
# Program

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# 3rd International Planetary Caves Conference

February 18–21, 2020
Southwest Research Institute, San Antonio, Texas

## Institutional Support

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Abstracts for this conference are available via the conference website at
**https://www.hou.usra.edu/meetings/3rdcaves2020/**
Abstracts can be cited as
Author A. B. and Author C. D. (2020) Title of abstract. In *3rd International Planetary Caves Conference,* Abstract #XXXX. LPI Contribution No. 2197, Lunar and Planetary Institute, Houston.

# Guide to Sessions

**Tuesday, February 18, 2020**

| | | |
|---|---|---|
| 8:30 a.m. | SwRI B263 Lobby | Registration |
| 9:00 a.m. | SwRI B263 Main Presentation Room | Opening Plenary: The State of Extraterrestrial Cave Science and Exploration |
| 10:15 a.m. | SwRI B263 Main Presentation Room | Pit Crater Chains and Lava Tube Formation Mechanisms I |
| 1:30 p.m. | SwRI B263 Main Presentation Room | Habitability and Astrobiological Potential of Caves and Pit Craters I |
| 4:45 p.m. | SwRI B263 Lobby | Poster Session: Cave and Pit Crater Science and Exploration |

**Wednesday, February 19, 2020**

| | | |
|---|---|---|
| 7:45 a.m. | SwRI | Field Trip to Natural Bridge Caverns and Robber Baron Cave |
| 9:00 a.m. | SwRI B263 | SwRI Lab and Archives Tour |

**Thursday, February 20, 2020**

| | | |
|---|---|---|
| 9:00 a.m. | SwRI B263 Main Presentation Room | Lunar Exploration Concepts |
| 1:30 p.m. | SwRI B263 Main Presentation Room | Decadal Whitepaper Workshop: Exploration of the Martian Subsurface through Lava Tubes and Pit Crater Chains |
| 3:15 p.m. | SwRI B263 Main Presentation Room | Mars Mission and Instrument Concepts |
| 5:30 p.m. | SwRI | 5:30 p.m. Transportation to Casa Rio Restaurant<br>6:00 p.m. San Antonio River Cruise<br>7:00 p.m. Casa Rio Dinner |

**Friday, February 21, 2020**

| | | |
|---|---|---|
| 9:00 a.m. | SwRI B263 Main Presentation Room | Habitability and Astrobiological Potential of Caves and Pit Craters II — Biosignatures |
| 12:30 p.m. | SwRI B263 Main Presentation Room | Pit Crater Chain Formation II |

# Program

**Tuesday, February 18, 2020**
**OPENING PLENARY:**
**THE STATE OF EXTRATERRESTRIAL CAVE SCIENCE AND EXPLORATION**
*This session will provide an overview of the state of cave science and cave exploration in planetary contexts.*
**Chairs: Charity Phillips-Lander and Penelope Boston**

| Times | Authors (*Denotes Presenter) | Abstract Title and Summary |
|---|---|---|
| 9:00 a.m. | | *Welcome and Introductions* |
| 9:15 a.m. | Kerber L. * | *The State of Extraterrestrial Cave Science and Exploration* |
| 10:00 a.m. | | *Q&A* |

**Tuesday, February 18, 2020**
**PIT CRATER CHAINS AND LAVA TUBE FORMATION MECHANISMS I**
*Discussion of formation mechanisms for lava tubes and pit craters on rocky and icy planetary bodies.*
**Chairs: Alan Whittington and Debra Buczkowski**

| Times | Authors (*Denotes Presenter) | *Abstract Title and Summary* |
|---|---|---|
| 10:15 a.m. | Whittington A. G. * Sehlke A. Morrison A. A. | *Tubular Hells: New Measurements of Lunar Magma Rheology and Thermal Properties Applied to Thermal Erosion and Lava Tube Formation* **[#1077]**<br>Lava tube formation mechanisms are discussed in the light of new experimental data on lava properties. |
| 10:35 a.m. | Kerber L. * Jozwiak L. M. Whitten J. Wagner R. V. Denevi B. W. | *The Geologic Context of Major Lunar Mare Pits* **[#1048]**<br>Lunar pit caves provide a unique opportunity to observe lunar bedrock layering, allowing us to access a pristine cross-sectional exposure of the geologic history of the Moon. This work discusses what we know from orbit about what each pit exposes. |
| 10:55 a.m. | Sauro F. * Pozzobon R. Massironi M. De Berardinis P. Santagata T. De Waele J. | *Volume and Morphology of Martian and Lunar Lava Tubes Revealed by Comparative Planetology* **[#1050]**<br>A morphometric study was performed on lava tube collapse chains on Earth for a comparison with similar chains on Mars and the Moon. We present a first dataset estimating the potential volumes of intact lava tubes on the three planetary bodies. |
| 11:15 a.m. | Wagner R. V. * Robinson M. S. | *What to Expect in Lunar Pits* **[#1045]**<br>Summary of our recent research on lunar pits, including interior morphology, visible layering, expected radiation levels, and suggested instruments for in-situ measurements. |
| 11:35 a.m. | Prettyman T. H. * Titus T. N. Cushing G. E. Okubo C. H. Sankey J. B. Williams K. E. Caster J. Boston P. J. Schorghofer N. Spilde M. N. | *Muon Overburden Gauge for Planetary Analog Studies of Cave Ice Stability* **[#1044]**<br>In-cave measurements of atmospheric muons constrain the macroporosity and permeability of cave ceilings and enable monitoring of the percolation of meteoric water. The data support analog studies of cave ice stability. |
| 11:55 a.m. | | LUNCH |

**Tuesday, February 18, 2020**

**HABITABILITY AND ASTROBIOLOGICAL POTENTIAL OF CAVES AND PIT CRATERS I**

*We will explore the habitability and astrobiological potential of caves and pit crater chains.*

**Chairs: Penelope Boston and Pascal Lee**

| Times | Authors (*Denotes Presenter) | *Abstract Title and Summary* |
|---|---|---|
| 1:30 p.m. | Boston P. J. * | *Caves and Cavities Throughout the Solar System: Prospects Revisited for Occurrence and Astrobiological Significance* **[#1076]**<br>Based on latest results from planetary and small body studies, I revisit my previously published matrix of known and hypothetical speleogenetic mechanisms classified by physical and chemical processes and reassess them for astrobiological value. |
| 1:50 p.m. | Martin-Torres J. * Zorzano M. P.<br>Bhardwaj A. Sam L. Singh S. | *Martian Caves as Special Region Candidates* **[#1060]**<br>Here we present a study of the environmental conditions in martian subsurface cavities such as caves and how it can be considered as Special Regions. |
| 2:10 p.m. | De Hon R. A. * | *Martian Alcoves as Havens from Harsh Surface Environment* **[#1030]**<br>The variety of surface modifying processes and stratified materials on Mars offers protected habitats other than lava tubes. Alcoves, which form in a wide array of terrains, may provide safe sites for early martian life or future astronauts. |
| 2:30 p.m. | Lee P. * | *Ice-Rich Caves on the Moon and Mars: Prospects and Pragmatic Recommendations for Exploration* **[#1066]**<br>We synthesize lessons learned from our recent studies of lava pits and caves on the Earth, Moon, and Mars, including of promising technologies to investigate these and offer pragmatic recommendations for future efforts. |
| 2:50 p.m. | | BREAK |
| 3:20 p.m. | Smith H. D. * | *An Astrobiology Exploration Strategy for Caves Based on the Tony Grove Karst Region in Northern Utah* **[#1072]**<br>We examine an exploration strategy for life detection and preservation in caves at a semi-arid karst dominated region. |
| 3:40 p.m. | Barry-Sosa A. * Flint M. K.<br>Gulley J. D. Summerall T.<br>Martin J. B. Christner B. C. | *The Upper Floridian Aquifer as an Analog for Extraterrestrial Subsurface Environments* **[#1034]**<br>The UFA is an energetically limited freshwater karstic aquifer that can be useful to evaluate signatures associated with subsurface life and its biogeochemical products including gases like nitrous oxide and methane, and the mineral goethite. |
| 4:00 p.m. | Phillips-Lander C. M. * Jordan B.<br>Stockton A. M. Elwood-Madden M. E. | *The Role of Phosphorous in Microbial Colonization of Lava Tube Caves* **[#1054]**<br>Microbial colonization and growth significantly influenced by P-availability. This provides an initial screening tool to select potentially habitable martian caves. |
| 4:20 p.m. | Miller A. Z. Gonzalez-Pimentel J. L.<br>Maurer M. Stahl S. Castro-Wallace S.<br>Bessone L. Martinez-Frias J. Sauro F. * | *Geomicrobiological Field Research in a Subsurface Analogue Environment for Future Planetary Caves Missions* **[#1052]**<br>During the ESA astronaut training and technology testing campaign PANGAEA, a microbiological experiment was performed in the Corona Lava Tube including in situ third generation sequencing. |

**Tuesday, February 18, 2020**
**POSTER SESSION:**
**CAVE AND PIT CRATER SCIENCE AND EXPLORATION**
**4:45–6:30 p.m. SwRI B263 Lobby**

| Authors | *Abstract Title and Summary* |
| --- | --- |
| Hong I. S. Choi YJ. Moon H. K. Yi Y. | *Detection of Subsurface Void in Pit Cluster Area by Using Gravity Analysis* **[#1036]**<br>We analyze pit cluster area with processed gravity model. We apply a few methods for low gravity in shallow depth. We discover low gravity in pit cluster area. And we are going to apply same method to other target area. |
| Sharma H. Jhalani A. Savla S. S.<br>Sheth H. Jones H. L. Whittaker W. L. | *Robot Autonomy for Acquiring Imagery for Planetary Pit Modelling* **[#1061]**<br>This abstract presents an autonomous robotic system that circumnavigates a lunar pit, acquires imagery of it by navigating up close to the pit edge taking into account the changing illumination within a lunar day. |
| Curtis A. G. | *Comparison of Earth's Fumarolic Ice Caves, with Implications for Icy Voids on Other Worlds* **[#1070]**<br>The author has worked inside fumarolic ice caves near the summits of Mt. Erebus, Mt. Rainier, Mt. St. Helens, and Villarrica. Comparisons will be presented and what might be encountered when caves in ice are visited elsewhere in the solar system, and how they might be studied remotely. |
| Bardabelias N. M. Holt J. W.<br>Christoffersen M. S. | *Potential Detection of Martian Lava Tubes from Mars Global Cave Candidate Catalog Skylight Locations Using SHARAD* **[#1068]**<br>This work aims to determine if lava tubes can be detected with SHARAD and if they exhibit a distinctive power echo. MGC3 skylight locations intersecting SHARAD tracks are examined for non-clutter reflectors, from which tubes depths can be derived. |
| Whizin A. D. Metzger P. Dreyer C.<br>Phillips-Lander C. Asquith C.<br>Focia R. Retherford K. | *Innovating Lunar ISRU Technologies for Long-Term Exploration and Habitation* **[#1078]**<br>We are developing an instrument-level architecture for magnetic induction additive manufacturing, which when applied to off-world applications, is a potentially revolutionary technique for the ISRU of lunar feed-stocks. |
| Kalita H. Thangavelautham J. | *Automated Design of Robotic Platform for Exploration of Planetary Caves, Pits, and Lava Tubes* **[#1065]**<br>Our approach is to find optimal design solutions of a robotic platform (SphereX) capable of exploring planetary caves, pits, and lava tubes. |
| Mitchell K. L. Kerber L. Malaska M. J. | ***JPL R&D for Deep Extraterrestrial Cave Exploration*** **[1079]**<br>JPL pursues approaches to cave missions with many partners. |

**Wednesday, February 19, 2020**
**FIELD TRIPS**

Field trip to Natural Bridge Caverns (a commercial cave) and Robber Baron Cave (a wild cave preserve owned by Texas Cave Management Association). During lunch, there will be a presentation by Geary Schindel, the Chief Technical Officer of the Edward Aquifer Authority on Karst of the Edwards Aquifer.

At Natural Bridge Caverns, there are three tour options:

- Cavern Tour — Geology-focused tour on regular paved tourist trail.
- Discovery Adventure Tour — Off-trail wild cave tour in main cavern with climbing and crawling in mud.
- Hidden Passages Adventure Tour — Off-trail wild cave tour to highly decorated portion of the cave accessed by being lowered down a 160 foot well shaft.

At Robber Baron Cave, there are three options:

- A relatively easy trip with mostly walking over uneven terrain, but some stooping in a couple of low spots.
- A slightly more challenging trip including climbing, crawling, and traversing over crevices.
- If you do not wish to enter the cave, there will be a side trip to San Antonio Springs to see a few other karst features in the area led by Dr. Evelynn Mitchell of St. Mary's University.

An optional tour of SwRI's archives has been arranged for conference attendees who choose not to join the caverns field trip. This SwRI tour will include history of the Institute and some of the cool things they have done (like the pressure capsule for the original Alvin submersible).

