelling this new set of anomalies within the framework set down in \cite{Dauphas2017}, we show that, to balance out the negative anomaly present in enstatite chondrites, the Zn budget of Earth must contain a considerable proportion (~30\%) of carbonaceous chondrite-derived Zn. Such a result could have serious implications for the source of Earth’s volatile budget; in particular, the carbonaceous chondrite vs. cometary debate over the source of Earth’s water.

The settings of aqueous alteration in the early solar system: A nanoscale STXM investigation of the Murchison CM2 chondrite

P. F. Schofield¹, A. J. King¹, B. Kaulich², M. Abyaneh², T. Araki² and S. S. Russell¹

¹Planetary Materials Group, Natural History Museum, London, SW7 5BD, UK.
²Diamond Light Source Ltd, Harwell Science and Innovation Campus, OX11 0QX, UK.

Corresponding author: p.schofield@nhm.ac.uk

Many studies have described petrographic evidence for in situ aqueous alteration on the asteroid parent body(ies) of CM chondrites [1]. However, the origin of fine-grained rims (FGRs) of phyllosilicates that surround pristine anhydrous fragments in CM chondrites remains controversial. The textures of FGRs suggest that they formed through accretion onto their host objects, but it’s not clear whether hydration of the dust occurred in a nebula [2] or asteroid [3] environment. The settings of aqueous alteration in the early solar system may be inferred from crystal chemical variations within the sub-micron mineralogy of FGRs and matrix within the CM chondrites.

Using synchrotron µXANES we observed systematic variations in Fe⁢³⁺/ΣFe across FGRs but not within the matrix [4]. To identify the source of this variation we used STXM and nanoscale XRF to compare the crystal-chemical relationships of the matrix mineralogy with that of the FGRs. Changes in Fe L- and O K-edge spectra from matrix areas can be attributed to oxide and phyllosilicate minerals. For FGRs, small changes in the relative intensities of the Fe L₃ edge main peaks suggest variations in the Fe⁢³⁺/ΣFe ratio. More grain-scale variability is observed in the FGR than in the matrix, and Fe-sulphides are detected in the FGR but not in the matrix.

Our data show that the composition of the FGR is mineralogically distinct from the matrix, showing it was surrounding the chondrules in their nebular sojourn prior to accretion and hence has sampled a different reservoir of dust to the matrix. A possible explanation for the data is the incorporation of ice and/or carbonaceous grains in the FGR which would cause local variability in redox states when these phases reacted on the asteroidal parent body.

Determining the redox state of planetary interiors: a new tool based on trace element partition in apatite

T. N. Stokes, G. D. Bromiley, N. J. Potts. K. E. Saunders,

School of GeoSciences, University of Edinburgh, Edinburgh EH9 3FE, UK

Corresponding author: thomas.stokes@ed.ac.uk

Oxidation state, and consequently oxygen fugacity ($fO_2$), within the interiors of terrestrial planets is an important variable for understanding planetary-scale processes. Everything from core formation, stability of mantle phases, atmospheric compositions, and even the origin of life itself may be dependent upon $fO_2$.

Recent modelling studies have suggested that apatite [$\text{Ca}_5(\text{PO}_4)_3(\text{F,Cl,OH})$], a mineral widely found in terrestrial, lunar, and martian rocks, may be a good proxy for understanding redox conditions in planetary interiors. In particular, the partitioning of redox sensitive elements, such as Mn, Ce, and Eu between apatite and coexisting melts is thought to be strongly dependent on $fO_2$. As such, characterisation of the crystal chemistry of apatite might provide information on $fO_2$ conditions in parental melts formed deep within planetary interiors.

We have investigated experimentally the potential of a Ce-, Eu-, or Mn-in-apatite geobarometer by exploring mineral-silicate melt partitioning of these elements, under the pressure-temperature conditions of planetary interiors, as a function of $fO_2$. Apatite grains and coexisting glasses (quenched melt) were analysed using an electron microprobe to obtain major and minor element totals. SIMS analyses will be completed to obtain apatite, and melt volatile contents. Broadly, results from this study indicate that $fO_2$ is an important parameter for understanding the partitioning of redox sensitive elements into apatite. As such, apatite has the potential to provide insight into magma redox conditions, and by extension, a probe of oxidation state in mantle source regions. Ongoing work is needed to explore other physio-chemical controls on partitioning to allow full constraint of a Ce-, Eu- or Mn-in-apatite oxygeobarometer.
An early Solar System origin for carbonaceous chondrite organics

R. Tartèse¹, M. Chaussidon², F. Robert³

¹School of Earth and Environmental Sciences, University of Manchester, Manchester, UK
²Institut de Physique du Globe de Paris, Université Sorbonne-Paris-Cité, Paris, France
³IMPMC, Muséum National d’Histoire Naturelle, Sorbonne Universités, Paris, France

Corresponding author: romain.tartese@manchester.ac.uk

Type 1-2 carbonaceous chondrites contain several wt.% carbon that mostly occurs as small patches of insoluble organic matter (IOM) dispersed in a fine-grained matrix. This IOM constitutes the main reservoir of C and N in the Solar System, two elements that have likely been central to the emergence of life as we know it. Therefore, the molecular structure and the chemical and isotopic characteristics of chondritic IOM have been extensively investigated (see 2 for a recent review). Yet, the physical environment and the chemical mechanisms at the origin of these organics grains are still poorly constrained, and we still debate whether they formed in the cold interstellar medium, in the protosolar nebula or on asteroidal parent bodies during metasomatism. To investigate further this issue, we have analysed for the first time with high precision the triple oxygen isotope composition of IOM residues isolated from three type 1-2 carbonaceous chondrites using secondary ion mass spectrometry. In the three oxygen isotope diagram, where the $^{17,18}$O/$^{16}$O ratios are expressed in their corresponding $\delta^{17,18}$O units, the results lie on a slope 1 correlation similar to that defined by high temperature carbonaceous chondrite components. Based on these results we argue that carbonaceous chondrite IOM can neither result from parent-body processes nor be inherited from the isotopically heterogeneous interstellar medium. Instead, the apparent lack of mass-dependent fractionation supports a high temperature origin in the protosolar nebula gas, presumably by photochemical dissociation of organic molecular precursors.

Fault textures in chondrites: does rarity imply insignificance?

Craig Robert Walton¹, Mahesh Anand²³

¹University of St Andrews, Scotland, ²Open University, Milton Keynes, ³Natural History Museum, London

Corresponding author: cw90@st-andrews.ac.uk

Fault textures in chondritic meteorites are rarely mentioned in the meteoritics literature¹. Here, we discuss two unclassified chondrites that contain microfault textures associated with shock-melt veins (Fig. 1). These features are exquisite in that they preserve a unique level of detail about the impact that formed them i.e. a textural record of the nature of stress fields associated with the impact and the end result of its interaction with the target lithology (e.g. magnitudes and directions of displacement²). Analysis of high-pressure phases present along shear-planes also has the potential to inform about the energies involved. It is currently not well understood why microfault textures are so rare given their ubiquitous formation in response to terrestrial impact events. It may be that fault-bearing samples such as these are rarely preserved, mostly having been brecciated by further impact events so as to be unrecognizable in most chondritic breccias & / or more easily breaking up during atmospheric-entry or final parent body ejection. Or, perhaps uncommon low angle¹ or high-energy impacts are required to produce them. Either way, the rarity of microfault textures in chondrites does not necessarily imply their insignificance – instead, these features could represent an as yet untapped well of information about early Solar System processes.

Remote Sensing of Solar System Bodies

Abstracts for the 1st British Planetary Science Congress
From lakes to sand seas: a record of early Mars climate change explored in northern Gale crater, Mars

Steven G. Banham¹, Sanjeev Gupta¹, David M. Rubin², Jessica A. Watkins³, Dawn Y. Sumner⁴, Kenneth S. Edgett⁵, John P. Grotzinger³, Kevin W. Lewis⁶, Lauren A. Edgar⁷, Kathryn M. Stack-Morgan⁸, Robert Barnes¹, James F. Bell III⁹, Mackenzie D. Day¹⁰, Ryan C. Ewing¹¹, Mathieu G.A. Lapotre³, Nathan T. Stein³ and Ashwin R. Vasavada⁸

¹Imperial College, London; ²UC Santa Cruz, CA; ³Caltech, CA; ⁴UC Davies, CA; ⁵Malin Space Science Systems, CA; ⁶John Hopkins, MD; ⁷USGS Astrogeology Centre, AZ; ⁸JPL, Pasadena, CA; ⁹Arizona State University, AZ; ¹⁰University of Texas, TX; ¹¹Texas A&M University TX.

Corresponding author: s.banham@imperial.ac.uk

While traversing the northern flank of Aeolis Mons, Gale crater, Mars Science Laboratory rover Curiosity encountered a decametre-thick sandstone unit unconformably overlying the lacustrine Murray formation. This sandstone contains cross-bed sets on the order of 1 m thick, composed of uniform mm-thick laminations of uniform thickness, and lacks silt- or mud-grade sediments. Cross sets are separated by sub-horizontal bounding surfaces which extend for tens of metres across outcrops. Dip-azimuths of cross-laminations are predominantly toward the north-east, which is oblique to the north-west slope of the unconformity on which the sandstone accumulated. This sandstone was designated the Stimson formation after Mt. Stimson, where it was delineated from the Murray formation.

Textural analysis of this sandstone revealed a bi-modal sorting with well-rounded grains, typical of particles transported by aeolian processes. Stacked cross-bedded sets, representing the migration of aeolian dune-scale bedforms, combined with the absence of finer-grained facies characteristic of interdune deposits, suggest that the Stimson accumulated by aerodynamic processes and that the depositional surface was devoid of moisture which could have attracted dust to form interdune deposits. Reconstruction of this “dry” dune-field based on architectural measurements suggest that cross sets were emplaced by the migration of dunes with minimum heights of ~10m, that were spaced ~160 m apart. The dune field covered an area of 30-45 km², and was confined to the break-in-slope at the base of Aeolis Mons. Cross-set dips suggest that the palaeowind drove these dunes toward the north east, oblique to the slope of the unconformity on which these sandstones accumulated.

Construction of a dry dune field in Gale crater required an environment of extreme aridity with absence of water at the surface and within the shallow subsurface. This is in stark contrast to the lacustrine environment in which the underlying Murray formation accumulated. The contrast in depositional environments between these units suggest that the prevailing climate in Gale crater changed, at least temporarily, from a humid environment with surface water that had potential for sustaining life, to a barren desert with reduced potential for habitability at the surface.
Analysis of potential fluvial features located in and around Lyot crater, Mars

Laura Brooker¹, Matthew Balme¹, Susan Conway², Axel Hagermann¹, Gareth Collins³

¹School of Physical Sciences, Open University, Walton Hall, Milton Keynes Mk 7 6AA, UK.
² CNRS Laboratoire de Planétologie et Géodynamique de Nantes, Université de Nantes, 2 rue de la Houssinière, 44322 Nantes, France.
³ Department of Earth Science and Engineering, Imperial College, Kensington, London SW7 2BP, UK.