**Thursday, February 20, 2020**
**LUNAR EXPLORATION CONCEPTS**
*This session will examine the advancement of lunar exploration concepts.*
**Chairs: Laura Kerber and Andrew Romero-Wolf**

| Times | Authors (*Denotes Presenter) | Abstract Title and Summary |
|---|---|---|
| 9:00 a.m. | | *Welcome and Introductions* |
| 9:15 a.m. | Bessone L. Carnelli I. Fontaine M. Sauro F. * | *ESA SysNova Lunar Caves Challenge* **[#1039]** The European Space Agency opened in August 2019 a campaign through its Open Space Innovation Platform, asking for novel ideas to address detecting, mapping, and exploring caves on the Moon. |
| 9:35 a.m. | Romero-Wolf A. * Devin C. Franklin G. Hawkins D. Haynes M. Lee M. Lazio J. Liu J. Mitchell K. Peters S. Robison D. Schroeder D. | *Passive Sounding of Lunar Lava Tubes* **[#1040]** We present a passive sounding technique that uses radio emissions from the Sun and Jupiter as signals of opportunity to map lunar lava tubes from orbit or from the ground using a lander or a rover. |
| 9:55 a.m. | Kerber L. * Moon Diver Team | *Moon Diver: Journey into the Ancient Lavas of the Moon* **[#1049]** After more than 50 years, Moon Diver aims to return to Mare Tranquillitatis, building on the legacy of Apollo by exploring a >50 m exposure of the Moon's secondary crust and descending into an extraterrestrial cave for the first time. |
| 10:15 a.m. | Whittaker W. L. * Jones H. L. Wong U. Y. Ford J. S. Whittaker W. C. Khera N. Horchler A. | *Micro-Rover Exploration of Lunar Pits Deployable by Commercial Lander* **[#1074]** This paper conceives high-return pit explorations achievable by the technologies of our time that can be delivered by commercial landers and economical missions. |
| 10:35 a.m. | | BREAK |
| 11:05 a.m. | Sauro F. * Massironi M. Santagata T. Pozzobon R. Rossi A. P. Torrese P. Cockell C. Bessone L. | *The ESA PANGAEA-X Testing Campaign in the Corona Lava Tube (Lanzarote, Spain) as an Analogue for Lunar Caves Exploration* **[#1055]** ESA PANGAEA-X campaign in 2017 has been focused on instruments and tools for lava tube exploration, mapping, and navigation, with several experiments as analogues for planetary caves study. |
| 11:25 a.m. | Bessone L. De Waele J. Sauro F. * | *The ESA CAVES Astronaut Training Program: Speleological Exploration as an Analogue for Space* **[#1056]** The ESA CAVES training program for astronauts has the specific goal to prepare astronauts for long duration space missions using caves environments and expeditions as a space analogue, also in preparation of planetary caves exploration. |
| 11:45 a.m. | Ximenes S. W. * Hooper D. M. Palat A. Cantwell L. Appleford M. Webb J. Wells R. Patrick E. L. Necsoiu M. | *Lunar Caves Analog Test Sites for Space-STEM Engagement* **[#1035]** A Lunar Caves Analog Test Sites (LCATS) program for Space-STEM education incorporates investigations of ISRU technologies, e.g., regolith simulant research and 3D printed manufacturing for habitat design and planetary construction. |
| 12:05 p.m. | Chandrachud R. A. * | *Development of ISRU Units on Moon with Lunar Caves as Source for ISRU Processing Materials* **[#1057]** This paper describes caves within area Oceanus Procellarum on the Earth's Moon enriched with materials for ISRU processing, availability of water, and future test on the Titan. Also, this paper propounds use of robotics for development of ISRU units. |
| 12:25 p.m. | | LUNCH |

**Thursday, February 20, 2020**
**DECADAL WHITEPAPER WORKSHOP:**
**EXPLORATION OF THE MARTIAN SUBSURFACE THROUGH LAVA TUBES AND PIT CRATER CHAINS**
**1:30 p.m. SwRI B263 Main Presentation Room**
**Moderator: Charity Phillips-Lander**
**Panel Members: Jut Wynne, Kyle Uckert, David Anthony, Tim Titus**

Decadal Whitepaper Submission: Examining the habitability and astrobiological potential of the martian subsurface through lava tube caves and atypical pit crater chains.

1. Why we're ready for a martian subsurface mission
2. Types of science that can be achieved
3. Robotic architectures to consider

## MARS MISSION AND INSTRUMENT CONCEPTS

*This session focuses on recent advances in instrumentation and mission concepts for exploration of lava tube caves and atypical pit crater chains on other worlds, with an emphasis on Mars.*

**Chairs: Jenifer Blank and Kyle Uckert**

| Times | Authors (*Denotes Presenter) | *Abstract Title and Summary* |
|---|---|---|
| 3:15 p.m. | Kalita H. * Thangavelautham J. | *Robotic Exploration of Planetary Caves, Pits, and Lava Tubes* **[#1064]**<br>We present an architecture of small, low-cost, modular spherical robot called SphereX that is designed for exploring planetary caves, pits, and lava tubes. |
| 3:35 p.m. | Blank J. G. * | *Robotic Mapping and Exploration of a Terrestrial Lava Tube: A Structured Planetary Cave Mission Simulation with a Remote Astrobiology Science Team* **[#1047]**<br>This presentation will discuss a planetary cave mission simulation conducted by the NASA BRAILLE Team. We used the NASA Ames testing rover, CaveR, at Lava Beds National Monument in Northern California, USA. |
| 3:55 p.m. | Uckert K. * Parness A. Chanover N. | *Deployment of an Instrument Payload on a Rock-Climbing Robot for Subsurface Life Detection Investigations* **[#1031]**<br>LEMUR, a four-legged climbing robot, was integrated with a representative astrobiology payload and deployed in a lava tube cave to mature a system architecture capable of identifying biosignatures in extreme terrain. |
| 4:15 p.m. | Wynne J. J. * Phillips-Lander C. M. Titus T. N. | *Proposed Mission Architecture and Technology Requirements for Robotic and Human Exploration of Martian Caves* **[#1043]**<br>We propose a simplified process to advance martian speleology from a rudimentary understanding to acquiring the data required to evaluate and select the best candidates for astrobiological investigations and human outposts. |
| 4:35 p.m. | Phillips-Lander C. M. * Wynne J. J. Parness A. Uckert K. Chanover N. Titus T. N. Williams K. Demirel-Floyd C. Eshelman E. Stockton A. Johnson S. Wyrick D. | *Science Returns Expected from MACIE: Mars Astrobiological Caves and Internal Habitability Explorer (A New Frontiers Mission Concept)* **[#1042]**<br>We detail the potential science returns expected from a New Frontiers Mission to explore a martian lava tube cave. |
| 4:55 p.m. | Sam L. * Bhardwaj A. Singh S. Martin-Torres F. J. | *UAV Imaging of Small Caves in Icelandic Lava Field as Possible Mars Analogues* **[#1053]**<br>UAVs can be extremely helpful in Mars analogue research and here we explore their application in studying small lava caves in Iceland. The high-resolution imaging provides interesting results on these volcanic features. |
| 5:15 p.m. | | *Adjourn* |

**Friday, February 21, 2020**

**HABITABILITY AND ASTROBIOLOGICAL POTENTIAL OF CAVES AND PIT CRATERS II — BIOSIGNATURES**

*This session will focus on how we detect and differentiate biosignatures of life on other worlds.*

**Chairs: Carole Lakrout and Michael Spilde**

| Times | Authors (*Denotes Presenter) | Abstract Title and Summary |
|---|---|---|
| 9:00 a.m. | | *Welcome and Introductions* |
| 9:15 a.m. | Sarbu S. M. * Fleming E. J. Nealson K. H. Barr C. Aerts J. Flot J.-F. Onac B. P. Tighe S. Vellone D. L. Popa R. | *Life in Subsurface Voids with Gas Chemoclines — An Earthly Proxy for Extraterrestrial Life* **[#1069]** We present a subsurface environment containing a gas chemocline that could be used as a proxy for the study of extraterrestrial life. Chemoautotrophic microbial biofilms are found in a cave containing a gas chemocline ($CH_4$ and $H_2S/O_2$). |
| 9:35 a.m. | Csuka J. M. * Adeli S. Baqué M. Iakubivskyi I. Kopacz N. Neubeck A. Schnürer A. Singh A. Stockwell B. R. Vilhelmsson O. Geppert W. D. | *Linking Biological and Geochemical Data from Icelandic Lava Tubes: Insights for Upcoming Missions in the Search for Extant or Extinct Life on Mars* **[#1051]** The Planetary Analogues and Exobiology Lava Tube Expedition (PELE) team investigates volcanic caves as Martian analogue sites. Here we present data from Icelandic lava tubes, with the aim of identifying biotically-formed speleothems as biosignatures. |
| 9:55 a.m. | Ford J. A. * Kulkarni H. V. Godet A. Blank J. Datta S. | *Mineralogical, Chemical, and Morphological Variations Among Analog Basaltic Lava Cave Speleothems* **[#1046]** Basaltic caves at terrestrial analog site Lava Beds National Monument contain microbial communities in contact with speleothems and liquid water. These speleothems exhibit unique geochemical signatures that may suggest biotic pathways of formation. |
| 10:15 a.m. | Spilde M. N. * Medley J. J. Northup D. E. Boston P. J. | *Mineral Biomarkers for Extraterrestrial Caves* **[#1071]** Unusual minerals found in terrestrial lava caves may provide biomarkers for Mars life. |
| 10:35 a.m. | Lakrout C. A. * Goldfarb E. J. Bontognali T. R. R. Tisato N. | *Biotic Influence on Speleothem Morphology* **[#1075]** We analyzed speleothems from a cave. Although the cave is an extreme environment, microbes control the formation and morphology of such speleothems. Such speleothems represent a potential starting point for the seeking of life on other planets. |
| 10:55 a.m. | Sandjaja I. Schubert K. E. * Gomez E. Boston P. J. | *Pattern Extraction from Cave Images* **[#1067]** Glare is a larger problem in caves due to the limited lighting, and thus multiple images and advanced speckle removal algorithms are needed. With glare removed, image regions with patterns and those that don't are separated and the patterns marked. |
| 11:15 a.m. | | LUNCH |

**Friday, February 21, 2020**
**PIT CRATER CHAIN FORMATION II**
*Discussion of formation mechanisms for lava tubes and pit craters on rocky and icy planetary bodies.*
**Chairs: Timothy Titus and Danielle Wyrick**

| Times | Authors (*Denotes Presenter) | *Abstract Title and Summary* |
|---|---|---|
| 12:30 p.m. | Morrison A. A. * Whittington A. G. | *Cryolava Tubes: A Feasibility Study* **[#1073]**<br>Lava tubes insulate lava allowing transport over large distances. Some of the largest lava flows on the terrestrial bodies are tube-fed flows. Lava tubes may also exist on icy bodies producing cave networks within the subsurface. |
| 12:50 p.m. | Wyrick D. Y. * Buczkowski D. L. | *Pit Crater Chains: Evidence for Subterranean Tectonic Caves* **[#1058]**<br>Pit crater chains have direct implications for fluid and volatile storage in the lithospheres of planetary bodies. These easily identifiable features are a target for future in situ resources and astrobiology exploration. |
| 1:10 p.m. | Buczkowski D. L. * Wyrick D. Y. | *Tectonic Caves on Small Bodies: Potential In Situ Resource Reservoirs* **[#1059]**<br>Asteroids are extremely common and yet their potential for in situ resource exploration remains poorly understood. Near-ubiquitous pit crater chains represent evidence of subsurface void space which may house stores of volatile and mineral resources. |
| 1:30 p.m. | Ford J. S. * Callaghan P. J.<br>Wong U. Y. Jones H. L.<br>Whittaker W. C. Whittaker W. L. | *Image and Lidar Dataset of the West Desert Sinkhole: An Analog for Steep-Walled Planetary Pits* **[#1062]**<br>This work presents a LIDAR and image dataset for studying steep-walled planetary pits. This paper describes the apparatus and procedures used to create the dataset, the organization of the dataset, and anticipated applications for the dataset. |
| 1:50 p.m. | Titus T. N. * Williams K. E.<br>Cushing G. E. Okubo C. H. | *Cave Breathing in a Terrestrial Analog Atypical Pit Crater — Insolation Induced Convective Cooling* **[#1041]**<br>Many factors can influence cave micro-climates. This abstract focuses on one component that may contribute to cave breathing when the cave entrance is located near the floor of an Atypical Pit Crater (APC). We use data collected from a Hawaii APC. |
| 2:10 p.m. | | *Wrap-Up* |
| 2:25 p.m. | | *Adjourn* |

## CONTENTS

**POTENTIAL DETECTION OF MARTIAN LAVA TUBES FROM MARS GLOBAL CAVE CANDIDATE CATALOG SKYLIGHT LOCATIONS USING SHARAD.** N. M. Bardabelias[1], J. W. Holt[2], and M.S. Christoffersen[3], [1]University of Arizona Department of Geosciences (nmb23@email.arizona.edu), [2]University of Arizona Lunar and Planetary Laboratory (jwholt@email.arizona.edu), [3]University of Arizona Lunar and Planetary Laboratory (mchristo@email.arizona.edu).

**Introduction:** Lava tubes are tunnel-like structures formed when exposed sections of effusive flows cool while material continues moving internally [1, 2]. These tubes thermally insulate the material flowing through it, allowing subsequent flows to travel long distances before beginning to crystallize [3]. As eruption rate slows, the lava level within the tube decreases, eventually creating a partially or fully hollow tunnel.

*Motivation.* For bodies with thin or no atmospheres, lava tubes provide shelter from harsh surface radiation environments, diurnal temperature swings, and micrometeorite bombardment [6]. This is of geologic and astrobiological significance for studies of past habitability or future human exploration: subsurface caverns may preserve biosignatures and/or volatiles which would make lava tubes an ideal exploration candidate for terrestrial bodies.

Lava tubes are difficult to identify in visual remote sensing data as their surface expressions are often the result of collapse - without this collapse, lava tubes are generally indistinct at the surface [1]. Skylights, large pits, and pit chains identified on Mars can indicate varying levels of possible lava tube collapse breaching the surface, while sinuous rilles observed on the Moon have also been suggested as an expression of tube collapse [4]. For terrestrial lava tubes, additional methods of detection include thermal infrared remote sensing, seismicity, magnetic field perturbations, and measuring low-frequency sounds; however, these methods only apply to active lava tubes and can yield ambiguous results [1, 2]. Ground penetrating radar (GPR) presents a unique solution to this problem, as it detects subsurface reflectors through differences in material permittivity and is thus capable of detecting inactive lava tubes [5]. This work hypothesizes that the difference in permittivity between a sufficiently large, evacuated lava tube and its surroundings could lead to a characteristic power echo in radar data. If so, analysis of radargrams can reveal the shape and extent of a single tube or tube network.

*SHARAD radar system.* The Mars Reconnaissance Orbiter (MRO) Shallow Radar (SHARAD) probes the subsurface using a frequency-modulated ('chirped') signal downswept from 25 MHz to 15 MHz. This 10 MHz bandwidth yields a 15-m resolution in free-space, reduced to 5 m in basaltic terrains [7]. Prior work from the SHARAD science team suggests that, for models of lava tubes under Martian conditions, their instrument may be able to detect these features in the shallow subsurface [7].

**Methods:** This work uses skylights, a known indicator of lava tube collapse on terrestrial bodies, to identify potential Martian lava tubes in SHARAD data. By correlating these skylight locations with radar ground tracks from SHARAD, this work aims to characterize radargrams in these areas and determine if Martian lava tubes exhibit a distinctive radar signal.

Martian skylights observed in both the Mars Odyssey Thermal Emission Imaging System (THEMIS) [8] Visual Imaging System (VIS) and the Mars Reconnaissance Orbiter (MRO) HiRISE and CTX data [9, 10] are mapped to the USGS Mars Global Cave Candidate Catalog (MGC[3]). Of the 1062 candidate cave targets, this work examines only the 354 targets identified in the MGC[3] as potential skylight entrances into lava tubes. Using the Java Mission-Planning and Analysis for Remote Sensing program (JMARS) [11], this work identifies SHARAD ground tracks that cross over or within 5 km adjacent to skylight locations. All but three of these skylights are within the Tharsis region, with one each in Acidalia Planitia, Elysium Planitia, and Margaritifer Terra.

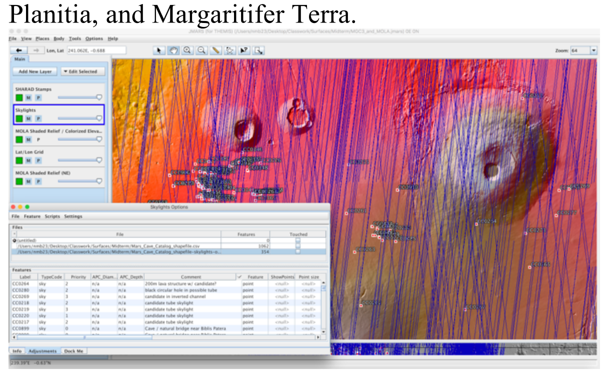

Figure 1: JMARS software showing a Mars Orbital Laser Altimeter (MOLA) elevation basemap for the Tharsis region, points and labels representing skylight candidates from MGC[3] (red), and SHARAD ground tracks (dark blue). The bottom left table displays additional MGC[3] data for candidate skylight locations.

SHARAD radargrams are then compared to MOLA-derived clutter simulations for identification of unique subsurface reflectors using the Geology by Seisware visualization software.

**Discussion:** Expected results from this work include the shape and depth of subsurface reflectors coinciding with $MGC^3$ skylight locations. Through further analysis of the geologic context around reflector locations and comparison of observed lava tube depths with available digital terrain models of collapse features, this work aims to ultimately determine whether lava tube detection is plausible with current orbital radar systems at Mars. These results may have implications for RIMFAX operations on the Mars 2020 rover [12], as well as for future orbital GPR at Mars and other terrestrial bodies.

**Acknowledgments:** The USGS Mars Global Cave Candidate Catalog was obtained from the Planetary Data System (PDS).

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**THE UPPER FLORIDIAN AQUIFER AS AN ANALOG FOR EXTRATERRESTRIAL SUBSURFACE ENVIRONMENTS** A. Barry-Sosa[1], M. K. Flint[2], J. D. Gulley[3], T. Sumerall[2], J. B. Martin[2] and B. C. Christner[1], [1]University of Florida, Department of Microbiology and Cell Sciences, 1355 Museum Dr., 32611, Gainesville, FL, [2] University of Florida, Department of Geological Sciences, 241 Williamston Hall, 32611, Gainesville, FL, [3]School of Geosciences, University of South Florida, 4202 E. Fowler Avenue, NES 107, Tampa, FL.

**Introduction:** The Upper Floridian Aquifer (UFA) is a karstic aquifer contained in Oligocene and Miocene limestone formations with thicknesses that range from 60 to 1000 m. It underlies most of the Floridian peninsula as well as parts of southern Alabama and Georgia, representing the largest natural freshwater source in the southeast US [1]. In regions where the confining unit has been removed by erosion, the aquifer becomes unconfined and water is discharged to the surface at numerous springs that serve as windows to understand the biogeochemical processes that occur in the UFA. Flooded cave systems that characterize carbonate karst aquifers could provide a useful analogue for low energy environments that may occur on Mars and potentially harbor life.

**Relevance:** The UFA has multiple features that make it ideal as an astrobiological analog and target for developing and testing life detection strategies. Regions that are relatively isolated from surface nutrient inputs and sunlight have low energy fluxes and the microbial communities must cycle organic matter or rely on chemosynthesis. Further, the UFA provides a testbed for establishing effective strategies for tracing and tracking biosignatures that indicate life and life-related chemistries. For example, supersaturated concentrations of $N_2O$ and $CH_4$ in UFA springs implies biogenic production in the subsurface hydrological system. Metabolic activities of microorganisms and resulting variations in redox stage form goethite deposits [2] on cave walls that provide opportunities to evaluate their biogenicity and potential as biosignatures.

**Methods:** Six spring systems (Fig. 1) were sampled to conduct geochemical and biological measurements. Of these, three experience periodic river water intrusions or reversals (PKS, LRS, MBH), and one is a river sink-rise system with ~7 km of subterranean flow (OLE). These systems periodically or continually receive direct surface inputs of organic matter and nutrients. In contrast, two of the springs can be considered low energy flux systems (GBS, ITS group) with longer residency times, estimated to be around 40 years [3], and stable geochemical compositions.

$N_2O$ samples were collected in He flushed vials and measured by gas chromatography. Physical and chemical properties of the water (pH, ORP, Conductivity, etc.) was measured in situ using a YSI ProDSS probe that was calibrated daily. Methane was measured using a Picarro G2201-i spectrometer, and for longer term monitoring in OLE, with a Pro-Oceanus mini$CH_4$ sonde.

Triplicate water samples (50 ml) were collected and fixed at a final concentration of 4% (v/v) formalin and stained for enumeration with SYBR gold. For nucleic acid extraction, 4 L of water was sequentially filtered through 1.2, 0.2 and 0.1 µm pore size filters. The DNA was extracted from the filters using the Qiagen PowerWater kit, a portion of the 16S rRNA gene was amplified with primers targeting the V4 region, and the product were sequenced with the Illumina MiSeq platform. The sequencing data were quality checked, parsed, and analyzed using QIIME2.

**Results:** Oxygen percent saturation ranged from a minimum of 1% (ITS group) to 55% (GBS). The dissolved concentration of $N_2O$ in all samples (range of 580 to 1900 ppb) were above that for equilibration with the atmosphere (~328 ppb). Correlation of N2O with $O_2$ across all springs implied that nitrification or denitrification as possible mechanisms of $N_2O$ production mediated by microorganisms. In OLE, the $N_2O$-$O_2$ correlation is negative, consistent with denitrification being a likely pathway for $N_2O$ production. In OLE, methane concentration in some samples were 100-fold higher than atmospheric, and the presence of methanogenic and methanotrophic taxa implies microbial methane cycling. Methane levels in OLE varied between 8.4 and 217 ppm and were dependent on the hydrological regime (i.e., high methane during matrix flow).

Cell counts in low energy springs (GBS, ITS group) were $7.3 \pm 0.5 \times 10^3$ cells/mL, which is similar to observations in other low energy karstic aquifers [4]. Springs with reversed flow had ~10 fold higher cell concentrations, with the with highest observed in the river rise system (OLE; $4 \pm 0.3 \times 10^5$ cells/ml). In general, the low energy springs (ITS group and GBS) that possessed the lowest dissolved organic carbon (DOC) concentrations (average 0.33 ± 0. 03 mgC/L) also had lowest cell densities. Negative correlation between DOC and Shannon diversity index ($r^2 = -0.69$) suggests efficient nutrient cycling, as observed in similar low energy subsurface environments [4,7].

Poorly characterized archaeal and bacterial taxa in the DPANN superphylum and Parcubacteria were identified, and their abundances were generally detected in samples that had passed through a filter with a 0.2 µm pore size. In one of ITS vents, these groups represented three quarters of the taxa identified. Although the ecological role of these small microorganisms is unknown, it has been speculated that they are symbionts of other archaea or bacteria [5,6].

**Conclusions:** Limited DOC input to some regions of the UFA creates a low energy flux environment for microbial ecosystems. Despite low cell densities their communities are nonetheless diverse and are a habitat for poorly described taxa whose ecological roles remain unknown.

The gases $CH_4$ and $N_2O$ are highly relevant biosignatures for detection of life in extraterrestrial atmospheres and hydrospheres. Detection of atmospheric $CH_4$ on Mars has raised the question of whether its source is biological or geological. Although underground environments on Mars will be limited in their energy sources, they would be advantageous as potential habitats since they offer protection from surface radiation, low temperature, and desiccation. Thus, methane is a good candidate biosignature for tracking and identifying life and life-related chemistries on Mars. In preparation for missions that search for life on alien worlds, the UFA provides an ideal system for evaluating signatures associated with subsurface life and its biogeochemical products.

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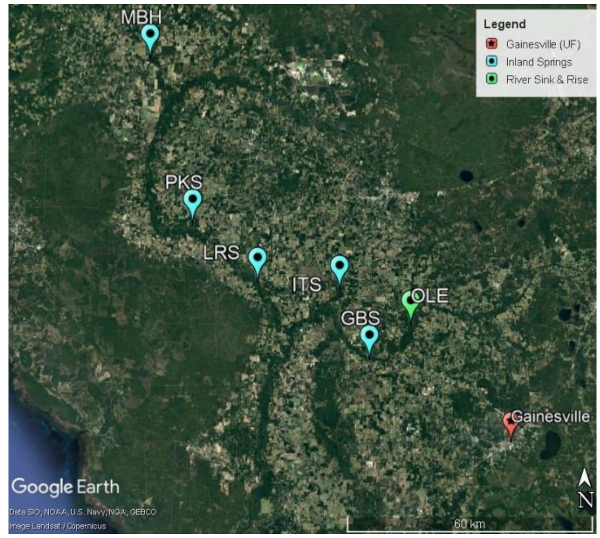


Fig. 1 Map of the sampled vents in the UFA. Madison Blue Hole (MBH), Peacock Springs (PKS) and Little River (LRS) suffer frequent reversals, whereas Ichetucknee Spring Group (ITS) and Gilchrist Spring (GBS) geochemistry remain constant throughout the year. The O'Leno River Sink and Rise (OLE) is a particular system where the Santa Fe river disappears underground, mixes with UFA water and comes back to the surface again.

**ESA SYSNOVA LUNAR CAVES CHALLENGE.** L. Bessone[1], I. Carnelli[1], M. Fontaine[1], F. Sauro[2]. [1]European Space Agency (loredana.bessone@esa.int), [2]University of Bologna (francesco.sauro2@unibo.it)

## Introduction

Recent years have seen a rapid expansion of international participation in lunar exploration. The Moon has become a focal point for many governmental and private organisations in the areas of technology development, scientific research, human exploration and public engagement. While the surface of the Moon has been documented with high resolution cameras by several satellite missions, very little is known about the presence and nature of subsurface cavities.

In several volcanic areas of the lunar Maria, planetary geologists have identified peculiar pits that could be related to the collapse of cavities. In Marius Hills, a pit on the bottom of a shallow rille has been interpreted as the partial collapse of a lava cave (scientifically termed pyroducts; colloquially termed lava tube) roof with a visible cavern below the overhanging ceiling [1, 2] . Gravity measurements by the mission GRAIL have revealed the probable presence of linear subsurface voids along sinuous rilles [3], while the Lunar Radar Sounder on board of the satellite Kaguya [4] has detected the presence of potential voids between 70 to 140 meters of depth in the Marius Hill region. Studies on the structural stability of lunar lava tubes in 1/6 g considering the strength characters of Maria basalts have showed that this type of cavities could theoretically reach dimensions of more than 2 km of width, 600 m of height below a roof of less than 20 meters of thickness [5].