Corresponding author: laura.brooker@open.ac.uk

Lyot crater (50°N, 30°E) is a ~215 km diameter, late-Hespanian aged impact crater, located north of Deuteronilus Mensae in the northern hemisphere of Mars¹,²,³. Lyot has an ejecta blanket composed of an inner continuous ejecta sheet and outer, more hummocky, ejecta²,³. To the north, west and east of Lyot are large outflow channels which extend beyond the ejecta margin which potentially formed by groundwater release during the impact event². This crater also contains and is surrounded by many geomorphic features indicative of prior fluvial activity¹,²,⁴, and possible periglacial and/or glacial activity⁴. Thus, Lyot crater potentially records the action of ancient water sourced from underground and more recent atmospherically sourced water. Fluvial valley networks and channels are located throughout the interior of the crater and within the inner ejecta blanket¹,²,⁴. These channels are up to hundreds of metres across and tens of kilometres in length, with several displaying branching. Some channels have been observed terminating in depressions, and several have fans at their terminations¹. Ages derived from impact crater size-frequency statistics date them as mid/late -Amazonian in age¹,⁴. We present observations and qualitative analysis of these channels.

References:
Environments of recent wet-based mid-latitude glaciation on Mars

Frances E G Butcher\textsuperscript{1*}, Matt R Balme\textsuperscript{1}, Colman Gallagher\textsuperscript{2,3}, Neil S Arnold\textsuperscript{4}, Robert D. Storrar\textsuperscript{5}, Susan J Conway\textsuperscript{6}, Stephen R Lewis\textsuperscript{1}, Axel Hagermann\textsuperscript{1}

\textsuperscript{1}The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK
\textsuperscript{2}UCD School of Geography, University College Dublin, Belfield, Dublin 4, Ireland
\textsuperscript{3}UCD Earth Institute, University College Dublin, Belfield, Dublin 4, Ireland
\textsuperscript{4}Scott Polar Research Institute, University of Cambridge, Lensfield Road, Cambridge, CB2 1ER, UK
\textsuperscript{5}Department of the Natural and Built Environment, Sheffield Hallam University, Sheffield, S1 1WB, UK
\textsuperscript{6}Laboratoire de Planétologie et Géodynamique de Nantes, UMR CNRS 6112, 2 rue de la Houssinière – BP 92208, 44322 Nantes Cedex 3, France

*Corresponding author: frances.butcher@open.ac.uk

Evidence for past melting of debris-covered water-ice glaciers in Mars’ mid-latitudes is extremely rare. Exceptional examples of eskers\textsuperscript{1,2} associated with young (100-150 Myr-old) mid-latitude glaciers show, however, that wet-based glaciation did occur recently in certain locations. Eskers are sedimentary ridges deposited in ice-contact (often subglacial) meltwater channels. The remarkably similar geologic settings of these eskers (both within tectonic rifts/graben with evidence for recent secondary tectonism) could imply that elevated geothermal heat flux provided critical excess heat to induce recent basal melting of some mid-latitude glaciers on Mars, despite the extremely cold climates of the late-Amazonian period\textsuperscript{1,2}.

We compared possible rates of geothermal and viscous strain heating of the basal ice with the likely rate of heat loss to the glacier surface. We estimate that, for an ice yield stress of 100 kPa, basal melting required 900 m-thick ice, and modest increases in geothermal heat flux (to 50 mWm\textsuperscript{-2}) and mean annual surface temperature (to 205 K)\textsuperscript{2}. We also use the JPL/University of California Ice Sheet System Model for more detailed 3D exploration of the environmental conditions required for basal melting. Additionally, we compared metre-scale 3D martian esker geometries to terrestrial eskers\textsuperscript{e,g,3} to explore hydraulic conditions (e.g. melt duration, discharge) under which they formed.

Hyperspectral Analysis of the Mars South Polar Residual Cap using CRISM

J. D. Campbell, P. Sidiropoulos and J-P. Muller,

Imaging Group, Mullard Space Science Laboratory, University College London, Holmbury St Mary, Surrey, RH5 6NT, UK

Corresponding author: jacqueline.campbell.16@ucl.ac.uk

The Martian South Polar Residual Cap (SPRC) is a permanent region of CO₂ ice exhibiting unique, dynamic, flat floored, circular sublimation features known colloquially as Swiss Cheese Terrain (SCT) [1]. Sublimation processes expose dust particles trapped within the ice during spring, which can then be analysed using data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on board NASA’s Mars Reconnaissance Orbiter (MRO) [2].

Polycyclic Aromatic Hydrocarbons (PAHs) are a type of organic molecule, and are considered to be important in astrobiology; they potentially play a role in abiogenesis, can be a biomarker for extant life, and have yet to be detected on Mars. PAHs would be rapidly destroyed by ultraviolet radiation at the Martian surface [3]. In this work, we analyse the composition of SCT dust rims, with a particular focus on the detection of PAHs that might have been preserved within the SPRC. CRISM spectra of regions of interest are compared with known Martian mineralogy and PAH laboratory data, with results suggesting the presence of Magnesium Carbonate dust content in depression rims, along with rims having been found to have a higher water content than regions of featureless ice. CO₂ frost and ice has been found to be the most limiting factor in looking for PAH diagnostic signatures on the SPRC. Further work is being undertaken to understand the contaminating effects of the Martian atmosphere, surface CO₂ frost and ice on PAH signatures.

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Investigating the development of putative fluvial features in southern Hale Crater ejecta

Jake Collins-May¹, J. Rachel Carr¹, Neil Ross¹, Andrew J. Russell¹, Matthew Balme²

¹School of Geography, Politics and Sociology, Newcastle University, Claremont Road, Newcastle upon Tyne, Tyne and Wear, NE1 7RU
²Dept. of Physical Sciences, Open University, Walton Hall, Milton Keynes MK7 6AA,

Corresponding author: j.collins-may@newcastle.ac.uk

Hale crater is a large and well preserved complex impact scar situated on the Northern rim of the Argyre impact basin. The ejecta facies which surround the crater are incised by valley networks that appear to be fluvial in origin. Fluvial valleys associated with impact craters are of great interest, due to the long period of time over which impact events have been occurring on Mars. However, there is a great deal of controversy over how the valleys form, and whether a similar process occurs amongst all craters. Previous works have explored the origins of the Hale valley network on a regional scale, and also investigated the morphology of the valley which incises Moanda crater. However no work has yet explored in depth the development of the most heavily incised section of Hale’s ejecta, which is found to the south of the cavity. We utilize CTX, HiRISE and THEMIS visible imagery complemented by MOLA, HRSC and HiRISE stereo derived elevation data, to conduct morphological mapping and visual interpretation of the valley morphology. These findings strongly suggest that the valleys are the result of surface water liberated from the ejecta material by dewatering, similar to a terrestrial lahar. The results from this project will be of great importance to understanding the development of fluvial channels surrounding other impact craters, and will also have wider implications regarding the study of other apparently fresh valley networks on the surface of Mars. In turn, these findings will aid in the search for the most hospitable locations for possible Martian life to develop and thrive.
Alternating glacial and gully erosion on Mars

Susan J. Conway¹, Tjalling de Haas²

¹Laboratoire de Planétologie et Géodynamique CNRS UMR6112, Université de Nantes, France.
²Dept Earth Sciences, Utrecht University, The Netherlands.

Corresponding author: susan.conway@univ-nantes.fr

The mid-to-high latitudes of Mars host assemblages of landforms reminiscent of a receding glacial landscape on Earth. It is hypothesised that these landforms are a result of dramatic changes in climate brought about by swings in Mars’ orbital obliquity, which can vary between 15° and 35° on timescales of ~100,000 years¹. At the highest obliquities it is thought that water ice is driven off the two permanent polar caps (which have combined mass equivalent to the Greenland icesheet) and redistributed to lower latitudes, and as the obliquity swings to lower values water ice is transported in the opposite sense². Here, we report on the relationship in time and space of two suites of landforms: gullies and glacial landforms. Gullies are kilometre-scale erosion-deposition systems comprised of a source alcove, a transportation channel and a deposition apron or fan³. The glacial landforms we describe here fall into two categories – extant viscous flow features where ice could still be present and relicts of glaciation including arcuate ridges commonly interpreted as moraines⁴. Both gullies and glacial landforms are particularly common at the mid-latitudes and show similar trends in orientation with latitude – hinting at a common climatological origin.

Our previous work has shown that dense concentrations of extant glacial forms are anti-correlated with dense gully-populations⁵, yet gullies are found very commonly associated with relict glacial landforms. Other authors have already highlighted the possibility that this landscape assemblage could result from a similar suite of processes to that experienced in paraglacial environments on Earth⁶. We present the results of our work which attempts to place bounds on the active processes, erosion rates and relative chronology associated with this landscape assemblage.

Visible-SWIR spectroscopy and alteration mineralogy of fluvial and lacustrine basaltic sediments from Iceland as an analogue for Mars

C. R. Cousins\(^1\), P. Mann\(^2\), E. Cloutis\(^2\), J. Cherry\(^1\), E. Allender\(^1\), M. Fox-Powell\(^1\)\(^2\), M. Gunn\(^3\)

\(^1\)School of Earth and Environmental Sciences, University of St Andrews, St Andrews, UK.
\(^2\)Department of Geography, University of Winnipeg, Winnipeg, Manitoba, Canada
\(^3\)Department of Physics, Penglais Campus, Aberystwyth University, Aberystwyth, UK

Corresponding author: crc9@st-andrews.ac.uk

Martian sediments are geochemically immature in comparison to their terrestrial counterparts, due to largely mafic sediment protoliths and a lack of crustal recycling via plate tectonics. Little is known about the alteration pathways recorded within such sediments and their spectral signatures, which are used to characterise much of the martian surface. We present a spectroscopic and mineralogical study of Mars-analogue basaltic sediments in Iceland. Here, deposition of immature sediments sourced from the predominantly basaltic crust occurs within a variety of minimally-vegetated fluvial, lacustrine, and glacial systems. We find sediments from all environments to be typically dominated by detrital basaltic minerals with a significant amorphous or poorly crystalline component, and low-temperature alteration phases dominated by smectite clays, chlorite, and zeolite. While smectite clays were identified in all but the youngest (2011) sediments, only a subset of these exhibited 2.2 and 2.3 \(\mu\)m absorption bands associated with Al-OH and Fe/Mg-OH bonds respectively. Fluvial sediments exhibit a stronger 1.91 \(\mu\)m \(\text{H}_2\text{O}\) absorption, have a higher Chemical Alteration Index, and major element geochemistry indicative of open-system high water-rock ratio alteration. Lacustrine and glacial sediments conversely have spectral profiles dominated by detrital basalt mineral phases, minimal hydration bands, and major element geochemistry indicative of closed, relatively low water-rock ratios.
The depositional system of Arabia Terra, Mars: inverted channels, palaeolakes, and regional sediment transport

J.M. Davis\textsuperscript{1*}, M. Balme\textsuperscript{2}, P.M. Grindrod\textsuperscript{1}, P.Fawdon\textsuperscript{2}, R.M.E. Williams\textsuperscript{3}, and S. Gupta\textsuperscript{4}

\textsuperscript{1}Dept. of Earth Sciences, Natural History Museum, London, UK
\textsuperscript{2}Dept. of Physical Sciences, Open University, Milton Keynes, UK
\textsuperscript{3}Planetary Science Institute, Taiuscon, Arizona, USA
\textsuperscript{4}Dept. of Earth Science and Engineering, Imperial College London, London, UK

*Corresponding author: joel.davis@nhm.ac.uk

Valley networks are some of the strongest lines of evidence for sustained fluvial erosion on early (Noachian) Mars \cite{1}, although their sparsity on certain ancient terrains, most noticeably Arabia Terra, has challenged the prevailing view that early Mars was “warm and wet” \cite{2}. Arabia Terra forms the most northerly part of Mars’ southern highlands, connecting the equatorial regions, where valley networks are prevalent, and the northern lowlands, where they are not. Here we will present recent work using Context Camera (CTX; 6 m/pixel) data that shows that there are few valley networks in Arabia Terra, there is abundant geomorphological evidence for fluvial and lacustrine processes \cite{3}. This evidence is in the form of quasi-continuous ridges, interpreted as topographically inverted fluvial channels, which connect with layered sedimentary deposits, interpreted as the palaeolakes. These features are Noachian in age and demonstrate that rather being a purely erosive system, the geology of Arabia Terra records the net deposition of regionally transported sediment. Our results are consistent with a “warm and wet” early Mars that supported widespread precipitation and runoff. Understanding the regional geology of Arabia will be critical for the upcoming ExoMars rover mission, due to land in either Oxia Planum or Marwth Vallis (NW Arabia Terra) in 2021 \cite{4}.