The exploration and mapping of lava caves could provide new data on the formation of plateau basalts on the Moon, providing access to vertical sections of lava flows. Caves formed by lava flow conduits could possibly provide long-term shelter for human habitats shielded by cosmic radiation and micrometeorite impacts on the Moon. Intact, open cave segments could be suitable for housing a permanent lunar base providing potential access to several resources, including volatiles and possibly water ice trapped in cave regolith.

Space agencies have started to discuss possible mission scenario and to evaluate the necessary technology. In the view of the Artemis mission and the renovated interest on the return to the Moon, also with the Gateway as support platforms for robotic exploration, the European Space Agency has also started to develop the topic of lunar caves mission scenarios.

In order to start a European discussion on the topic involving academia and industrial partners, the European Space Agency in August 2019 opened a Campaign through its Open Space Innovation Platform, asking for novel ideas to address detecting, mapping and exploring caves on the Moon. The implementation path foreseen for this campaign are small system studies, addressing overall mission architecture design. These have maximum budget from ESA of €100 000 per activity and a maximum duration of six months. New system studies are used by ESA either as a precursor for technology developments or to assess the feasibility of systems for space. Following ESA's SysNova technology assessment scheme, these studies serve to competitively determine the most interesting concepts among a typically relatively large number of alternative solutions, recognising the beneficial role of parallel and joint studies by both academic and industrial institutions during this exploratory phase.

For the Lunar Caves Challenge ESA plans to select about five system studies on the basis of the evaluation criteria.

## Campaign Goals

In order to shape future missions to the subsurface of the Moon and to evaluate the accessibility and morphology of these cavities it is necessary to develop robotic platforms and scientific instruments that will address a number of key areas, like:

- Lunar caves detection from surface instrumentation
- Lunar caves access and exploration through robotic systems
- Lunar cave navigation and mapping
- Communication/power network from surface/orbit toward the lunar caves interior

For the ideas campaign ESA has provided a detailed description of these themes as below. Ideas submissions were required to address at least one of these themes. However, concepts that address more than one challenge theme have been highly encouraged.

*Theme#1 Robotic concepts for cave access along vertical wall;* in order to access volcanic cavities it is necessary to develop robotic technologies that could overcome vertical obstacles like the pit walls. Pits observed on the Moon have depth ranging from 30 to more than 100 meters, often with over hanging walls. To access the bottom of these pits and explore the void that generated the entrance collapse, it is necessary to develop safe systems through methods like: rappelling, tethering, anchoring, soft high-precision landing, free-falling and others.

*Theme#2 Navigation and progression inside the cave on horizontal segments;* once the bottom of the pit is accessed, it is necessary to develop robotic systems able to progress inside the cave. Lava conduits analogues on Earth show that this progression and exploration could face several natural obstacles like rock piles, loose fine sediments, crevices, giant boulders, low ceiling passages, vertical steps, etc.

These obstacles could be overcome with new robotic concepts and solutions.

*Theme#3 Cave mapping and navigation;* While exploring the cavity it is necessary, both for navigation and scientific purposes, to keep track of the surrounding environment through high-precision mapping. The lack of georeferencing systems represent a high challenge that can be overcome only with real time mapping through technologies like laser scanners, photogrammetry, inertial systems and others. Innovative solutions are necessary, including multi-robot systems or integration between surface and subsurface instruments.

*Theme#4 Communication/power network cave interior/lunar surface;* once inside the lunar cave it is necessary to keep the communication with the surface and finally with Earth. This theme focuses on how to bring the data to the lunar surface (Moon-Earth segment excluded) from a subsurface environment, including scientific and mapping data. Another problem to be addressed is the power network, since in the cave there is no possibility to directly access solar energy for battery recharge. Any innovative proposal addressing these issues will be welcome.

*Theme#4 Science payload;* the robotic system should carry any instrument that could provide scientific data regarding the environmental conditions of the lava tube, including the presence of volatiles, water ice or others. The science payload should provide to the mission the possibility to fulfil a meaningful scientific objective in the context of the overall exploration concept and the general future exploration strategy for lunar exploration"

**System Constraints for the ideas**

The campaign is looking to mission concepts based on single rover/robot or on a distributed system of robotic/rover systems operating together to meet mission objectives.

In both system architectures, the following assumptions and constraints were required to apply to the challenge:

- A robotic/rover system shall be landed on the Lunar surface in the proximity of the Marius Hill skylight, which is situated at coordinates 14.091 1N, 303.223 1E
- Each robotic/rover system landed on the surface needs to meet the physical constraints implied by existing launch and transportation systems.
- The cave detection system from the surface must be able to identify a void at a depth between 30 to 150 meters, and dimensions between 100 to 1000 m, in basaltic material.
- The robotic/rover system, or part of it, must be able to access pits to a depth of at least 50m, vertical or overhanging walls, instable pit rims (can be approached safely only up to few meters from the edge).
- The robotic/rover system accessing the cave at the bottom of the pit must be able to penetrate for at least 200 meters inside.
- The communication of data must happen from a depth of minimum 50 meters to the surface.

**Preliminary results of Sysnova Lunar Cave challenge**

A total of 34 ideas have been submitted to the call, of which 22 have been found eligible for evaluation. An Evaluation Board composed of planetary geologists, volcanologists, robotic and system engineers and mission planners have thoroughly evaluated the submissions. Eight submissions were evaluated promising and a full proposal has been requested. In the early months of 2020 the up to five selected proposals will be funded in order to develop the proposed concepts within a 6 months period. The resulting concept analyses will support ESA's strategy for future exploration of lunar caves and promising concepts may be further developed within ESA's Concurrent Design Facility (CDF).

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**THE ESA CAVES ASTRONAUT TRAINING PROGRAM: SPELEOLOGICAL EXPLORATION AS AN ANALOGUE FOR SPACE** L. Bessone[1], J. De Waele[2] , F. Sauro[2], [1]Directorate of Human and Robotics Exploration, European Space Agency, loredana.bessone@esa.int, [2]Department of Biological, Geological and Environmental Sciences, Italian Institute of Speleology, Bologna University, Italy, cescosauro@gmail.com, jo.dewaele@unibo.it

**Introduction:** Space agencies are concerned with training of their astronauts for long duration missions, not only for current and future orbital missions but also for future human and robotic planetary surface exploration. Preparing for expeditions to other planets requires a realistic replication of environmental and situational characteristics of the extreme conditions of space in earth analogue platforms, where stressors similar to those encountered in long duration spaceflight are provided (Morphew, 2011). The environments in which such training events are carried out must have realistic perceived risk and must enable the execution of complex technical tasks, as well as requiring group living in isolated and/or confined settings. This requires the identification of suitable terrestrial analogue environments and the design of high-fidelity training courses / mission scenarios with representative operational set-up.

Since 2008 the European Space Agency has started investigating the use of scientific expeditions into caves as a novel platform for astronaut training, taking advantage of the natural analogies of the cave environment and associated technical operations with space missions. In 2011 a new ESA training programme named CAVES (Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills) was launched, with the specific goal to prepare astronauts for long duration space missions.

**Environmental and expeditionary analogies:** The cave environment naturally shares several of the stressors that are usually found in human spaceflights [1]. From a physiological point of view the absence of natural zeitgebers can cause alteration of the circadian rhythms [2] and the related physiological stress can be avoided only through earth-like work/rest schedules, similar to those developed for the ISS. In the dark environment of a cave there is a decrease in sunlight exposure requiring consequent adaptation to artificial light, similar to conditions on the ISS, due to confinement and the sixteen day/night cycle/day, and for future interplanetary travel, due to external lighting conditions, as well as the need to live in artificial habitats. The three-dimensionality of cave progression, the lack of common references, the use of headlights and the associated presence of shadows and badly illuminated/visible or inaccessible/keep-out zones increase the hostilility of the environment, similarly to what is experienced during Extravehicular Activities (EVA).

Behavioural issues for isolated, confined teams in future planetary missions are one of the least known factors with a very high potential impact on the mission success. From a psychological and psychosocial point of view, much of the spaceflight stressors are present in cave exploration. When inside a cave, days of progression far from the entrance, the isolation is complete. Cave environments are obviously confined, but mainly mobility is constrained, for safety reasons, to specific paths along walls, like in EVA. Communication with the surface is extremely limited and relies only on technologies that are not trustworthy. This sense of isolation is directly correlated with the distance (in time) from the entrance, given the awareness that every hour of progression would most probably require one full day for a rescue team to get back to the surface an injured or incapacitated person. Some stress elements are directly related to the rough nature of the cave environment and to the difficulty of creating comfortable habitability settings at the base camp. That is translated in lack of privacy, uncomfortable sleeping, limited hygiene, exposure to cold and humidity, dust and mud, etc. All these stressors, if not managed, in the long term induce irritation, social conflicts within the team, altered decision-making or even physiological discomfort and health issues. Different cultural approaches to leadership, information sharing, decision making and teamwork are employed during current ISS missions, all while respecting established hierarchies, rules and procedures. Whilst not all cave expeditions have a structured approach to team processes, the CAVES programme builds upon the situational analogies, while imposing a structured approach to the development of the team, while maintaining flexibility, strongly emphasising team growth via thorough analysis of its own activities and decisions.

**CAVES concept and training structure**: Caves are hostile and dangerous environments that shall be dealt with clear operational safety rules, requiring the mastering of technical progression skills. The environment is however just a “container”: analogies should be based on similarities in experiences, not just in environment [3]. During CAVES astronauts are trained in the use of single rope ascension tools and techniques, to negotiate obstacles and long traverses rigged with iron cables. This technical training resembles skills and safety protocols required to move and operate in extravehicular activity, with reduced field of view, shadows, tri-dimensional progression through viable paths, confused perception of obstacles and distances, keep-out and no-touch zones.

This preparatory training is propedeutical to an extended caves exploration phase, where the astronauts autonomously perform a scientific expedition as a multicultural and multidisciplinary team. Astronauts are trained to use a buddy system and to maintain team situational awareness through briefings and debriefings in order to maintain control on the safety of the whole group, to allow informed decision making for each member of the team, and to enable team learning through analysis of failures and successes. Analogue team training needs to be based on the concept of operations [4], and provide real challenges, stressors and a credible programme. During the CAVES mission, astronauts will explore new branches of the cave, and are required to survey all newly explored areas, as well as provide photographic documentation of all activities performed.

**Scientific and technological program**: As for space missions, in CAVES astronauts carry out a comprehensive scientific program, according to a flexible operational timeline and space-like procedures. The scientific tasks the astronauts are asked to carry out are numerous: microbiological sampling of air, water, and solid material, monitoring of cave air temperature, relative humidity, $CO_2$ concentration, and wind speed and direction, sampling of waters and minerals for follow-up laboratory analyses, and monitoring (and, in some cases, sampling) of cave dwelling fauna (mainly troglobites). During the pre-expedition training, crewmembers test the different experiment procedures and methodologies assisted by scientists, in order also to achieve a good understanding of the relevance of observation and sample collection or data analysis acquisition methodology to the achievement of good scientific objectives.

The scientific programme not only offers a set of realistic tasks and objectives, but it also provides really interesting scientific results. Multidisciplinary researches allow a continuative and detailed study on the caves visited during the course. The environmental monitoring and the geological and geochemical studies are giving important information about the cave environment in this karst area of Sardinia. Moreover systematic microbiological and biological researches provide new information on these peculiar ecosystems, even discovering previously unknown species. All these important scientific goals were achieved thanks to the careful astronauts' performance of strict scientific protocols and procedures.

Aside of scientific experiments and research the mission is also the ground for technological testing of new innovative equipment that has the overall goal to improve operations in the cave environment, but also with potential applications in space. In the last three editions much of the efforts have been dedicated to the evaluation of two wireless cave radio systems, called TEDRA and XFERRA. Both of them have provided interesting results, allowing to the crew the set up of an advanced camp, ensuring the communication with the ground team, required for safety reasons. Also, collision resistant drones specifically developed for inspecting confined and dangerous environments have been tested. The tests are used to improve the instruments and their user procedures for the next editions, but also these systems could provide a base from which to develop reliable communication systems from lunar lava tube missions in the future. Other technologies tested are those related to survey and documentation, like new laser measurement tools (Cavesniper, Megaplot SJ).

**Conclusions**: The environment scientific, operational and situational realism, as well as the real, albeit controlled risk of makes this it a highly credible and valuable training venue. Astronauts are directly involved in one of the open human frontiers of exploration on Earth: the underground. Despite various important differences with space stations, that host current space missions, caves are complex alien environments, offering several of the same situations and associated spaceflight stressors and team processes, as well as science opportunities, making this training platform a valuable tool to enforce team processes and skills, as well as offering complex scientific and technological operations in an unusual and risk controlled environment.

Differently to other analogues, communication inside a cave is rather unreliable, forcing the development of very autonomous mission operations, with reduced reliance on control and directions from ground teams. This offers a rather interesting testbed for future planetary exploration scenarios, which will include delayed communication and higher level of autonomy.

Progression tools, safety and emergency procedures that are used in the CAVES training could be in the future used to develop concepts for moonwalks and surface traverse activities on planetary bodies like asteroids, or even for lunar or martian lava tube exploration.