ExoMars Landing Site Characterisation

P. Fawdon¹, M. Balme¹, J.C. Bridges², P. Grindrod³, J. Davis³, E. Sefton-Nash⁴, S. Gupta⁵, A. Ruxston², E. Robson¹, S.M. Turner², Rachel Henson² F. Butcher¹ N. Cook²,

¹ The Open University
² University of Leicester.
³ The Natural History Museum
⁴ European Space Agency
⁵ Imperial College London

Corresponding author: peter.fawdon@open.ac.uk

The primary goal of the ExoMars rover mission is to search for signs of past and present life on Mars. To do this the rover, which is due for launch in 2020, will investigate the geochemical environment in the shallow subsurface over a nominal mission of 218 martian days (sols) [1]. To meet the ambitious mission goal the rover must land in a location where the paleoenvironment was suitable for either formation or concentration of biosignatures, as well as being conducive to long term preservation and have recent exposure in the landing site area.

Due to the small rover traverse distance (<5 km) relative to the size of the landing ellipse (109 km major axis) it is crucial to understand the context of the landing site as a whole before the rover arrives. This is important not only to understand the possible geological history that has affected the landing site biomarker preservation potential, but also to make the best use of the instruments over the limited duration of the mission.

We present a brief overview of the ExoMars landing site characterisation process to date, a summary of the current understanding of the geology at the two remaining ExoMars rover landing sites – Mawrth Vallis and Oxia Planum and our ongoing work characterising the geological context of sites, and developing our understanding of the processes that may have affected the biosignature preservation potential of Northwest Arabia Terra since the late Noachian.

Needle in a haystack: Rayed candidate source craters for Martian meteorites

Harris, J. K1, Grindrod, P. M.1

1Natural History Museum, London, UK

Corresponding author: jennifer.harris@nhm.ac.uk

Planetary science is reliant on a wide variety of data, most of which are collected remotely and at coarse spatial scales. Mineralogical exploration of a planetary surface using these remotely collected data requires some sort of groundtruth in the form of samples that can be directly analysed in laboratories here on Earth. In the case of Mars, the only such samples we have are a small number of meteorites. These rare stones can share with us a wealth of information about the Martian atmosphere and surface. However, to date no consensus has been reached as to where on the planet these samples have come from. Discovering the exact source region(s) for these rocks would have important implications for Martian science.

Broad candidate source locations have been identified based on two primary factors: 1) the relatively young crystallisation ages of the majority of the meteorites, and 2) the minimum size of crater that would have been created by an impact energetic enough to eject pieces of the surface out of Mars's atmosphere and gravitational influence. A third additional constraint is the recent ejection ages of all of the meteorites. Impacts can create a distinctive pattern of radial rays of material around the resulting crater. This pattern degrades with age and is thus an indicator of a young crater. Various authors1–4 have identified numerous rayed craters on the surface of Mars large enough to have ejected material, using day and night-time THEMIS imagery, however a complete global survey has not previously been undertaken. A global survey of rayed craters ≥ 3 km diameter is presented here for the first time and used together with other remote sensing datasets, including global dust coverage and geological unit ages, to identify potential source craters for the SNC martian meteorites that could be further investigated through high resolution VNIR spectral imaging.

References:
Origin of longitudinal ridges and furrows observed in long runout landslide: the study of a martian landslide.

Giulia Magnarini¹, Tom Mitchell¹, Peter Grindrod², Liran Goren³, and Harrison Schmitt⁴

¹Department of Earth Sciences, University College London, London, UK.
²Natural History Museum, London, UK
³Department of Geological and Environmental Sciences, Ben Gurion University of Negev, Israel.
⁴Department of Engineering Physics, University of Wisconsin Madison, United States.

Corresponding author: giulia.magnarini.14@ucl.ac.uk

The formation mechanism of long runout landslides remains matter of discussion as does, yet poorly investigated, the origin of longitudinal ridges and furrows observed on the surface of their deposits. We use high resolution images and stereo-derived DEMs to conduct detailed morphological and morphometric characterization of longitudinal ridges for one martian landslide in Coprates Chasma, Valles Marineris, Mars. We suggest that these results constitute supporting evidence of the observed spontaneous formation of longitudinal vortices within dense rapid granular flow. This implies that the origin of longitudinal ridges does not necessarily depend on the nature of the substrate, as often inferred by comparison of martian landslides with the terrestrial Sherman Glacier landslide. Understanding whether the origin of longitudinal ridges and furrows is inherent to the nature of long runout landslides is important for understanding the mechanism responsible of such catastrophic emplacements. On Mars, this can provide constraints about the presence of water, ice, and specific mineralogical facies both within the collapsed material and in the valley floor, which eventually can be used as indicator of martian climatic evolution.

Identification of small smooth units abutting lobate scarps on
Mercury.

C. C. Malliband¹, D. A. Rothery¹, M. R. Balme¹, S. J. Conway²

¹ School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, UK
² LPG Nantes–UMR CNRS 6112, Université de Nantes, France

Corresponding author: chris.malliband@open.ac.uk

Units on Mercury are typically classified principally on the basis of their geomorphology¹,² Here we present small (<15 000km²) areas of smoother morphology abutting against lobate scarps, widely recognised to be surface expressions of contractional faults³. This pooled magma would have to postdate considerable movement on these lobate scarps and so may represent magmatism occurring late in the history of Mercury’s global contraction. We have identified a number of these flow units globally. Characterisation of these flow units in ongoing to attempt to understand where they fit within Mercury’s global stratigraphy.


Figure 1: Calypso Rupes. Note the more heavily cratered surface on the hanging wall (north) and smooth plains abutting against the scarp.

Unusual sediment transportation processes under low pressure environments and implications for gullies and recurring slope lineae

Raack, J.¹, Conway, S.J.², Herny, C.³, Balme, M.R.¹, Carpy, S.², Patel, M.R.¹,⁴

¹ School of Physical Sciences, STEM - The Open University, Milton Keynes, UK
² Laboratoire de Planétologie et Géodynamique - Université de Nantes, Nantes, France
³ Physikalisches Institut - Universität Bern, Bern, Switzerland
⁴ Space Science and Technology Department - STFC Rutherford Appleton Laboratory, Oxford, UK

Corresponding author: jan.raack@open.ac.uk

Recently and presently active mass wasting features such as the formation/modification of gullies [1,2,3] as well as the formation of recurring slope lineae (RSL) [4] are common on the surface of Mars, but their origin and triggering mechanisms are still not completely understood and are under intense debate. Liquid water flows are one proposed formation mechanism: investigations have shown that maximum surface temperatures can exceed the frost point of water and that liquid water could exist on the surface of present-day Mars in a transient state.

We will present the outcomes of a series of experiments with surface and water temperatures between ~278 and 297 K and low pressures (~9 mbar) [5,6]. We simulated sediment transport by liquid water over a sloping bed of unconsolidated sediment. Our results reveal a suite of unusual and very active sediment transport processes, which are not produced under terrestrial pressures. We will discuss the impact of these unusual sediment transport processes on estimates of water budgets for active mass wasting processes on the martian surface.

Oxford Space Goniometer and 3D Thermophysical Modelling

Tristram Warren¹, Neil Bowles¹

¹Oxford University

Corresponding author: warren@atm.ox.ac.uk

Measurements of the light scattering behaviour of the regoliths of airless bodies via remote sensing techniques in the Solar System, across wavelengths from the visible to the far infrared, are essential in understanding their surface properties. A key parameter is knowledge of the angular behaviour of scattered light, often represented mathematically by a phase function (PF). The PF is believed to be dependent on many factors including: surface composition, surface roughness and the wavelength of radiation. Although there have been many PF measurements of regolith analogue materials in the laboratory across visible wavelengths, there have been no equivalent measurements made in the thermal infrared (TIR)¹. Since the launch of Diviner to the Moon in 2009, OSIRIS-Rex to the asteroid Bennu in 2016 and the planned launch of BepiColombo to Mercury in 2018, there is now a large quantity of TIR remote sensing data that needs to be interpreted²–⁴. It is therefore important to extend laboratory PF measurements to the TIR. This session will describe the design, build, calibration and initial measurements from a new laboratory instrument that is able to make PF measurements of analogue planetary regoliths across wavelengths from the visible to the TIR.

Geological mapping of the Hokusai (H05) quadrangle of Mercury

J. Wright¹, D. A. Rothery¹, M. R. Balme¹, S. J. Conway²

¹School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, UK
²LPG Nantes – UMR CNRS 6112, Université de Nantes, France

Corresponding author: jack.wright@open.ac.uk

Data from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft are being used to construct 1:3M scale quadrangle geological maps of Mercury¹,²,³,⁴,⁵. These will provide context and targets for the upcoming BepiColombo mission to Mercury⁶. We present our progress mapping the Hokusai (H05) quadrangle (0-90° E, 22.5-66° N), which was imaged for the first time by the MESSENGER mission. Monochrome mosaics (~166 m/pixel) with low, moderate and high illumination angles, from both east and west, are used as basemaps. Ancillary datasets include individual MESSENGER images, topography and colour. Using ArcGIS, linework is being drawn at 1:400k, in accordance with USGS stipulations and the published MESSENGER quadrangle maps¹,²,³. Smooth volcanic plains occupy northern H05. Large (>100 km) and small (<10 km) buried impact craters in close proximity show that the plains were formed by multiple eruptions. The densely cratered southern plains likely represent older eruptions. Subdivision of these plains into distinct units is underway. H05 also contains Mercury’s largest explosive volcanic deposit and young, post-impact volcanism.