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# ROBOTIC MAPPING AND EXPLORATION OF A TERRESTRIAL LAVA TUBE: A STRUCTURED PLANETARY CAVE MISSION SIMULATION WITH A REMOTE ASTROBIOLOGY SCIENCE TEAM

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**Introduction:** Volcanic caves are compelling targets in the search for extant and past life on Mars (e.g., Boston et al., 2001; Cushing et al., 2007; Léveillé & Datta, 2010; Blank et al., 2018). A recent survey using data from the Mars Reconnaissance Orbiter's Context and High Resolution Imaging Cameras has identified more than 1,000 candidate cave entrances on the surface of Mars (Cushing et al., 2017).

BRAILLE (Biologic and Resource Analog Investigations in Low Light Environments) is a NASA-funded analog Martian cave mission project centered around field research at Lava Beds National Monument (Northern California, USA). The BRAILLE Team's objectives are to (1) characterize microbial life and microbial community structure in terrestrial lava caves and the nutrients in rock and water that sustain them; (2) distinguish secondary minerals associated with microbes in the caves – macroscopic, putative signatures of life and a geochemical record of life that could persist long after any life died away; and (3) practice robotic life-detection and mapping mission operations by directing remote rover activities in one of the caves, Valentine Cave, from a surface command center located at park headquarters. The first two of these objectives are independent of the mission simulation but provide valuable ground truth information that aids in the interpretation of remote observations collected using the rover. Here, we will focus on the mission simulation and its relevance to future planetary cave mission efforts.

**Astrobiology Investigations at Lava Beds:** Our interdisciplinary science effort at Lava Beds focused on 9 caves selected to encompass a range in flow age, length, depth, number of entrances, and human visitation. While our team conducted individual disciplinary studies of the microbial community, geochemistry, and secondary mineralogy, our collective goal was to correlate in situ photographic imagery with laboratory analytical probe results, moving from apparent "bare rock" (basalt) surface, through mineral crusts and coatings, secondary mineral products with small (several mm to cm), coral-like morphologies coating the cave walls, and on to biofilms and, finally, oozes. Compositionally, the mineral features consisted primarily of several forms of amorphous silica, which enhances their preservation potential. Details of this "ground truth" work is being reported elsewhere.

**Robotic Operations and Mars Mission Simulation:** The cave environment presents several challenges for scientific investigation that will need to be overcome through mission design or the development of novel technologies. Not least of these are ingress, maneuvering inside a cave, and operational and data uplink and downlink with out-of-line-of-sight communication paths. BRAILLE's simplified mission simulation focused on science activities and relied on out-of-sim assistance for out-of-line-of-sight communication relays (which NASA and others have developed elsewhere) and refinements in rover positioning within the cave.

The robotic operations aspect of our project used the NASA Ames testing rover, CaveR, which was modified for our use. The rover's mast was removed, reducing the rover height to 1m. The scientific instrument payload, consisting of cameras and spectrometers including the NIRVSS suite optimized for water detection on the moon, were housed in a rectangular pod mounted to one side of the rover and aligned with the top of the rover platform. This pod, able to tilt 45°, was aimed at one side of the cave as the rover moved downslope during mission activities. Its orientation maintained a roughly constant focal length for the instruments of 0.75m from the cave wall.

Prior to mission simulation activities, the rover was transported via truck from NASA Ames to Lava Beds, where we could park within 10m of the cave entrance. To avoid damage to the point of ingress, the rover was disassembled partially and ported manually into Valentine Cave.

The concept of our mission operations is summarized in Table 1. CaveR mapped 20m segments of one side of the cave wall autonomously using a laser scanner, collecting images every 2 seconds and recording time stamp and distance from the starting point. These images were stitched together to form a mosaic, with resolution to ~0.3 mm, which was delivered to a remote science team. The science team worked individually and then as a group to select priority targets of interest on the mosaic, developed an operations plan, and returned that to the rover operators via a human runner. CaveR then returned to interrogate the targets of astrobiological interest, as directed by the remote team. These activities were conducted under a mission timeline constraint. These same transects were examined by a separate group of astrobiology scientists, in the cave, in similar, timed exercises. We will report correlations between the groups in and out of the mission simulation and initial lessons learned from this planetary mission operations concept.

Table 1. BRAILLE Operations: 4-5 Phases of Cave Exploration.

| | | *Phase* | *Activity (location)* |
|---|---|---|---|
| *BRAILLE Mission Operations* | I | Exploration & Mapping | **Scouting pass** (Rover Transect, in cave) |
| | II | Science Planning | **Data review and science task planning** (Mission Control, LBNM Park Headquarters) |
| | III | Science Sensor Deployment | **Execution of science tasks by rover as defined in (2)** (Rover Reverse Transect, in cave) |
| | IV | Science Interpretation | **Data review & creation of follow-up task plan** (Mission Control, LBNM Park Headquarters) |
| | V | (Optional) Ground Truth Assessment | **ATP Swab and in-person target evaluation** (Out-of-Sim Scientists, in cave) |

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# Cavities and Caves Throughout the Solar System: Prospects Revisited for Occurrence and Astrobiological Significance.

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**Background:** Our earliest work suggesting that the Martian subsurface could be the last best place to look for life on Mars [1], has been followed up by 28 additional years of considering all aspects of the potential occurrence of cavities on other Solar System bodies [2], their potential for astrobiological significance [3], as repositories for other types of geological, volatile, and atmospheric indicators, and as potential human habitats on the moon and Mars [5]. It is time to revisit earlier deliberations and conclusions in light of large amounts of new data from Mars, the Moon, and many other Solar System bodies [e.g. 6, 7].

**Speleogenetic Matrix:** In 2004, I first published a systematic treatment of the potential mechanisms of cave formation in a wide variety of planetary/small body environment types [2]. It has been updated twice for presentations and is now nearing its third major update for presentation at this conference. Figure 1 shows the last version prior to the work currently ongoing but to be completed and shown at the present meeting.

**Online Bibliography:** To support the goals of producing a highly interdisciplinary picture of the likely occurrence of planetary/small body cavity occurrences, their utility for astrobiological studies, and easily accessible information for mission concept planners and engineers, I have compiled a comprehensive cross-indexed bibliography of relevant work between the speleological, planetary, and astrobiological communities. It will be unveiled at the present meeting.

Process-based Cave Classification

| CAVE TYPE | Dominant Processes | Parent Materials | Earth Examples | Possible Extraterrestrial Variations |
|---|---|---|---|---|
| | | | | |
| Solutional | Dissolving rock by solvent *(With or without chemistry)* | Soluble solids plus a solvent | Classic karst, gypsum, halite | Non-water solvents, different thermal regimes |
| Erosional | Mechanical abrasion via wind, water, grinding, crystal wedging, etc. | Any solid | Sea coast caves, Tafonation, Aeolian rock shelters, etc. | Non-Earth erosional processes, e.g. radiation sputtering, frozen non-water volatile wedging |
| Tectonic | Fracturing due to internally or externally caused earth movements | Any rocky solid | Seismic caves | Tidal flexure from a massive primary planet or sun, impact fracturing in craters |
| Suffosional | Cavity construction by the fluid-borne motion of small particles | Unconsolidated sediments | Mud caves, some thermokarst | Ground ice sublimation (?) pocking at Mars poles |
| Phase Transition | Cavity construction by melting, vaporization, or sublimation | Meltable or sublimable materials capable of solidifying at planet-normal temperatures | Lava tube caves, glacial caves (i.e. caves in ice as bedrock) | Perihelionic sublimation of frozen volatiles in comets (Temple), frozen bubbles in non-water ices, non-basalt lavatubes (Io) |
| Constructional | Negative space left by incremental biological or accretional processes, often around an erodable template | Any solid capable of ordered or non-ordered accretion, or biogenic processing | Coralline algae towers, travertine spring mound caves | Crystallization in non-polar ices leaving voids? |

Modified from P.J. Boston 2004. Extraterrestrial Caves. In, *Encyclopedia of Caves and Karst*, J. Gunn, ed.
Titus & Boston, 2012. Interdisciplinary research produces results in the understanding of planetary caves. EOS Trans. 93(20):196.

Figure 1. The cave classification scheme from the revised 2012 version [8].

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**TECTONIC CAVES ON SMALL BODIES: POTENTIAL IN SITU RESOURCE RESERVOIRS.** D. L. Buczkowski[1] and D. Y. Wyrick[2], [1]Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA (Debra.Buczkowski@jhuapl.edu), [2]Southwest Research Institute, San Antonio, TX (danielle.wyrick@swri.org)

**Introduction:** Asteroids are extremely common in the Solar System, populating both the near-Earth environment, the Main Belt, and the L4 and L5 Lagragian points of several planets (Trojans). And yet their potential for in situ resource exploration remains poorly understood. Recent research suggests that these small bodies often have significant fracture porosity, as well as geomorphic evidence of subsurface void space in the form of pit crater chains (Fig. 1) [1]. Tectonic mapping on several asteroids has shown the near-ubiquitous nature of pit crater chains and extensional fractures on these bodies, which in turn may house significant stores of important volatiles and other mineral resources.

**Tectonic Caves:** Pit crater chains are linear assemblages of small depressions, theorized to form by drainage of regolith into an underlying extensional fracture [e.g., 2, 3, 4, 5, 6]. They have been identified on several small bodies throughout the Solar System, ranging from small asteroids to large protoplanets [1]. These small bodies include Phobos [2, 3], Eros [7], Gaspra [8], Ida [9], Vesta [10], and Ceres [11].

Long structural features on the surface of an asteroid indicate substantial internal strength, despite a low density that indicates high porosity. Intriguingly, this implies that the high porosity of these asteroids is due to their fractures. Additionally, many of the lineaments are identified as extensional fractures that propagate into a mechanically layered subsurface, meaning that many of the fault and fracture systems on small bodies may be dilational in nature, capable of opening void space into the subsurface [4, 5]. Pit crater chains are theorized to form over dilational fractures [4, 5], and so serve as a surface geomorphic representation of subsurface void space. These dilational fracture systems may then become subsurface permeability pathways for volatile transport and trapping.

**Methods of Measuring Void Space on Small Bodies:** Fracture porosity on Earth is responsible for the majority of subsurface fluid and volatile reservoirs [e.g. 12, 13, 14, 15]. Therefore it is quite likely that fracture porosity plays a similar role in trapping volatiles on small bodies. Understanding and quantifying the locations and magnitude of fracture porosity on small bodies is thus a necessary next step to determining their volatile storage capabilities.

Pit crater chains have been identified on Earth in Iceland, Hawaii, Idaho, and other basaltic terrains. The void space underlying terrestrial pit crater chains have been observed firsthand (Fig. 2) and can be referred to

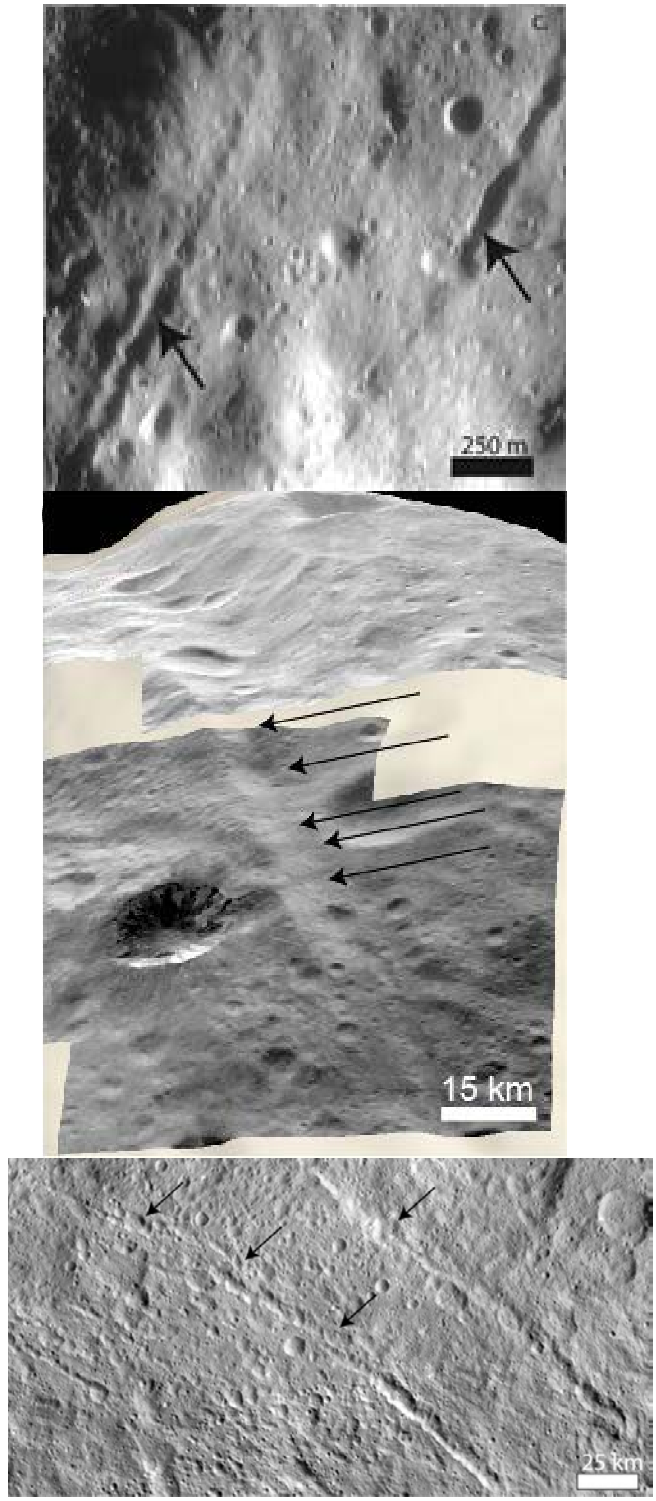


*Figure 1. Pit crater chains on Eros (upper), Vesta (middle) and Ceres (lower). Arrows point to features.*

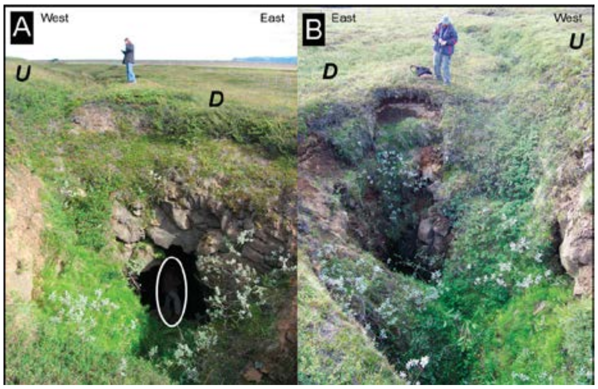


*Figure 2. Image from [5] shows field photographs of a pit crater chain in Iceland. Part (B) shows an overhead view of the pit while part (A) shows the tectonic cave beneath it.*

as "tectonic caves" [5]. While the volume of terrestrial tectonic caves can be measured directly, it is more difficult to accurately measure the void space underlying planetary pit crater chains. The size of the void space can be constrained by determining the volume of the overlying pit [4], as the dimensions of the cave must be at least the volume of the collapsed material. But a more accurate estimation of fracture porosity is needed to accurately predict what resources could be identified and accessed.

Previous geophysical investigations of basaltic terrains in Nevada utilized GPR to map moist subsurface interfaces under loose regolith [16]. Since they form in regolith, we may be able to similarly use GPR to detect subsurface wetness and volatiles trapped in pit crater chains on asteroids. Performing geophysical analyses of terrestrial pit crater chains will provide constraints on future geophysical examinations of subsurface void space on small bodies. This in turn will provide the starting point to determining volatile storage capabilities, volumes, and stability of volatiles stored on these small bodies over time.

**Implications:** Identifying fracture void spaces has potential implications for human exploration, as the need for in situ resource utilization becomes a driver for exploration targets. Near-Earth Asteroids (NEA) are considered the most likely early candidates for these exploration activities. Finding water and other volatiles on site in these asteroids is considered vital toward in situ resource utilization. While water is relatively common on the C-type asteroids, it is unlikely to be abundant on the S-type NEAs. However, there might be water ice trapped in the impact-formed fracture systems, brought in by the impactor. Even other asteroid types (C-type or the water-bearing D-type) would also benefit from the mapping of their void spaces, as the fractured regions would likely be where the valuable volatiles would be most easily accessible.

Other types of in-situ resource identification would also benefit by extensive void space mapping and measurement. Determining the viability of asteroid mining is becoming a priority as it becomes clear that many key elements important to industry will be depleted on Earth within the next 50-60 years. S-type asteroids, the most common type of NEA [17, 18, 19, 20], could potentially provide important metals, such as nickel and cobalt. M-type asteroids contain far more of these materials than S-type, but are considerably more rare. Meanwhile, C-type asteroids could contain useful carbon and phosphorus, as well as water. Identifying existing void spaces would make accessing these resources easier and less time consuming.

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# DEVELOPMENT OF ISRU UNITS ON MOON WITH LUNAR CAVES AS SOURCE OF MINERALS.

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**Introduction to LUNAR ISRU:** Lunar In Situ Research Utilization Units are future of lunar surface exploration. For the first time to establish ISRU units on the moon its payload co-ordinates on the moon's surface and mining range from metals. ISRU units are the future technologies for the permanent habitation for human beings on the moon which would cover wide areas from catering the energy need to the water processing and mineral refining over the lunar surface.

**Ideal Location on moon for ISRU Project:** The Oceanus Procellarum is a mare on the surface of the moon. It has been found that there exists lava tube with potential for human habitation coming years. This cave structure could save humans from the radiation storms and extreme weather conditions which include drastic temperature change. Thus for human exploration missions the caves would serve as natural shelters and help cave dwelling humans to turn into cave dwelling martians. The water processing ISRU has a capacity of 500 tons of water in the form of a below-ground pool walled with sintered lunar regolith. After the complete water extraction structure is abandoned and new structure is built on new ice deposit. Much more units can be built once a trial unit is tested.

**Use of robotics for Surface Exploration:** . As mentioned importance of Oceanus Procelarum the metal refining ISRU units would be situated here. Most metals are found in high concentration here Namely, Thorium (Th), Titanium (Ti), and Iron (Fe) are commonly found in the area which is around Copernicus crater. For ISRU processing the lunar regolith around ISRU is mined and ISRU grinds up the lunar regolith with the power generated from a rector (The power supply is clearly mentioned in ISRU project).

**Use of robots as transportation systems:** It is possible that the mobile transportation robots used for transportation of lunar reoglith are initially powered by Li-ion batteries, If Li-ion batterires lose charge they may be retrofitted with new hydrogen cells when the improvised system is available. With today's battery charging algorithms if we consider improvements on smaller scale for charging and discharging cycle with increased battery capacity as Tesla cars are expected in near future these vehicles would require nearly half charging time. One must consider for a 24 hours schedule the device works for 12 hours a day with 6 hours for unloading and maintenance. As the battery degrades there would be extra time required for charging the device. Afterwards, When extracted regolith has been transported to the ISRU with help of mobile vehicles, it is separated into its composite oxides via selective reduction. This result into several different oxides, such as CaO, $TiO_2$, FeO, $Fe_2O_3$, $Al_2O_3$, and others, which can be easily, separated using magnetic or chemical means.

**Use of robots on the moon of Saturn 'Titan':** With Similar Physics as the Earth, Titan has an exception of water ice as rocks due to cold. ISRU plant would be placed near a point on the surface where the crust is thin, allowing water to seep up from Titan's interior. The site ultimately chosen was on the slopes of a cryo volcano near Titan's equator compared to geothermal power plants near volcanoes and geysers to take advantage of the heat seeping up from the Earth's interior. On Titan, a small fleet of protected rovers designed to cut out blocks of water ice from the cryovolcano flows. ISRU lander perform melting, purification, and processing of these blocks. Nitrogen and methane could be harvested from Titan's atmosphere. The only technological needs are those robot rovers and shuttles which would carry export of materials from ISRU Units.

**Future Scope:** In near future the importance of lunar surface structures would be emphasized like never before due to moons position and resource availability. The team studying this project would identify the use of resources obtained from lunar caves on the lunar structures, their feasibility, practical implementation This work is under my project ISRU Units whose paper was published in Annual Meeting of Lunar Exploration Analysis Group (LEAG) 2019 (Link for E-poster : https://www.hou.usra.edu/meetings/leag2019/eposter/5030.pdf)

# LINKING BIOLOGICAL AND GEOCHEMICAL DATA FROM ICELANDIC LAVA TUBES: INSIGHTS FOR UPCOMING MISSIONS IN THE SEARCH FOR EXTANT OR EXTINCT LIFE ON MARS

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**Introduction:** The search for extraterrestrial life in our solar system has been pursued most extensively on our close neighbor, Mars. Early Mars may have been just as hospitable to life as early Earth, with surface liquid water and a mild climate capable of sustaining microbial life [1]. Sampling on the Martian surface has thus far not resulted in the detection of any traces of life, which is unsurprising given the instruments used and the areas sampled, where ionizing radiation has most likely degraded any signatures of potential past life (see [2] for a review). However, it is possible that microbial life migrated to the subsurface as the surface radiative environment became increasingly harsher.

Subterranean environments on Mars would have provided shelter from ionizing surface radiation, a relatively stable internal temperature, and potential entrapment of volatiles, such as water, that may have sustained life. If life was able to flourish in such environments, it or traces of it should still exist in the form of kerogens, permineralized polymers [3], mineral structures or fossils [4], or other geochemical signatures, since the preservation of biosignatures in cave minerals may be stable for many millions of years [5].

Lava tubes form from basaltic flows, typical of pahoehoe eruptions from low lying shield volcanoes. The High Resolution Imagining Experiment (HiRISE), a camera on board the Mars Reconnaissance Orbiter (MRO) launched in 2005, has shown features indicative of lava tube entrances on Mars. The Elysium Mons shield volcano is postulated to have formed in the more habitable time period of Mars, whereas the Tharsis Montes region is potentially too young and was formed after the loss of the magnetic field [6]. This range in the age of lava flows creates a debate on where potential microbial fossils (or life) may lie, but the existence of these lava tubes nonetheless presents a possibility for habitable environments.

Lava caves on Earth are mineralogically similar to caves on Mars, as are the energy sources for life inside, namely redox gradients of iron, sulfur and manganese for example. The chemoautotrophs that feed off of these gradients, and subsequent heterotrophs that feed off of the organic carbon they produce, together form biofilms and microbial mats of incredible complexity. As a consequence, microbes in caves alter their host rocks chemically and induce the dissolution and precipitation of speleothems, either passively, where microbial cells act as nucleation sites, or actively, where bacterially produced enzymes control mineralization [7]. Many speleothems are also produced abiotically. It is in differentiating between the biotically- and abiotically-formed speleothems wherein the art of biosignature detection in caves lies.

Lava caves on Earth provide analogue sites where these processes can be studied and the art of biosignature detection developed. To differentiate between abiotic and biotic speleothems, it is necessary to put them in context, i.e. to understand the chemical environment in which they formed. For biotically-formed speleothems, it is also necessary to understand the biological agent which facilitated its formation. To this end, both geological and biological information, as well as the interface between the two, need to be acquired.

The expeditions of the Planetary Analogues and Lava Tube Expedition (PELE) team involve the collection of interdisciplinary sample sets in order to characterize the interaction between the biological activity and its mineral substrate in Icelandic lava caves, with the goal of identifying possible biosignatures which might be expected to be preserved in deep time.

Here we report some of the findings from several Icelandic lava caves located at the Laki and Óðáðahraun lava fields in south-eastern and northern Iceland, respectively. The caves were chosen for their relatively oligotrophic nature, making them good candidates as analogues to Martian caves.

**Methods:** Lava caves are very isolated, fragile and potentially dangerous environments, and as such their exploration requires much care, planning and special equipment. The PELE team consistently works with local speleological societies during our sampling expeditions. The Icelandic Speleological Society (ISS) was indispensable to this work, with in-depth knowledge of the terrain, and by doing its best to keep these caves in their pristine states by protecting them from vandalism and human contamination.

*Sampling strategy.* Sampling spots were chosen based on visual appreciation of suspected biomass and nutrient sources. Several expeditions with the same core team honed the sampling strategy which follows: each area sampled is first approached by the biologists, who under sterile conditions collect microbial mat samples.

After they finish, a handheld X-ray fluorescence spectrometer (XRF) is used on the rock below the sampled mats to record the elemental composition. This is then followed by geological sampling, which consists of chipping away a small amount of surface rock with a geological hammer.

*Analytical techniques.* DNA is extracted from biological samples using a Phenol/Chloroform protocol and analyzed with 16S rRNA gene sequencing on the Illumina MiSeq platform. Geological samples are characterized by means of X-ray diffraction (XRD) and thin section optical microscopy. The organic fraction is extracted from these samples for lipidomics analysis. Additionally both biological and geological samples are analyzed with Raman spectroscopy and scanning electron microscopy (SEM) for supplementary compositional and morphological information.

**Results and Discussion:** A high diversity of geochemical and microbiological features were detected in each cave. Differences in microbial populations were found to exist between the northern and southern caves, though some species were found in all caves.

As reported in other lava caves around the world, Proteobacteria were ubiquitous in the investigated caves but varied in abundances of 20–90% depending on the sampling site and cave. This differs from previously reported comparison studies between Hawai'ian and Azorean lava caves, where *Actinobacteria* were more abundant in the former and *Acidobacteria* in the latter [8]. Thirty three bacterial phyla and more than two hundred genera were found across the samples. *In situ* XRF data indicates a high diversity of substrates, with significant concentrations of iron, copper, calcium and silica, and traces of cobalt, nickel and titanium. Interesting genera were identified capable of feeding off of these substrates. Several genera have been found to be fairly ubiquitous, e.g. *Methylobacterium*, *Cupriavidus* or *Lactobacillus,* whereas some were only found in limited sample sites within caves or in distinct geographical areas. For example, *Dechlorobacter* and *Leptolinea* were only found in the northern region of the Oðáðahraun lava field. The former is potentially interesting as some species are known to reduce perchlorate salts, which are of high relevance for a Martian electron acceptor. Correlations between elemental abundances derived from the XRF and the presence and relative abundances of bacterial genera have yet to be established.

Archaeal and fungal communities, understudied in cave environments, will be further investigated as some of the bacterial genera found, such as *Chitinophaga,* are known endosymbionts of fungi.

Raman microspectroscopy data (acquired with a 532 nm excitation wavelength as that of the Raman Laser Spectrometer instrument on-board the ESA/Roscosmos ExoMars2020 rover) revealed the presence of carotenoid molecules which are invaluable targets as potentially detectable biosignatures on Mars. The mineral natrojarosite, usually formed in highly oxidizing conditions and detected on Mars by Spirit and Opportunity, was also interestingly found in several samples.