Investigation of an automated method for construction of a 3-D block diagram of Promethei Lingula in the Martian SPLD

Si-Ting Xiong¹, Jan-Peter Muller¹, Raquel Caro Carretero²

¹Imaging Group, Mullard Space Science Laboratory (MSSL), Department of Space & Climate Physics, University College London, Holmbury St Mary, Dorking, Surrey, RH5 6NT, UK; Email: siting.xiong.14@ucl.ac.uk; j.muller@ucl.ac.uk
²Universidad Pontificia Comillas, Madrid, Spain; Email: rcaro@cau.comillas.edu

Corresponding author: siting.xiong.14@ucl.ac.uk

Subsurface layers are well preserved in the polar regions on Mars, which preserve a record of past climate changes. Orbital radar instruments, such as SHAllow RADar (SHARAD) onboard Mars Reconnaissance Orbiter (MRO), transmit radar signals and receive a set of signals returned from the subsurface regions. These radar data, often called radargrams, show profiles of subsurface regions to different penetration depths, depending on the frequencies utilised and the intervening probed material. Linear features in radargrams reflect depths where there is a change in dielectric properties in the probed materials. In the Martian South Polar Layered Deposits (SPLD), an angular unconformity which is a discontinuity caused by non-parallelism in the stratigraphic sequence is observed in SHARAD radargrams over Promethei Lingula [1,2]. In this study, subsurface layers representing the unconformity are interpreted manually. We have developed an automated method for picking out subsurface layers from SHARAD radargrams fully automatically [3]. Furthermore, we investigate the possibility of an automated method for reconstructing the subsurface planes, e.g. the angular unconformity plane, and further a 3-D block diagram by combining radargrams acquired from multiple orbital paths.

References:
Sample Return & Curation

Abstracts for the 1st British Planetary Science Congress
**40**Ar-**39**Ar age determination of basaltic fines from Apollo 12 soil sample 12070,889 and implications for future sample return missions.

L. Alexander1,2, K. H. Joy3, J. F. Snape4, R. Burgess3, and I. A. Crawford1,2

1Department of Earth and Planetary Sciences, Birkbeck College, University of London, UK.
2Centre for Planetary Sciences at UCL-Birkbeck.
3School of Earth and Environmental Science, University of Manchester, Manchester, UK.
4Department of Geosciences, Swedish Museum of Natural History, Stockholm, Sweden.

Corresponding author: l.alexander@bbk.ac.uk

Introduction: Mare basalt samples provide us with information on the composition and melting history of the Moon’s upper mantle [1,2]. By dating samples we can learn about the evolution of lunar volcanism over time. We present work that forms part of a study of basaltic diversity in Oceanus Procellarum through the analysis of 1-2 mm sized regolith-derived rock fragments (fines) from the Apollo 12 mission [3,4].

Methods: Samples were split two for petrographic study and Ar dating. **40**Ar-**39**Ar ages were determined by step heating neutron irradiated samples using a Photon Machines Fusions IR 10.6 µm wavelength CO2 laser coupled to an Argus VI multicollector mass spectrometer at the University of Manchester.

Results: From the textures and chemistries of the 12 fines presented, most can be classified into the well-established lithological groups of ilmenite, pigeonite and olivine basalts. Several samples (12070,889_3, 889_6, 889_10 and 889_11) could not be characterised due to their coarse-grained nature [5].

Ages of the samples mostly fall between 3.04 and 3.3 Ga, generally consistent with the ages of basalt flows reported at the Apollo 12 site. Apparent age spectra indicate that many samples have had partial resetting of their argon isotopes. This is typical of mare basalt samples that have resided close to the lunar surface and may reflect degassing during impact shock events [e.g., 6,7]. Two samples (subplits 889_5 and 889_6) display **39**Ar release patterns reflecting more complex Ar loss histories and giving the youngest ages. **38**Ar/ **37**Ar ratios are used to provide the apparent cosmic ray exposure (CRE) ages. These are highly variable between 30 and 591 Ma.

Conclusions: This work brings together petrological, geochemical and age data for a group of small, 1-2 mm basalt chips, demonstrating that information about parent lava flows and source regions together with the age relationships can be determined depending on the crystal grain size. This has important implications for future lunar sample return missions that are likely to return regolith and small rock masses. Future sample allocations will require multi-technique based approaches integrating non-destructive and destructive analyses to maximise scientific return.

Crystal size distribution analysis of Apollo 15 mare basalts using QEMSCAN

S. K. Bell¹, M. E. Hartley¹, K. H. Joy¹ and J. F. Pernet-Fisher¹

¹School of Earth and Environmental Sciences, University of Manchester, Manchester, UK

Corresponding author: samantha.bell@manchester.ac.uk

Crystal size distributions (CSDs) are a quantitative measure of magmatic processes using the population density of a mineral phase within different crystal size intervals [1]. In this study, we use CSD analysis to identify and interpret the magmatic and eruptive processes which produced the range of mineral textures observed in the Apollo 15 mare basalts [2]. We also investigate the potential advantages and limitations of using automated quantitative petrology systems, such as QEMSCAN (Quantitative Evaluation of Minerals by SCANing electron microscopy), for generating crystal size measurements for CSD analysis.

Traditional methods of CSD data collection require the manual tracing of crystal boundaries for use in image processing software, such as ImageJ. Crystal lengths may then be processed using programs such as CSDslice [3] and CSDcorrections [4] to convert the 2D measurements into estimates of true 3D crystal lengths. Signatures of accumulation, fractionation and crystal mixing are then identified by plotting population density against crystal length. The automated petrological system QEMSCAN includes software processors designed to separate ‘particles’ of a selected mineral phase, recording information on their compositions and sizes. This, theoretically eliminates the need for time-consuming manual methods, but with the potential loss of resolution especially at crystal boundaries.

Preliminary results suggest both the number of crystals measured and their location within the thin section can significantly skew CSD analysis. This study will provide a greater insight into the processes during magma storage and subsequent eruption of the Apollo 15 mare basalts in Mare Imbrium on the nearside of the Moon.

EURO-CARES: A Vision for European Curation of Extraterrestrial Materials

Grady, M.M.\textsuperscript{1,2}, Smith, C.S.\textsuperscript{1}, Russell S. S.\textsuperscript{1,2} and the EURO-CARES Consortium

\textsuperscript{1}Open University, Milton Keynes, MK7 6AA, UK
\textsuperscript{2}Natural History Museum, Cromwell Road, London SW7 5BD, UK

Corresponding author: m.m.grady@open.ac.uk

Most of the samples that fuel the laboratory-based planetary science investigations are from meteorites. Almost all European countries have at least one internationally-acknowledged collection of meteorites maintained at a major museum or other academic centre. There are also at least two specialist collections of meteorites and one of micrometeorites returned from Antarctica by Europe-led expeditions. Most importantly, there is also the collection of Luna samples returned from the Moon, and held by the Russian Academy of Sciences in Moscow.

At the moment, there is no single European Sample Curation Facility (ESCF), and no call for one for the samples currently available within Europe. However, European scientists are very hopeful that within the next decade, they will need such a facility, to curate material recovered by a new generation of sample return missions. Any such facility will certainly be an international initiative, and require substantial investment – not just in financial terms, but in infrastructure and training. In its most recent strategic research programme, Horizon 2020, the European Union (EU) recognized the importance of facilitating the work of ESA by funding a programme of space-related activities. One of the activities is EURO-CARES (European Curation of Astromaterials Returned from Exploration of Space; http://www.euro-cares.eu/). This is a three year, multinational project, in which a team of experts from academia and industry is developing a roadmap for a European Sample Curation Facility (ESCF). A complementary activity is EuroPlanet (http://www.europlanet-eu.org/) which coordinates inter-institutional access to laboratory instrumentation, as well as outreach and networking activities.
Planetary Drilling Technologies: Progress and Applications

Patrick Harkness, Kevin Worrall, David Firstbrook, and Ryan Timoney

University of Glasgow

Corresponding author: patrick.harkness@glasgow.ac.uk

Planetary sampling tools are required for a wide range of scientific mission profiles. This presentation will discuss developments in drilling technologies at the University of Glasgow, from ultrasonically assisted penetration of granular materials\(^1\), to drillstring assembly techniques\(^2\), to the lessons learned from field trials in planetary analogue locations ranging from mine shafts\(^3\) to the Antarctic ice sheet\(^4\).

These technologies are finding applications on Earth as well as on Mars. A key focus of this presentation shall be the technology transfer processes we have undertaken to adapt many of these concepts to terrestrial science. This process helps to advance the readiness of our space technologies, making them more attractive for future missions, while at the same time advancing science today.

In this context, we will use the Percussive Rapid Access Ice Drill, a collaboration with the British Antarctic Survey, as an example. This device is based on planetary sampling technologies but is being redeveloped for subglacial exploration in the polar regions, and is scheduled for deployment to Rothera during the winter of 2018-19.


Sample Return from Antarctica: UK meteorite recovery plans

K. H. Joy\textsuperscript{1} and G. W. Evatt\textsuperscript{2}

\textsuperscript{1}School of Earth and Environmental Sciences, University of Manchester, Manchester, UK
\textsuperscript{2}School of Mathematics, University of Manchester, Manchester, UK

Corresponding author: Katherine.Joy@manchester.ac.uk

Over two thirds (~35,000) of the world’s classified meteorites have been recovered from Antarctica\textsuperscript{[1]}. This is primarily because ice flow dynamics transports meteorites, buried at depth in the ice for hundreds of years, up to localised surface regions, known as Meteorite Stranding Zones, allowing for efficient recovery and scientific study\textsuperscript{[2]}. Intriguingly, only 0.7% of the meteorites recovered from Antarctica are iron-based, compared with 5.5% from ‘witnessed falls’ in the rest of the world. Evatt et al.\textsuperscript{[3]} developed a hypothesis to account for this discrepancy. They suggested that iron-bearing meteorites, by nature of their thermal conductivity, may be heated by solar irradiation within the ice layer during the summer months meaning that they never emerge at the ice surface. They predict that they may be an englacial layer at about depths of 20-40 cm, where iron bearing meteorites may preferentially reside.

A UK team have now been funded by the Leverhulme Trust and supported by the British Antarctic Survey to undertake two excursions to Antarctica in Dec. 2018 and Dec. 2019 to investigate new potential meteorite-bearing icefields, and test the buried meteorite theory\textsuperscript{[3]}. Surficial meteorites will be recovered to test collection site statistics: such meteorites will be curated and made available for scientific research. We will present here an update on the project’s progress and plans for the field excursions, and seek to engage the community in potential cosmochemistry research and networking opportunities. A separate breakout session on the topic will be used to further facilitate discussions.

Characterising the Heavy Noble Gases of Comet Wild 2 with Closed-System Stepped Etching

T. P. Lawton¹, S. A. Crowther¹, H. Busemann², and J. D. Gilmour¹

¹School of Earth and Environmental Sciences, University of Manchester, UK
²IGP, ETH Zurich, Switzerland

Corresponding author: Thomas.Lawton-3@manchester.ac.uk

Samples returned from comet Wild 2 by NASA’s Stardust mission are some of the most primitive solar system materials available on Earth, and may contain a record of ancient reservoirs of heavy noble gases. Characterising the Kr and Xe contained in cometary refractories and ices elucidates processes in the early solar system, models of terrestrial atmosphere formation, and cometary evolution [1]. However, the silica aerogel used by Stardust to capture samples contains high concentrations of atmospheric gases, which the conventional stepped heating approach of noble gas spectrometry cannot discretely separate from extraterrestrial components [2].

We avoid aerogel’s atmospheric contamination by employing a closed-system stepped etching (CSSE) sample extraction technique to sequentially etch the different materials contained in Stardust samples, releasing discrete noble gas components with each step [3]. To separate components associated with aerogel from silicates and organics, we plan stepwise etching with HF followed by HNO₃ [4]; xenon isotopic analysis will be made with the RELAX mass spectrometer [5]. We are currently validating the technique using a Stardust analogue comprising aerogel, a solar wind-rich lunar regolith breccia (PCA 02007) and Q-rich organic residue from HCl/HF digestion of the Vigarano (CV3) carbonaceous chondrite. We have established baseline compositions of the analogue materials with stepped heating, and have conducted preliminary HF etch steps of the entire Stardust analogue with closed-system stepped etching and RELAX. When validated, we plan to apply this stepwise etching approach to flown Stardust material returned from comet Wild 2.

UK Involvement in the NASA OSIRIS-REx asteroid sample return mission to Bennu

Russell S. S. ¹, Bowles N. ², Franchi I. A. ³, Donaldson-Hanna K. ², Rozitis B. ³, King, A.J. ¹, Schofield, P.F. ¹, Connolly, H.C. Jr. ⁴,⁵, Lauretta D. ⁵

¹Planetary Materials Group, Natural History Museum, Cromwell Road, London SW7 5BD, UK
²AOPP, Clarendon Laboratory, University of Oxford, Parks Road, OX1 3PU, UK
³Open University, Walton Hall, Milton Keynes, MK7 6AA, UK
⁴Department of Geology, Rowan University, Glassboro, NJ 08028, USA
⁵Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA

Corresponding author: sarr@nhm.ac.uk

This presentation will describe NASA’s New Frontiers 3 asteroid sample return mission, OSIRIS-REx, and highlight the contributions being made by teams here in the UK. OSIRIS-REx was launched in September 2016 and is now on course to rendezvous with primitive asteroid Bennu next summer (2018) to prepare for sampling its surface in 2020. Based on Spitzer and Earth-based remote sensing observations Bennu is believed to be a primitive carbonaceous asteroid, type B, possibly similar to CM meteorites. OSIRIS-REx’s primary mission is to acquire at least 60 g and up to 2 kg of the asteroid’s surface and return it to Earth in 2023. The spacecraft includes a comprehensive suite of cameras and spectrometers and will carry out a global multispectral survey at the asteroid to assist with sample site selection and provide context for the returned sample.

OSIRIS-REx is led by Prof. Dante Lauretta (University of Arizona) and teams from the UK have been involved in the mission since its selection. Teams at Oxford and Natural History Museum recently participated in a project to characterise Bennu analogue samples [1]. During 2018 and 2019, groups at the Open University and University of Oxford will be providing support for the mapping phase of the mission, through thermal modelling, laboratory spectroscopy and remote sensing data analysis. The Natural History Museum is providing input to the Sample Site Selection Working Group. Once the sample is returned to Earth groups from the Open University and the Natural History Museum will be part of the sample analysis team.

References: [1] Schrader D. L. et al., 2017. LPSC 48; #1273
European Space Agency Exploration Sample Analogue Collection (ESA2C) and Curation Facility

C. L. Smith¹, M.S. Rumsey¹, S-J. Gill¹, K. Manick¹, C. Mavris¹, H. Schroeven-Deceuninck² and L. Duvet²

¹Department of Earth Sciences, Natural History Museum, London, SW7 5BD, UK
²ESA ECSAT, Fermi Avenue, Harwell Campus, Didcot, Oxfordshire, OX11 0XD, UK.

Corresponding author: c.l.smith@nhm.ac.uk.

The In support of the Robotic Exploration mission preparation programmes the European Space Agency (ESA) contracted the Natural History Museum (NHM) in order to:

• Define the requirements for an Exploration Sample Analogue Collection (ESA2C) for Mars, Phobos, Deimos, C-Type Asteroids and the Moon; and build a geologically appropriate analogue collection based on these requirements;
• Characterise the ESA2C in terms of the fundamental physical and mechanical, as well as chemical and mineralogical properties of the analogues;
• Set up a curation facility to manage and support the ESA2C and carry out characterisation work.

The overall objectives of this work have been to produce a useful and useable resource for engineers and scientists developing technologies for ESA missions in support of human and robotic exploration of Mars, Phobos, Deimos, C-Type Asteroids and the Moon. Within the scope of this activity the NHM has developed detailed policies and protocols for sample curation which not only ensure consistent and reliable analytical results, but also support the loan of material to suitably qualified PIs from the planetary science and engineering communities, providing a relevant and practical resource of planetary analogue materials. Although the ESA Exploration Sample Analogue Curation Facility is still being developed, to date our analogues have been used in both industry and research projects in Hungary, the UK and the USA. We look forward to further developing this resource and providing an accessible and sustainable supply of planetary analogues to ESA and the broader planetary science and engineering communities involved in space exploration.
Technologies and Missions

Abstracts for the 1st British Planetary Science Congress
ProSPA: An In-situ laboratory for analysing lunar polar volatiles within the PROSPECT mission


Introduction: The PROSPECT (Package for Resource Observation and In-Situ Prospecting for Exploration, Commercial Exploitation and Transportation) is currently in development by ESA (European Space Agency) as part of an international lunar exploration effort over the coming decade. It is intended that PROSPECT will identify and characterise volatiles in the lunar polar regions as part of the Russian Luna-27 mission with the intention of investigating the viability of these volatiles as resources.

ProSPA is the Sample Processing & Analysis subsystem of PROSPECT. The intention is for it to receive solid samples, extracted from the lunar subsurface by the ProSEED drill, and to perform a suite of experiments to ascertain the presence, quantity and isotopic composition of volatiles as a function of depth within the first 1.2 m of the lunar surface.

ProSPA chemical Laboratory: The chemical laboratory of ProSPA is designed to exploit both heritage instruments such as the Gas Analysis Package flown on Beagle 2 [1] and the Ptolemy instrument from Rosetta Philae [2], as well as larger lab-based instrumentation such as the Open University’s Finesse instrument. It consists of a full gas handling system, including micro-reactors, a reference system, and sensors for both temperature and pressure. These will feed gas into one of the two mass spectrometers: an ion trap device for analytical mass spectrometry (target m/z range 2-200 amu), and a magnetic sector instrument capable of ~1‰ precision. Gas extraction will be accomplished by one of three methods.

Evolved gas analysis: A linear heating experiment with continuous analysis of the gas produced from the sample, similar to those that have already been produced from Apollo samples [3].

In Situ Resource Utilisation (ISRU) demonstration: Gases from the reference system are routed into the furnace in order to test the potential for the extraction of useable resources by reduction.

Stepped extraction: Samples are heated in either pyrolysis or combustion experiments with the evolved gases processed by release temperature. The presence of reactors (e.g. cold fingers) in the main system allows specific gases to be sequestered and analysed separately either in static or dynamic modes on the magnetic sector mass spectrometer.

Current status: ProSPA is currently within its preliminary design review period. Tests are ongoing to optimise the performance of the ovens and reactors, as well as characterise a novel design of reference metering valve. Experiments for ISRU are also currently under evaluation.

Scientific Integration of ExoMars Pancam, ISEM, and CLUPI instruments

Allender, E.J.¹, Cousins, C.R.¹, Gunn, M.D.², Coates, A.J.³

¹School of Earth and Environmental Sciences, The University of St Andrews, Irvine Building, North Street, St Andrews, Fife, KY16 9AL.
²Department of Physics, Aberystwyth University, Penglais, Aberystwyth, SY23 3BZ.
³Mullard Space Science Laboratory, University College London, Holmbury St Mary, Surrey

Corresponding author: Elyse Allender (ea63@st-andrews.ac.uk)

As the launch for ExoMars 2020 draws nearer, the need for tools to exploit the wealth of data to be returned by PanCam [1], ISEM [2], and CLUPI [3] instruments becomes increasingly important; the exploitation of integrated data from these instruments will be invaluable in detecting evidence of past habitability on Mars. Here we present initial results from fieldwork undertaken in the geothermal area of Námafjall, Iceland.

Using NERC Airborne Research Facility Eagle and Hawk hyperspectral imagery as an analogue for orbital data, instrument emulators were deployed in the field to simulate the PanCam, ISEM, and CLUPI instruments onboard ExoMars 2020. Soil and rock samples were also collected at regular intervals across the study site to provide spectral ground truth after Q-XRD analysis. Thus, we utilise a multi-scale approach to develop and test software tools for analysis of PanCam, ISEM, and CLUPI imagery. These image analysis tools will be constructed as extensions to ENVI + IDL, and combine procedures from [4,5] to perform pre-processing and generate false colour band depth visualisation products for PanCam images. Proposed extensions include: a spectral fitting utility for image classification using ISEM and PanCam spectra, and ISEM footprint unmixing using HRC and CLUPI for image segmentation. We anticipate these tools will greatly facilitate the analysis of ExoMars 2020 data and will make them publicly available upon their completion.

MURFI 2016 – Mars Utah Rover Field investigation

Matt Balme¹, Mike Curtis-Rouse² and the MURFI team³

¹Open University, Walton Hall, Milton Keynes, UK, MK7 6AA
²Science & Technology Facilities Council, UK
³ For full MURFI team see Balme et al. (2017)¹

Corresponding author: Matt Balme (matt.balme@open.ac.uk)

The Mars Utah Rover Field Investigation “MURFI 2016” is a Mars Rover field analogue mission run by the UK Space Agency (UK SA) in collaboration with the Canadian Space Agency (CSA). MURFI 2016 took place during October and November 2016 and consisted of a field team including an instrumented Rover platform and an Operations Team based in the Mission Control Centre (MOC) at the Harwell Campus near Oxford in the UK. The main objectives of MURFI were (i) to develop logistical and leadership experience in running field trials within UKSA and (ii) to provide members of the UK Mars Science community with Rover Operations experience, and so to build expertise that could be used in the 2020 ExoMars Rover mission. Here, we summarise the Rover instruments, field site, and Operations.

The focus of MURFI 2016 was an accelerated “ExoMars-like” mission in which ~10 ‘sols’ of a Rover mission were simulated, beginning with the first active drive sol and ending with a drill sample. MURFI 2016 was a vital training activity for the science team, allowing them to perform tactical operations under a tight deadline, rather than having time to examine the data in full. MURFI also produced ExoMars-relevant operations insights. For example, the complexity and difficulty both of performing field-geology and targeting a Rover-mounted drill using a Rover with mainly stand-off instruments became apparent during MURFI, forcing the team to improvise innovative operational solutions.

Mars in 3D – 3D geological analysis and terrestrial validation of rover-derived stereo-images for the ExoMars 2020 PanCam

Robert Barnes¹, Sanjeev Gupta¹, Matt Gunn², Gerhard Paar³, Christoph Traxler⁴, Thomas Ortner⁴, Arnold Bauer³, Kathrin Juhart³, Bernhard Nauschnegg³, Laura Fritz⁴, Gerd Hesina⁴, Jan-Peter Muller⁵, Yu Tao⁵.