**Conclusion:** By linking biological and geochemical data, we aim to characterize the metabolisms of primary and secondary bacterial colonizers of one of the only initially sterile environments found on Earth, and to describe how they alter their host rocks. Further investigation of secondary mineral deposits with Raman, XRD and SEM will hopefully elucidate whether these are of biological origin, and their potential as biosignatures.


Figure 1: Copper-rich precipitate in Icelandic lava tube.

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**Comparison of Earth's fumarolic ice caves and implications for icy voids on other worlds.** A. G. Curtis[1] [1]JPL aaron.curtis@jpl.nasa.gov

**Introduction:** Volcanic and geothermal activity on earth melts extensive ice caves into glaciers or snowpack. These features are useful indicators of heating and form a warm, moist, radiation-shielded, stable microclimate which can be hospitable to life. In particular, the thermal buffering effect due to latent heat of phase change leads to stable temperatures. The highest permanent liquid water masses in Antarctica and North America are inside fumarolic ice caves.

Beyond Earth, ices are prevalent in our solar system. Wherever ice undergoes phase change to liquid or vapor, caves are possible. Ocean worlds such as Enceladus and Europa certainly have void spaces in their ice masses. Layering of $CO_2$ and water ice in Mars' polar caps, combined with seasonal insolation changes, leads to the formation of voids in the ice. Complex icy environments like Titan and Pluto are likely to exhibit similar void systems.

Comparing and contrasting between Earth's diverse range of ice caves in terms of their micoclimates and their morphologies helps us imagine properties and behaviors of caves in ice elsewhere in the solar system. Additionally, learning how to detect Earth ice caves from aerial or orbital data could help us to recognize them when we find them on other planets.

The author has worked inside the fumarolic ice caves near the summits of Mt Erebus, Mt Rainier, Mt St Helens, and Villarrica. He will present a comparison of their overall shapes, scales, formation mechanisms, and microclimates, using photos, maps and time series data. He will then muse on what we might encounter when we begin to visit caves in ice elsewhere in the solar system, and how we might study them remotely.

**Martian Alcoves as Havens from Harsh Surface Environment:** René A. De Hon, Department of Geography, Texas State University, San Marcos, Texas 78666. dehon@txstate.edu

**Introduction:** Geologic processes and geologic history are more varied on Mars than on the Moon. Stratified rock layers on Mars offer a greater opportunity to analyze past environments and geologic history as opposed to those offered on the volcanic- and impact-dominated moon. In addition, stratified sediments on Mars offer targets in the search for past life.

In the selection of a protective habitat for early explorers, lava tubes are suggested as a ready-made shelter for astronauts on the Moon or Mars [1, 2]. On Mars, caves provide protected environments not only for astronauts, but for the preservation of evidence of current or past lifeforms [3]. The variety of surface modifying processes and stratified materials on Mars offers the possibility of safe habitats other than lava tubes. Solution caves are unlikely because of the apparent scarcity of limestone, but alcoves in stratified sedimentary and volcanic rocks are quite likely [4, 5].

**Alcove Formation:** Alcoves form by many different processes; in many different types of terrains; and varied environments. Volcanic and sedimentary layered materials are equally suitable. In the simplest means, all that is required is a resistant layer underlain by a less resistant layer. On steep scarps of layered materials, partial removal of less-resistant material leads to the creation of an overhanging ledge with a protected alcove. The removal of underlying material can be accomplished by one of several processes including wind scour, plunge pool of waterfall, dissolution by groundwater, or spring sapping. Some of the best developed alcoves on Earth are fashioned by spring sapping in limestone or soluble cement in sandstone. An alcove develops as spring sapping removes weakened rock above the impermeable contact at the outcrop. Spalling of the roof enlarges the alcove. Continued spring sapping creates amphitheater-headed, steep walled, u-shaped valleys. Necessary components for alcove formation—steep exposure of stratified materials and groundwater existed in the Martian past and still exists as ground-ice in the present [6, 7].

**Terrestrial Alcoves:** Terrestrial analogs of Martian alcoves include the abundant alcoves formed in the Mesozoic Navajo Sandstone and the Eocene Claron Sandstone of the in the southwestern United States [8, 9] and the alcoves in Cliff House Sandstone at Mesa Verde [10]. Alcoves from at the head and on the side walls of box-canyons. These are typical sandstone alcoves formed by weakening calcite cement by groundwater solution at the basal contact with an impermeable layer. Alcoves range from small openings to those large enough to incorporate pueblos housing hundreds of inhabitants.

In Central Texas prominent alcoves are formed along the Pedernales River at the contact between the Cretaceous Cow Creek Limestone and underlying Hammett Shale. Hamilton Pool is a popular park formed where a stream impinges into an embankment of limestone. The sideward migration of the stream has cut into limestone and increased the groundwater discharge along the limestone-shale contact to create a large alcove and pool. Across the Pedernales River from Hamilton Pool, a short, steep-walled, amphitheater-headed, tributary canyon is cut by a headward erosion into limestone by a combination of spring sapping. An alcove and small pool have developed at the valley head, and a second, small alcove formed in the side wall of the canyon is partially walled in by the formation of dripstone across the opening of the alcove.

**Martian Alcoves:** Alcoves are hidden from direct view from above. Their probable presence may be implied by a few simple *tells* seen in vertical imagery (Fig.1). The initial search by satellite imagery should look for scalloped cliff faces formed by thinning of the alcove roof near the slope face. Closer examination by drone could verify initial suspect sites. The obvious places to search for alcoves include anywhere there are stratified materials exposed on steep surfaces; amphitheater-headed valleys carved by groundwater sapping; and walls of valleys or canyons. The value of any suspected lava tunnel will not be known until on-the-ground-inspection by an astronaut or a rover is able to confirm the unseen portions. On the other hand, alcoves can be evaluated rather quickly and simply by drone.

Alcoves are excellent sites for exploration for evidence of Martian life. Alcoves provide a refuge from harsh Martian surface environment. The overhanging rock provides radiation screening—reducing radiation levels by as much as 80% of that on the open surface. Sun-facing alcoves trap heat to raise local temperature, and springs in the back of alcoves may provide a water source. As habitats for astronauts, sealing the space would be no more difficulty than sealing a lava tunnel.

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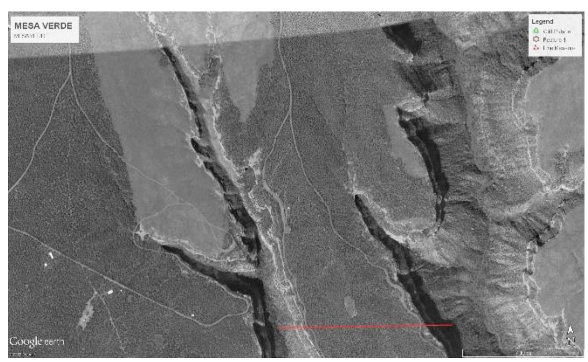


Figure 1**.** Mesa Verde, Colorado. Prominent alcoves are found at the heads of canyons and wherever scallops have formed on steep canyon walls.

**Mineralogical, Chemical and Morphological Variations among Analog Basaltic Lava Cave Speleothems**

J. A. Ford[1], H. V. Kulkarni[2], A. Godet[2], J. Blank[3], and S. Datta[2] Kansas State University, [2]University of Texas at San Antonio, [3]Nasa Ames Research Center

**Introduction:** Basaltic caves at Lava Beds National Monument (LBNM), CA, offer a unique analog environment for potentially similar caves on Mars and other planetary bodies[1]. In the presence of liquid water, caves at LBNM host diverse microbial communities and morphologically distinct secondary mineral deposits (speleothems) that could have formed via chemical or biochemical pathways. We investigate the potential pathways to discern between the biotic or abiotic mechanisms of speleothems formation using a combination of chemical, mineralogical and morphological techniques, which may serve to support future unmanned exploratory missions.

**Methods:** Speleothem samples (n = 100) and water samples (n=60) from 8 caves varying in physical factors (age of lava flow, visitation frequency, moisture content, temperature, light penetration) were collected and analyzed using conventional microscopy, x-ray diffraction (XRD), and fluorescence (XRF) to determine the mineralogical and elemental composition. A subset of 35 speleothem samples were also analyzed using a wavelength dispersive XRF spectrometer for validating the elemental data obtained with handheld XRF. Water samples, collected as droplets from lavacicles and puddles on cave floors, were analyzed using ion chromatography (IC) and ICP-OES for ionic and elemental composition. Dissolved organic carbon and nitrogen were quantified using a TOC/TN Analyzer.

**Results and Interpretation:** The host basalt consists of the following primary minerals: plagioclase, clinopyroxene, and olivine. A significant amount of speleothem samples were enriched in secondary minerals: cryptocrystalline silica (opal) and carbonates (Mg-calcite). Minor occurrences of hematite, magnetite, vanadium oxide, apatite, iron hydroxide were also detected in some samples and their concentrations were comparable to that in the basalt in the surrounding Medicine Lake.

Speleothem morphology, as described in prior cave studies[2], can largely be categorized as: Polyps (round bulb with short stem), Fingers (elongated), Coralloids (coral-like), Gours (flow-deposited / rimstone), and Encrustations (mineral crust on bare rock).

The samples that were dominated by the above primary minerals contain 42 – 50 wt% of $SiO_2$, while those enriched in secondary minerals contained up to 96 wt% $SiO_2$. Significant concentrations of biologically important elements (Ca, Mg, Fe, Mn, S, P, V) were detected in several speleothem samples. Other trace elements were also measured in elevated concentrations compared relatively to bare rock: Cu, Cr, Sr, Rb, and Ni. There appears to be a positive correlation between speleothem $SiO_2$ content and trace elements concentration. For example, some speleothems with high $SiO_2$ content (>80%) had excess of 1000 mg/kg Cu. Although the exact pathway of precipitation (biotic vs abiotic) is currently unknown for high $SiO_2$ speleothems, the precipitation process(es) are preferentially incorporating higher concentrations of the above elements as compared to the host rock and other basaltic features.

Thin sections of speleothem samples analyzed under both plane- and cross-polarized lights revealed microstromatolitic-like laminations. These laminae were composed of cryptocrystalline silica in some speleothem morphologies, similar to siliceous sinter deposits, while others contained laminae comprised of alternating calcite and cryptocrystalline silica. Moreover, the laminations of cryptocrystalline silica contain inclusions of glass fragments (as well as plagioclase, pyroxene, and clay fragments), indicative of the incorporation of volcanically produced fragments in a post-eruptive period in which the speleothems were in earlier stages of growth. Furthermore, the inclusions are most concentrated at the base and interior of the speleothem, which may suggest the inclusions in part acted as potential nucleation sites for further mineral growth.

The cave waters were found to be dominated by Si (23 ± 1 mg/L) followed by Na (8 ± 3 mg/L) and Ca (4 ± 2 mg/L) and varied within and among the caves. Elevated levels of $NO_3^-$ (9 ± 8 mg/L) may be attributed to agriculturally influenced recharge or to in-situ microbial $NH_4^+$ oxidation. Total P is also elevated (4 ± 1 mg/L). The cave waters also contained high concentrations of dissolved organic carbon (DOC, 13 ± 6 mg/L), which could support microbial growth. Composition of speleothems and cave water from the same location was found to be correlated. For example, high $Ca^{2+}$ (7 ± 0.5 mg/L) was found in cave waters in the proximity of ~33% CaO carbonate polyp speleothems. P correlates strongly ($R^2$ = 0.91) with dissolved Si, possibly indicative of a phosphate precipitation associated with silicate dissolution within these secondary deposits.

**Summary:** Our results provide a link between the morphology, mineralogy, and elemental composition of speleothems alongside the water that interacts with these features in lava caves at LBNM. Findings of this study will help in determining the abiotic, biotic or combined pathways of speleothem formation. This

work is part of the NASA BRAILLE (Biologic and Resource Analog Investigations in Low-Light Environments) Project, an interdisciplinary PSTAR study of volcanic caves and associated biosignatures in preparation for possible future forays into similar resource-restricted environments on other planets, especially Mars.

**Acknowledgements:**

We thank the National Park Service for their support and aid and the Cave Research Foundation for use of their research facility while working at LBNM. This work was supported by the NASA PSTAR program (NNH16ZDA001N**).**

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**IMAGE AND LIDAR DATASET OF THE WEST DESERT SINKHOLE: AN ANALOG FOR STEEP-WALLED PLANETARY PITS.** J. S. Ford[1], P. J. Callaghan[1], U. Y. Wong[2], H. L. Jones[1], W. C. Whittaker[1], W. L. Whittaker[1],[1]Carnegie Mellon University, [2]NASA Ames Research Center

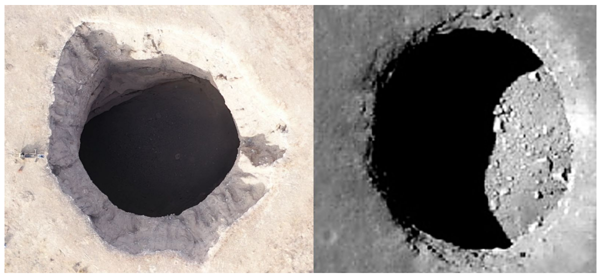

*Figure 1. The West Desert Sinkhole is a close terrestrial analog to a steep-walled lunar pit.*

## Introduction

This work presents a LIDAR and image dataset for studying steep-walled planetary pits. A custom camera gantry captured sets of 1500 images from 27 locations encircling the West Desert Sinkhole at heights and angles relevant for small rover exploration, mapping, and modeling. The combined laser scans provide a dense, precise, textured model of the pit that is useful as ground truth for benchmarking image-derived models and algorithms, for developing and evaluating robot planning, and as a standalone data source for studying planetary pits. All images and laser scans are localized within a single coordinate frame using a survey instrument and are publicly available online. This paper describes the collection apparatus and procedures used to create the dataset, the organization of the dataset, and anticipated applications for the dataset.