¹Imperial College London, UK
²Aberystwyth University, UK
³Joanneum Research, Austria
⁴VRVis, Austria
⁵Mullard Space Science Laboratory, University College London, UK

Corresponding author: robert.barnes@imperial.ac.uk

A key focus of planetary rover missions is to use panoramic stereo camera systems to image outcrops along rover traverses, in order to characterise their geology and focus the search for ancient life. 3D reconstructions of this data are processed to enable quantitative analysis of the stratigraphy and geometry of those outcrops. Processing, visualisation and geological analysis tools have been developed with 3D Ordered Point Clouds (OPCs) of reconstructed stereo images from NASA’s MER and MSL rover missions, allowing geoscientists to roam around and collect detailed measurements, much as they would do with a terrestrial outcrop. A major outstanding issue with this data is assessing the accuracy of the reconstructions and measurement tools, with ground-truthing presently not possible. To address this problem for ESA’s upcoming ExoMars 2020 Rover, the Aberystwyth University PanCam Emulator (AUPE) has been developed to collect stereo-image data of outcrops in the UK which are considered to be analogous to those in the candidate landing sites. Stereo-image panoramas collected with AUPE are rendered in PRo3D, and full geological analyses of these outcrops are carried out. The results are compared with detailed field investigation of the same outcrops, allowing us to understand the reliability of this data when the ExoMars 2020 Rover carries out its mission.
Igneous compositions recorded in Gale crater’s sediments

C. C. Bedford\textsuperscript{1}, J. C. Bridges\textsuperscript{2}, S. P. Schwenzer\textsuperscript{1}, R. C. Wiens\textsuperscript{3}, E. B. Rampe\textsuperscript{4}, J. Frydenvang\textsuperscript{5}, P. J. Gasda\textsuperscript{3}

\textsuperscript{1}The Open University, UK
\textsuperscript{2}University of Leicester, UK
\textsuperscript{3}Los Alamos National Laboratory, USA
\textsuperscript{4}NASA Johnson Space Centre, USA
\textsuperscript{5}University of Copenhagen, Denmark

Corresponding author: Candice.bedford@open.ac.uk

Gale crater has two identified stratigraphic groups deposited in an early Hesperian fluviolacustrine system\textsuperscript{[1, 2]}. The Bradbury Group (sols 1-750) is dominated by fluvial conglomerate and sandstone, with lacustrine mudstone in Yellowknife Bay\textsuperscript{[1, 2]}. The Mt Sharp Group (Murray formation) is mainly well laminated lacustrine mudstone\textsuperscript{[2]}. We have analysed NASA Curiosity rover ChemCam\textsuperscript{[3]} observation point compositions for targets up to sol 1482, using those that hit \textit{in situ} host rock and – using MastCam, MAHLI imagery – removing diagenetic features. ChemCam data for the stratigraphic units are plotted on scatter and density contour plots to highlight compositional ranges and end members\textsuperscript{[4]}. Our results show that coarse grained (>1 mm\textsuperscript{[5]}) targets are dominated by trachybasalt\textsuperscript{[6]} and subalkaline basalt\textsuperscript{[6]} igneous endmembers. Sandstone (0.062 – 1 mm\textsuperscript{[5]}) targets indicate a mixture of subalkaline basalt\textsuperscript{[6]}, trachybasalt\textsuperscript{[6]} and potassic igneous\textsuperscript{[7]} sources. Finally, mudstone units (<0.062 mm\textsuperscript{[5]}) are dominated by the subalkaline basalt\textsuperscript{[6]} at Yellowknife Bay, and a relatively silica-rich, subalkaline basalt endmember in most of the Murray formation\textsuperscript{[4]}, with an even more silica-rich volcanic component at Marias Pass\textsuperscript{[8]}. This demonstrates that Gale crater sediments record a variety of igneous compositions, with subalkaline basalts dominant, but also including lesser amounts of alkaline and silica oversaturated igneous components.

Philae lander mission and science overview

Hermann Boehnhardt and the Philae mission team

Max-Planck Institute for Solar System Research, Göttingen, Germany

Corresponding author: boehnhardt@mps.mpg.de

The Philae lander accomplished the first soft landing and the first scientific experimenting of a men-made spacecraft on the surface of a comet. Planned, expected, unexpected and unwanted things happened during the descend, the touch-downs and hopping across and the stay and operations on the surface. The key results of the mission were obtained during an about 60 hours long period on 14-16 November 2014. Thereafter, Philae went into hibernation, waking up again in late April 2015 with subsequent short communication periods with Earth. The science return of the mission comes from 8 of the 10 instruments onboard and focuses on morphological, thermal, mechanical and electrical properties of the surface as well as on the surface composition. It allows a first characterization of the local environment of the touch-down and landing sites. Unique conclusions on the organics in the cometary material, the nucleus interior, the comet formation and evolution became available through measurements of the Philae lander in the context of the Rosetta mission.
CASTAway: A mission to map the evolution of the Solar System

N.E. Bowles, C. Snodgrass, A. Gibbings, J.P. Sanchez, the CASTAway proposal team

1University of Oxford, UK (neil.bowles@physics.ox.ac.uk), 2The Open University, UK, 3OHB System AG, Germany, 4Cranfield University, UK

Corresponding author: neil.bowles@physics.ox.ac.uk

CASTAway is a mission concept to explore our Solar System’s main asteroid belt. Asteroids and comets provide a window into the formation and evolution of our Solar System and the composition of these objects can be inferred from space-based remote sensing using spectroscopic techniques. Variations in composition across the asteroid populations provide a tracer for the dynamical evolution of the Solar System. The mission combines a long-range (point source) telescopic survey of over 10,000 objects, targeted close encounters with 10 – 20 asteroids and serendipitous searches to constrain the distribution of smaller (e.g. 10 m) size objects into a single concept. With a carefully targeted trajectory that loops through the asteroid belt, CASTAway would provide a comprehensive survey of the main belt at multiple scales. The scientific payload comprises a 50 cm diameter telescope that includes an integrated low-resolution ($R = 30 – 100$) spectrometer and visible context imager, a thermal (e.g. 6 – 16 $\mu$m) imager for use during the flybys, and modified star tracker cameras to detect small (~10 m) asteroids. The CASTAway spacecraft and payload have high levels of technology readiness and are designed to fit within the programmatic and cost caps for a European Space Agency medium class mission, whilst delivering a significant increase in knowledge of our Solar System.

Acknowledgements: The CASTAway proposal team acknowledges the support of OHB System AG for providing mission analysis and their respective organizations during proposal preparation. J.P. Sanchez acknowledges the support of the UK Space Agency (NSTP2-GE11516-020 “CASTPath”). N. Bowles acknowledges the support of the Leverhulme Trust (RPG-2012-814). C. Snodgrass was supported by an STFC Ernest Rutherford fellowship.
Igneous Differentiation of the Martian Crust

J.C. Bridges\textsuperscript{1}, L.J. Hicks\textsuperscript{1}, C. Bedford\textsuperscript{2}, S.P. Schwenzer\textsuperscript{2} J. MacArthur\textsuperscript{1}, P.H. Edwards\textsuperscript{1}

\textsuperscript{1}Space Research Centre, Leicester Institute for Space and Earth Observation, University of Leicester LE1 7RH. SEES, \textsuperscript{2}Open University, UK.

Corresponding author: j.bridges@le.ac.uk

Our understanding about the differentiation of the Mars crust is increasing rapidly as a result of the combination of 129 distinct SNC meteorites, lander and orbiter data. Recent debates have centred on the existence of alkaline versus tholeiitic and silicic magmatism, crystal fractionation versus partial melting controls on melt composition, and the oxidation state of mantle source regions. Recently we have used MSL ChemCam data to show the presence of trachybasalt float rocks, of tholeiitic affinity, in Gale Crater [1]. Other igneous components recorded in Gale sediments suggest the presence of alkaline and silica oversaturated magmatism as well [2,3,4]. When we compare martian datasets, it is apparent that a key primary melt composition in the ancient highlands is basalt with SiO$_2$ 45 wt\%, Na$_2$O + K$_2$O 3.5 wt\%, and high Fe, low Al. Crystal fractionation from this has led to trachybasalt and possibly in extreme cases to rhyolites [4]. The juxtaposition with some likely alkaline source regions is analogous to intraplate magmatism on Earth. Although one martian meteorite (a regolith breccia) shows clasts of alkaline affinity [5,6], the 112 shergottites are silica saturated. We classify them on the basis of their REE abundances, reflecting mantle source compositions rather than crustal contamination [7]. Bulk compositions indicate that their source regions – probably under Tharsis and the Northern Lowlands - were alkali-poor compared to the Ancient Highlands’ basalts. Limited evidence for crystal fractionation has been identified. Here we present the results of new work comparing shergottites, Gale, MER and terrestrial analogue igneous rocks to determine the key controls on martian magmatism.

First 3D test particle model of Ganymede’s ionosphere

Carnielli G.1, Galand M.1, Leblanc F.2, Leclercq L.3, Modolo R.4, Beth A.1

1 Department of Physics, Imperial College London, London SW7 2AZ, UK
2 LATMOS/CNRS, UPMC Univ. Paris 06 Sorbonne Universités, UVSQ, Paris, France
3 University of Virginia, Charlottesville, Virginia, US
4 LATMOS/IPSL, UVSQ Université Paris-Saclay, UPMC Univ. Paris 06, Guyancourt, France

Corresponding author: gianluca.carnielli10@imperial.ac.uk

Our knowledge of the plasma composition, density and dynamics in Ganymede’s magnetosphere is currently limited by a few observations. The JUICE spacecraft will characterize in detail the exosphere, ionosphere and particle environment around the moon. Prior to arrival, models have been developed to predict these regions and their interaction with the background Jovian particles and magnetic field.

We have developed the first 3D test particle model of Ganymede’s ionosphere. The model is driven by: (1) the number densities of neutral species from the exospheric model of Leblanc et al. (2017) (2) solar extreme ultraviolet radiation (Woods et al. 2005), (3) electron fluxes coming from the Jovian plasma around the moon (Mauk et al., 2004) and (4) the electromagnetic field from the hybrid model of Leclercq et al. (PSS, in revision). In the simulation, the ionospheric ions are produced via photoionization and electron-impact ionization of the neutral exosphere, and move under the influence of the magnetic and electric fields derived from the hybrid model.

We will present the first three-dimensional maps of number densities and bulk speeds of the main ion species produced in Ganymede’s ionosphere. We will show and interpret our derived ion-impact 2D maps at the surface for both ionospheric ions and Jovian ions (coming from the Jovian plasma sheet), and provide sputtering rates of neutral molecule production resulting from these impacts. We will also quantify the importance of the charge-exchange process between the ions and exospheric species in terms of production of energetic neutrals, which is relevant for exospheric models.

In view of the JUICE mission, in addition to providing support to the interpretation of data that will come from the spacecraft, the results of our model can be used for optimising the operation mode of some instruments such as the Radio Plasma Wave Instrument (RPWI). Our model allows also to calculate the production rate and density map of Energetic Neutral Atoms (ENAs) by charge-exchange between the ions and the neutral species. This is relevant to the Particle Environment Package (PEP) instrument which will study the properties and the distribution of these particles around Ganymede. Finally, the ionospheric model will be coupled self-consistently with the magnetospheric model of Leclercq et al. (PSS, in revision), allowing to study in detail the interaction between Ganymede’s ionosphere and the surrounding magnetosphere. This could be highly critical for the interpretation of the magnetic field data that will be measured by the magnetometer on board the JUICE spacecraft (J-MAG) in the moon’s environment.