## Background

Lunar pits are primary scientific destinations with potential to reveal the formation history of the moon or to shelter human settlements from harmful radiation and micrometeorite impacts. While many proposed missions target lunar pits, existing lunar pit data derives from orbital imagery taken at oblique angles and resolutions too low for mission development. Wong et. al. identify King's Bowl Crater and the Indian Tunnel site as terrestrial analogs to lunar caves and lava tubes, and they provide detailed datasets for their study. However, these sites differ significantly in morphology from the lunar pits identified by the Lunar Reconnaissance Orbiter. Utah's West Desert Sinkhole is a more appropriate terrestrial equivalent due to its similar geological layering, dimensions, and appearance, as well as its accessibility to many sensing modalities.

## Sensor Setup

*PitCam* — PitCam (Fig. 2) is a custom camera gantry designed to capture high-resolution images at prescribed poses around the edge of the West Desert Sinkhole. It features an x-y gantry capable of positioning a camera at three heights above the ground and three ranges from the edge of the pit. It carries a Prosilica GE4900-C color camera mounted on a FLIR PTU-D48E pan-tilt unit programmed to cycle through pan and tilt angles from -90° to 90° and -90° to 0°, respectively. At each camera pose, three to five images are captured at exposures bracketing the autoexposure value, enabling the creation of high dynamic range imagery (Fig. 3).

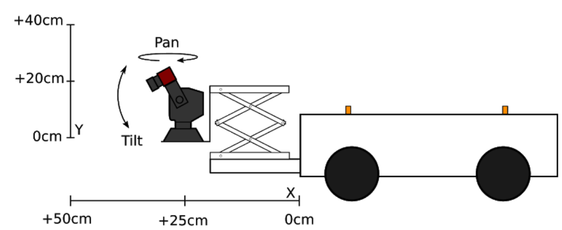


*Figure 2. PitCam is a custom wheeled camera gantry which captures images at three ranges, three heights, seven pan angles, and six tilt angles.*

*Laser Scans* — The dataset includes 44 laser scans captured using a FARO Focus 120 and a Focus$^s$ 350. Scans are registered against each other using fiducial spheres placed at the corners of a fence surrounding the pit. Each laser scan provides a dense, colored point cloud, and the combined scans form a comprehensive 3D model of the pit and its immediate surroundings.

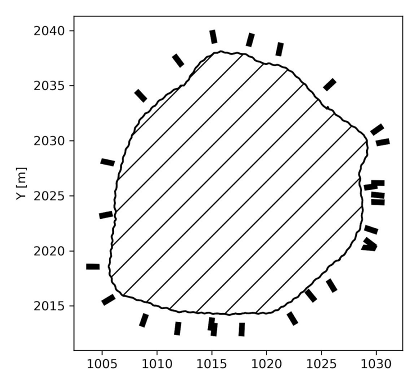


*Figure 3. The dataset contains imagery from the 27 locations depicted above.*

*Total Station* — PitCam and the two laser scanners carry target prisms used by a Leica TS15A 003" to accurately measure their pose. The dataset includes coordinates for every PitCam capture location and every laser scan. The expected accuracy of surveyed coordinates is +/- 2mm in the global frame.

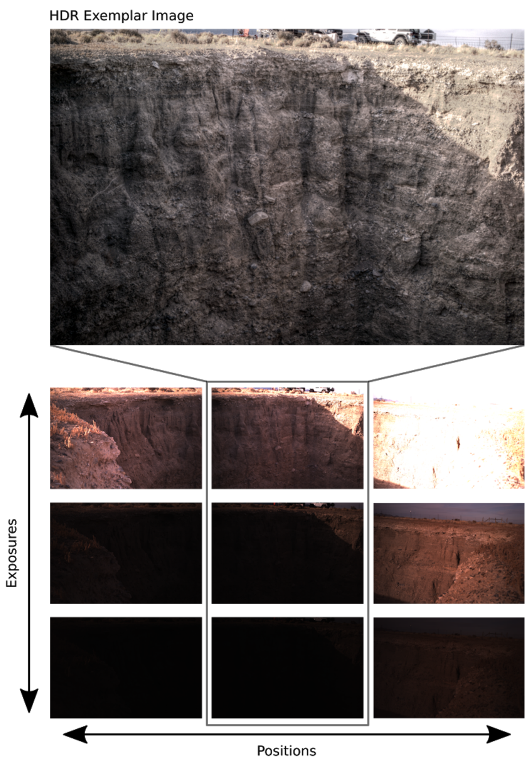


*Figure 4. For each camera pose, multiple images with differing exposures are combined to create a single high dynamic range image.*

## Dataset

*Statistics* — The dataset contains 42,297 16-megapixel images and 44 high density laser scans. In total, it contains 585GB of imagery and 14.8GB of laser scans. Images were captured from 27 distinct locations surrounding the pit (Fig. 4). Sun elevations corresponded to 4x northern latitude at times from 7:40 AM to 4:53 PM MST over a period of five days from Nov. 12 to Nov. 16. 2019.

*Organization* — The dataset root directory contains one directory of images, one directory of laser scans, and two .csv files containing metadata. For each image, the metadata contains a timestamp, the 6-DoF pose of the camera in the global coordinate frame, the exposure used to capture the image, and the relative path to the image file within the dataset. For each laser scan, the metadata contains a timestamp, a pose, and a relative file path. Raw images are saved as 16-bit TIFF files in BayerGRGB format compressed via zlib.

*Figure 5. A three dimensional, top-down view generated by stitching eighteen LIDAR point clouds captured from the perimeter of the pit.*

## Applications

This dataset provides registered RGB-D point clouds and high-resolution imagery captured using various exposures under a range of lighting conditions. Applications for this dataset and derivative data products will include:

- Creation of DEMs for mission operations and traverse planning.
- Generation of terrain models for rover safeguarding, navigation, and autonomy development.
- Use as ground truth for science mapping development, including sensor placement, resolution trades, and algorithmic reconstruction evaluation.

## Future Work

This dataset will inform the development of the first mission to explore and model a planetary pit using an autonomous micro-rover.

## Dissemination

The dataset and associated code is available at www.westdesertsinkhole.com/data

## Acknowledgements

This work is supported by NASA Phase III Contract #80HQTR19C0034. Special thanks to Austin Day, Haidar Jamal, Jay Maier, and Will Sandford for their field work and support.

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**DETECTION OF SUBSURFACE VOID IN PIT CLUSTER AREA BY USING GRAVITY ANALYSIS.** IS Hong[1,2], YJ Choi[2,3], HK Moon[2], Y Yi[1], [1]Department of Astronomy, Space Science and Geology, Chungnam National University, Daejeon 34134, Korea (ishong@cnu.ac.kr) [2]Korea Astronomy and Space Science Institute, Daejeon 34055, Korea, [3]University of Science and Technology, Daejeon 34055, Korea

**Introduction:** When human enters the moon, caves can be used as outposts[1]. The discovery of a pit as a feature related to cave caused the possibility of subsurface voids [2, 3]. There are about 200 lunar pits distributed throughout the moon and classified according to their form [4]. There was a geophysical approach through gravity fields and radar sounders to find voids below the lunar surface, demonstrating the existence of subsurface voids [5, 6]. However, due to the limited spatial resolution of the data, researchers are only talking about the existence of voids on the scale of several kilometers. If the pit acts as a void entrance, it may have a plumbing system under the surface of the area where the pit is clustered. The pit single entity cannot be analyzed because it is a sub-pixel scale feature when viewed from the remote sensing data. In this study, Gravity Recovery and Interior Laboratory (GRAIL) uses gravity field data to demonstrate the possibility of subsurface voids in areas where small impact melt pit clusters.

**Methods:** We conduct the analysis using the GRAIL gravity model (GL1500E). Data processing was done using SHTOOLS (https://shtools.oca.eu/shtools/public/index.html). The data processing sequence first localizes the model to the target area. Calculate admittance for localized model. Calculate the crust density from localized admittance using the relationship between admittance and crust density[7]. This crust density is used to calculate the precise Bouguer anomaly, which is then used to calculate the localized Bouguer anomaly for the target area. Then, the power spectrum of the localized Bouguer anomaly is analyzed to find the maximum degree that exclude the error. Filter out over a 100 to maximum degree range to exclude regional trends and errors. The next step is to calculate the combined maximum absolute eigenvalue. In the calculation, accumulate 5 degrees from 100 degree to maximum degree to see the change of signal according to the order. This calculation allows you to see the change in gravity of a related depth at a specific location. The data processed in several stages are formed similar to three-dimensional spectral image (line-latitude, sample-longitude, band-degree), and the band math is performed like the spectral image analysis method to emphasize the shallow depth signal.

**Target Area:** Our target is a lava pond (6.5°N, 119.8°E) in the northern King crater, with a large number of pit cluster areas(with fractures) [4, 8].

**Results:** Localization was set at 10-degree radius in spherical cap shape around target point. The surface crust density from the admittance of the area was calculated as 2317.3 kg/m$^3$, and Bouguer anomaly was calculated as the corresponding value. The maximum degree to be used for the calculation was obtained as 603 degree from spectrum analysis. Band math was calculated to 600 degree subtract from 603 degree in the eigenvalue map.

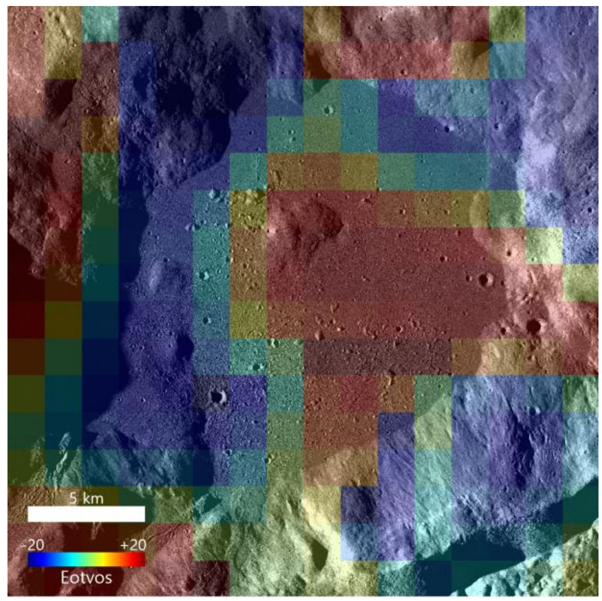


**Figure 1. Maximum eigenvalue map of Bouguer gravity in northern King crater lava pond. Positive signals(red) show lower gravity(mass deficit). In lava pond, many pits and fractures are distributed in red zone especially[8].**

**Discussion:** The pit that makes up the cluster is an impact melt pit that is distributed like fracture. Comparing the distribution of the features shown in the optical image with the gravitational eigenvalue map in this study, we found that they corresponded somewhat to the positive value (negative gravity anomaly) region. If existence of subsurface voids is assumed to beneath pit cluster regions, the data processed only for the shallow depth can appear to have low gravity. There may be several causes for the low gravity in the region, among which pit cluster and subsurface voids. And it can be considered dominant lower gravity signals made pit cluster and subsurface voids. If we get same result from this method to other areas with pit clusters, we can argue that there is a cave-like void under the pit cluster.

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**CLASSIFYING LEVEES AT THE OLYMPUS MONS USING MACHINE LEARNING FOR SAFE SPACECRAFT DEPLOYMENT SITE IDENTIFICATION** J. C. Johnson[1,2,3], P. A. Johnson[1,3], and A. A. Mardon[2,3], [1]Faculty of Engineering, University of Alberta (email: jcj2@ualberta.ca ), [2]Faculty of Medicine and Dentistry, University of Alberta (email: paj1@ualberta.ca ) [3]Antarctic Institute of Canada (103, 11919-82 Str. NW, Edmonton, Alberta CANADA T5B 2W4; email: aamardon@yahoo.ca )

**Introduction:** Observed telescopically as early as the 19th century, the Olympus Mons teems with scientific and hobbyist interest. The Olympus Mons is a Martian shield volcano that is currently the tallest planetary mountain and second-largest volcano in the solar system discovered. Unfortunately, it is an unlikely site for deployment of probes due to low atmospheric density and higher dust concentrations that impede rock sample collection. [1]

However, images from the *Mars Global Surveyor* and the *HiRISE* have depicted lava flows of varying ages located at the base of the Olympus Mons. It has been previously described that older flow has lava caves with levees. Here, we suggest that pinpointing the edges of levees can provide more accurate estimations for Martian rover landing sites to be deployed. [2]

This abstract briefly details the importance of collecting field data in this region, particularly focusing on its value in elucidating water on Mars and as a plausible sign of life, both ancient and present. It also suggests the adoption of a classification system to detect Martian levees using polarimetric Synthetic Aperture Radar (polSAR) data analysis.

**Fluvial Channelized Flow Controversy:** Ancient channelized flows have been