Development of a hierarchical Bayesian model for end member age extraction: for application of $^{40}$Ar/$^{39}$Ar dating of Mars

J. Carter$^1$, D.F. Mark$^{1,2}$, M.R. Lee$^3$, S. Gupta$^4$

$^1$Scottish Universities Environmental Research Centre, Rankine Av, East Kilbride, G75 0QF
$^2$Department of Earth & Environmental Science, University of St Andrews, St Andrews, KY16 9AJ
$^3$School of Geographical & Earth Sciences, University of Glasgow, Glasgow G12 8QQ
$^4$Department of Earth Sciences & Engineering, Imperial College London, London SW7 2AZ/9

Corresponding author: j.carter.1@research.gla.ac.uk

Currently high precision $^{40}$Ar/$^{39}$Ar geochronology is limited to isolated mineral phases however, work by Vanlangingham and Mark 2011 has shown the potential and proof of concept for there to be more information in some multi-component age spectra than previously realised [1]. If an approach could be developed to un-mix and retrieve end member age components from mixed spectra then such a tool could be used to reconstruct provenance and further geological processes (e.g., deposition, authigenesis, weathering…). Equally, it may be possible to take a bulk sample from a meteorite (e.g., NWA 7034) and recover age information for individual components of different age. Unmixing techniques (hierarchical Bayes) used in hyperspectral imaging [2] have the potential to produce unique and true end member age solutions for multi-component spectra, and once tuned for the $^{40}$Ar/$^{39}$Ar process, may have the potential to be used for dating the individual components of the Martian regolith.

References:


Re-interpretation of the Ptolemy data from the Rosetta Mission

Q. H. S. Chan, I. P. Wright, A. Morse, S. Nicoara

Planetary and Space Sciences, School of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK

Corresponding author: queenie.chan@open.ac.uk

The Ptolemy mass spectrometer (MS) onboard the Philae lander of the European Space Agency’s (ESA) Rosetta Mission is an ion trap (IT) MS which is capable of storing and releasing mass-selective ions by adjusting the radio frequency voltage. The high abundances of outgassing species such as water\(^1\) on the target comet 67P accounts for prevalent ion-molecule (I/M) reactions in the IT. While Rosetta’s COSAC and ROSINA detected nitrogen-bearing\(^2\) and aromatic components\(^3\), Ptolemy detected only low concentrations of these compounds\(^4\). We investigated if I/M reactions are causative to such disparities. ITMS and quadrupole (Q) MS spectra are generally comparable as the fragmentation sites should correspond to the molecule structure to give the same fragments. However, the relative abundances of the fragments are different, and together with the protonation effect, ITMS allows us to cross-check the presence of a molecule by providing a fragmentation pattern that is slightly different from the NIST database. In particular, the base peak is different in some compounds such as methanol (33 m/z [ITMS]; 31 m/z [QMS]), but remain the same in others e.g. toluene and benzene are 91 m/z and 78 m/z respectively in both MS). The absence of the 78 m/z fragment but abundant 91 m/z in the Ptolemy spectra suggest the conversion of benzene to toluene via Friedel-Crafts alkylation involving abundant methyl group containing precursors, which is supported by the presence of alkanes (43 m/z and 57 m/z fragments). The relative abundance of different molecules also plays a role in determining the fragmentation pattern. For instance, by increasing the ratio of water:methanol from 0.1 to 10 vol.%\(^1\), the base peak of methanol moved from 33 m/z to 31 m/z. These results provide significant implications for future space missions such as ESA’s lunar exploration mission PROSPECT which also utilises ITMS.

A Hyperspectral Camera for Planetary Exploration

Matt Gunn¹, Dave Langstaff¹, Carys Huntly¹, Claire Cousins²

¹Department of Physics, Aberystwyth University
²School of Earth and Environmental Sciences, University of St Andrews

Corresponding author: mmg@aber.ac.uk

Camera systems have been present on every Mars surface mission as one of the main key instruments for remote exploration - they produce context images and scientific measurements. For the last 4 decades[1, 2], the cameras on Mars surface missions have had multispectral capabilities allowing them to capture images at between 6 and 12 discreet wavelengths in the Visible and Near InfraRed (400 – 1000nm). Hyperspectral camera systems such as CRISM [3] which produce contiguous spectral measurements have found widespread use in orbital remote sensing imagery but established hyperspectral technologies have been unsuitable for planetary surface missions due to operational and environmental constraints.

Hyperspectral cameras based on the filter technologies used for previous Mars surface context cameras have been developed at Aberystwyth University. These cameras are compatible with the mass, volume, power, environmental and operational constraints of planetary surface missions. They will allow a significant increase in the amount spectral information which can be collected, offering many benefits for mission science return.

The operating principles, development, calibration and data processing of a prototype instrument will be discussed and both laboratory and field test data will be presented.

SUPER-SHARPi: A High Resolution Interplanetary CubeSat Imaging Platform for Astronomy, Space and Planetary Science

Michael J. Johnson¹, George A. Hawker¹, Ian R. Parry¹

¹Institute of Astronomy, University of Cambridge, United Kingdom

Corresponding author: mj507@cam.ac.uk

With missions such as EM¹¹ and InSight² preparing to deploy interplanetary CubeSats to the Moon and Mars, and studies of mission concepts for such spacecraft at asteroids³ and Europa⁴, the time has come for a generic high-resolution survey orbiter interplanetary CubeSat platform that could be flown as standard with such missions. SUPER-SHARPi (Space-based Unfolding Primary for Exploration and Research via Spectroscopic High Angular Resolution Photography – interplanetary-CubeSat) is 1.2m space telescope packaged within a standards compliant solar powered rad-hard 3U CubeSat platform, capable of capturing ground images with 30cm resolution from 400km. Other formats could permit apertures of 2m or more.

The spacecraft is built around a SUPER-SHARP self-aligning mirror sub-system (designed to be available as an off-the-shelf drop-in subsystem for other applications), with modular avionics and sensors that can be used as is or substituted with custom end-user components as missions require. A prototype is currently being assembled, with flight hardware for an on-orbit demonstration to follow shortly.

Applications might include an orbiter for Europa, performing imaging flybys of multiple near-earth asteroids, fly-through/impactor probes for ring studies, or any application that needs Hubble class imaging in a CubeSat package.

References:
The NOMAD spectrometer suite for nadir and solar occultation observations on the ExoMars Trace Gas Orbiter.

Jon Mason¹, M.R. Patel¹², M. Leese¹, B. Hathi¹, W. Hewson¹, S. Lewis¹, J. Holmes¹

¹The Open University, Walton Hall, Milton Keynes, MK7 6AA
²Rutherford Appleton Laboratory (RAL space), Harwell Campus, Didcot, OX11 0QX

Corresponding author: jon.mason@open.ac.uk

NOMAD, the Nadir and Occultation for MArs Discovery, is a spectrometer suit, on the ExoMars Trace Gas Orbiter (TGO), that will conduct a spectroscopic survey of Mars’ atmosphere in the UV, visible and IR regions covering the 0.2–0.65 and 2.2–4.3 µm spectral ranges. NOMAD has two primary observational modes to spatially map (nadir) and vertically profile (occultation) trace gases and aerosols. The high sensitivity of NOMAD [2,3] will offer the possibility to observe as yet undetected species or isotopologues. The detection of the different CH₄ isotopologues (¹³CH₄, CH₃D) will be crucial for the discussion on the origin of methane on Mars. UVIS, the Ultraviolet and Visible Spectrometer [4], is sensitive to O₃, the most reactive gas in the Martian atmosphere, and SO₂, a gas which can be related to volcanism. NOMAD will also extend the survey of the major climatologic cycles of Mars such as the water, carbon and ozone cycles, and provide information on their different components, including isotopic fractionation and atmospheric escape processes.

By performing simultaneous measurements of CO₂, CO, aerosols, clouds, surface ices, and vertical temperature profiles, together with H₂O and HDO, NOMAD will directly assess all the components of the water cycle and will allow us to investigate important production and loss processes for the major cycles: water, carbon, and dust. More generally, source and sink processes for all trace species measured by NOMAD can be investigated in correlation with each other and with dust, ice and temperature profiles, whether they are related to photochemistry, gas-phase chemistry, physical processes (e.g. phase transitions).

References:
Impact-facilitated Hydrothermal Alteration in the Rim of Endeavour Crater, Mars

Mittlefehldt D.W.\textsuperscript{1}, C. Schröder\textsuperscript{2,*}, W.H. Farrand\textsuperscript{3}, L.S. Crumpler\textsuperscript{4}, A.S. Yen\textsuperscript{5}

\textsuperscript{1} NASA/Johnson Space Center, Houston, TX, USA. \textsuperscript{2}University of Stirling, Stirling, Scotland, UK. \textsuperscript{3}Space Science Institute, Boulder, CO, USA. \textsuperscript{4}New Mexico Museum of Natural History and Science, Albuquerque, NM, USA. \textsuperscript{5}JPL-Caltech, Pasadena, CA, USA.

*Corresponding author: christian.schroeder@stir.ac.uk

Endeavour crater, a Noachian-aged, 22 km diameter impact structure on Meridiani Planum, Mars, has been investigated by the Mars Exploration Rover Opportunity for over 2000 sols (Mars days). The rocks of the western rim region (oldest to youngest) are: (i) the pre-impact Matijevic fm.; (ii) rim-forming Shoemaker fm. polymict impact breccias; (iii) Grasberg fm., fine-grained sediments draping the lower slopes; and (iv) Burns fm., sulfate-rich sandstones that onlap the Grasberg fm. The rim is segmented and transected by radial fracture zones. Evidence for fluid-mediated alteration includes m-scale detections of phyllosilicates from orbit, and cm-scale variations in rock/soil composition/mineralogy documented by the Opportunity instrument suite.

The m-scale phyllosilicate detections include Fe\textsuperscript{3+}-Mg and aluminous smectites that occur in patches in the Matijevic and Shoemaker fms. Rock compositions do not reveal substantial differences for smectite-bearing compared to smectite-free rocks. Interpretation: large-scale hydrothermal alteration powered by impact-deposited heat acting on limited water supplies engendered mineralogic transformations under low water/rock, near isochemical conditions.

The cm-scale alterations, localized in fracture zones, occurred at higher water/rock as evidenced by enhanced Si and Al contents through leaching of more soluble elements, and deposition of Mg, Ni and Mn sulphates and halogen salts in soils. Visible/near infrared reflectance of narrow curvilinear red zones indicate higher nanophase ferric oxide contents and possibly hydration compared to surrounding outcrops. Broad fracture zones on the rim have reflectance features consistent with development of ferric oxide minerals. Interpretation: water fluxing through the fractures in a hydrothermal system resulting from the impact engendered alteration and leaching under high water/rock conditions.

Late, localized alteration is documented by Ca-sulfate-rich veins that are not confined to fracture zones; some cross-cut the Grasberg fm. Interpretation: late fluid mobilization of soluble elements, likely in a later alteration event, possibly associated with the environment present during emplacement of the sulfate-rich sandstones of the Burns fm.
Status of DTM production on Mars from the EU-FP7 iMars project

Jan-Peter Muller, Yu Tao

Imaging Group, Mullard Space Science Laboratory, University College London, Holmbury St Mary, RH5 6NT, UK

Corresponding author: j.muller@ucl.ac.uk

There has been a revolution in 3D surface imaging of Mars over the last 14 years with systematic stereo photogrammetric imaging from HRSC. Digital Terrain Models (DTMs) and OrthoRectified Images (ORIs) have been produced for almost 50% of the Martian surface from HRSC. DLR, together with the HRSC science team, is now producing 3D HRSC mosaic products for large regions comprising around 100 individual strips per region (MC-11E/W half-quadrangles) [1]. The iMars project [2] has been exploiting this unique set of 3D products as a basemap to co-register NASA imagery going back to the 1970s. We have developed an automated processing chain for CTX and HiRISE 3D processing based on the open source NASA Ames Stereo Pipeline called CASP-GO (Co-registered ASP using Gotcha Optimisation) to densify the global HRSC dataset with DTMs down to 18m and 75cm respectively [3]. Around 4,350 CTX DTMs + ORIs have been processed using the Microsoft Azure® cloud and our in-house linux cluster. Around 50 HiRISE DTMs of interest have similarly been processed for areas of scientific interest. All of these new products are being published after QA assessment (Putri, this conference) and are viewable through an OGC-compliant webGIS developed at FUB and hosted at MSSL on http://www.i-Mars.eu/web-gis. [4]. As all products are co-registered to a hierarchy of other DTMs in a nested fashion, which are themselves all congruent to MOLA through HRSC, we demonstrate some of their applications to surface science.

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Automatic Quality Assessment of Batch-Produced Martian DTMs from CTX

Alfiah Rizky Diana Putri¹, Panagiotis Sidiropoulos², Jan-Peter Muller¹

¹Imaging Group, Mullard Space Science Laboratory, Dept. of Space and Climate Physics, University College London, Holmbury St Mary, Surrey, RH5 6NT, UK
²Department of Informatics, King’s College London, London, WC2B 4BG, UK

Corresponding author: alfiah.putri.15@ucl.ac.uk

A fully automated DTM processing chain based on the open-source NASA Ames Stereo Pipeline (ASP) called CASP-GO (Co-registration ASP-Gotcha Optimised) has been developed at UCL to process a very large number of NASA MRO Datasets¹. With its approach, more than 4000 CTX DTMs have been produced over a short time period, with similar production parameters resulting in varying qualities in the produced DTMs. Because of the number of produced DTMs, it is difficult to assess the quality of the products manually.

We are developing an automatic method to assess the quality of the DTMs. These DTMs are classified into 5 grades based on the completeness of the DTMs (as a result of the matching) and the appearance of artefacts. We used some 900+ manually assessed CTX DTMs as a training and testing set. The percentage of no data values, assessment using a corresponding MOLA DTM, and filters for artefacts are used as inputs for a SVM-based classifier. We test the method for our sample set and a separate set of manually assessed DTMs. We plan to test and develop the method for CASP-GO produced HiRISE DTMs, other CTX DTMs produced from different method, and other planetary DTMs.

References:
CaSSIS: martian life so far

Rollof V¹, Gruber M¹, Gubler P¹, Becerra P¹, Thomas N¹, SGF², and the CaSSIS team

¹Physikalisches Institut, Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
²SGF Technology Associates Co. Ltd., Pipiske u. 1-5/20 1121 Budapest, Hungary

Corresponding author: victoria.roloff@space.unibe.ch

The ESA-led ExoMars Trace Gas Orbiter (TGO) was launched to Mars on 14 March 2016 [1]. The TGO will search for signs of past and present life on Mars, investigate its geochemical environment, and search for atmospheric trace gases and their sources. The TGO carries 4 scientific instruments in order to reach these goals: this includes the orbiter’s telescopic imager, CaSSIS (Colour and Stereo Surface Imaging System). CaSSIS is capable of taking high-resolution stereo images, in 4 colours, of the martian surface from on board the TGO. A full description of the instrument can be found in [2]. A detailed on-ground calibration campaign was performed [3], and a number of calibration products were gathered and utilised as part of the in-flight calibration campaigns.

We will present an account of CaSSIS’s journey so far, what we have learnt from the in-flight commissioning phases to-date, and how the software development tool - the Ground Reference Model (GRM) - has become the effective ‘Flight Spare’ model, being used to assess the behaviour and performance of the Flight Model (FM). We will show results from testing the timing of commanded stereo image pairs with the GRM, verification of a new flight software patch to be uploaded to the FM next year, investigation of the two not-yet-on-board image-compression algorithms, and the resulting implications for the FM and the science phase (beginning ~April 2018).

References:
MIMOS IIa, a combined Mössbauer and X-ray fluorescence spectrometer for the in situ analysis of the Moon, Mars, and asteroids

Christian Schröder¹, Göstar Klingelhöfer²

¹Biological and Environmental Sciences, University of Stirling, Stirling FK9 4LA
²Institute of Inorganic Chemistry and Analytical Chemistry, Johannes Gutenberg-University, Mainz, Germany

Corresponding author: christian.schroeder@stir.ac.uk

Introduction: MIMOS IIa is a light-weight (<500 g), low-volume (sensorhead 50 × 50 × 90 mm³, electronics board 100 × 160 × 25 mm³), low-power (4 W) combined Mössbauer and X-Ray Fluorescence spectrometer (Fig. 1, Table 1) for the in-situ characterization of iron-bearing mineralogy, iron oxidation states, magnetic properties and chemical composition of planetary surface materials [1,2]. The precursor instruments, the miniaturized Mössbauer spectrometer MIMOS II and the Alpha-Particle X-ray Spectrometer (APXS), have extensive flight heritage, e.g. from NASA’s Mars Exploration Rovers [3-9], Beagle 2 [10], or the ESA Rosetta mission [11]. MIMOS IIa has an ESA-assessed Technology Readiness Level (TRL) 5.8. Here we present applications of a MIMOS IIa prototype or its precursor instruments relevant to Moon, Mars, and asteroid exploration.

Lunar Exploration: MIMOS IIa geochemical and mineralogical data differentiate between maria, highlands or KREEP material, distinguish between volcanic-ash regolith and impact-derived regolith; or determine metallic iron nanoparticle abundance as a measure of exposure time or to constrain the flux of micrometeoroids [12]. The instrument has been used as prospecting tool and process monitor in ISRU oxygen production experiments from lunar regolith [13].

Mars Exploration: The combination of iron mineralogy and geochemical data provided evidence for past aqueous activity and habitable conditions in the forms of the mineral jarosite [4], silica deposits [14], carbonate deposits [6], or gypsum veins [15]. Iron oxidation states have been used to derive the first chemical weathering rate for Mars [16].

Asteroid Exploration: Mineralogical and geochemical data help to establish the link between specific asteroids and meteorite groups. Mössbauer and APXS data allowed to identify and group iron and stony meteorites found on Mars [16].

Automated surface change detection on Mars: a status update from the EU-FP7 iMars project

Panagiotis Sidiropoulos and Jan-Peter Muller

Imaging Group, Mullard Space Science Laboratory, University College London, Holmbury St Mary, RH5 6NT, UK

Corresponding author: p.sidiropoulos@ucl.ac.uk

There has been a revolution in 3D surface imaging of Mars over the last 14 years with systematic stereoscopy from HRSC. Digital Terrain Models (DTMs) and OrthoRectified Images (ORIs) have been produced for almost 50% of the Martian surface. DLR, together with the HRSC science team, produced 3D HRSC mosaic products for large regions comprising around 100 individual strips per region (MC-11E/W half-quadrangles). The iMars project has been exploiting this unique set of 3D products as a basemap to co-register NASA imagery going back to the 1970s. A fully Automated Co-Registration and Orthorectification (ACRO) system was developed at UCL [1] and applied to the production of around 15,000 NASA images. These images are co-registered to a HRSC pixel (typically 12.5m/pixel) and orthorectified to HRSC DTMs of 50m spacing [2] over MC-11E/W half-quadrangles.

All of these new products images are viewable through an OGC-compliant webGIS developed at FUB which is hosted at MSSL (http://www.i_mars.eu/web-gis). This includes tools for viewing temporal sequences of co-registered ORIs over the same area [3]. An automated data mining system has been developed at UCL [4] for change detection to search and classify features in images going back to Viking Orbiter of IFoV ≤100m. In parallel, a citizen science project at Nottingham University [5] has defined training samples for classification of change features and for verification of change. Scientific use cases include new craters & slope streaks.

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End-to-End Simulation of the ExoMars PanCam Wide Angle Cameras

R.B. Stabbins\textsuperscript{1,2}, A.D. Griffiths\textsuperscript{1,2}, A.J. Coates\textsuperscript{1,2}, M. Gunn\textsuperscript{3}, C. Huntly\textsuperscript{3} and the PanCam Science Team

\textsuperscript{1}Mullard Space Science Laboratory, University College London, UK
\textsuperscript{2}Centre for Planetary Sciences at Birkbeck & University College London, UK
\textsuperscript{3}Department of Physics, Aberystwyth University, UK

Corresponding author: roger.stabbins.10@ucl.ac.uk

The context of the ESA ExoMars 2020 rover will be recorded and characterised by a suite of cameras, with PanCam\textsuperscript{1} as the principal scientific camera system, recording visible to near-infrared (VNIR) images across a stereo baseline using a suite of band-pass filters\textsuperscript{2}. Three cameras comprise the PanCam system. A stereo pair of Wide Angle Cameras (WACs) allow for 3D reconstruction, each hosting an 11 position filter wheel for multispectral imaging, and a High-Resolution Camera (HRC) provides close-up images of distant or small objects.

Here we present an end-to-end simulation of the WAC response, from spectral scene radiance to digital image formation. The variance of the fore-optic spectral transmission is modelled for each filter, across the field of view, and the noise sources and nonlinearities of the CMOS APS Star 1000 detector are comprehensively modelled.

The simulation software allows for synthetic scenes to be rendered, under a variety of illuminant spectral distribution functions and for various surface materials, and virtually imaged. Simulation parameters can be adjusted iteratively, such that data processing algorithms can be tuned, and imaging procedures optimised, to the specific case of PanCam on the Martian surface.

References:
Automated dynamic feature tracking of RSLs on the Martian surface from HiRISE using super-resolution restoration and 3D reconstruction

Yu Tao, Jan-Peter Muller

Imaging Group, Mullard Space Science Laboratory, University College London, Holmbury St Mary, RH5 6NT, UK

Corresponding author: yu.tao@ucl.ac.uk

Understanding dynamic processes including whether liquid (saline) water is present on the Martian surface is essential to constrain Mars’ present-day habitability. In this work, we demonstrate using a novel combination of new methods in computer vision including super-resolution restoration (SRR) [1] and 3D modelling [2] how to build statistically robust 3D imaging datasets at high spatial-temporal resolution to better support analysis of dynamic features.

Recent work has focused on one of the previously identified Recurring Slope Lineae (RSL) sites in Palikir Crater where 8 repeat-pass 25cm HiRISE images have been employed to restore a 5cm RSL-free SRR image and a 75cm gridded 3D model. By automatically tracking and classifying any unmatched (dynamic) features in the original HiRISE images, we are able to isolate the RSLs and analyse their statistics including propagation and areal growth rates, details of the surrounding surface texture, and the slope and curvature of the hosting terrain.

In the future, we plan to create a regional map of RSL occurrence for an extensive area using MRO CTX (1-2m from 6m) and ExoMars TGO CaSSIS (≤ 1m from 4m), with associated growth rates, timings (including inter-annual variability) and topographic information (including slopes and orientation), allowing a much greater statistical robustness when testing models of RSL formation.

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References: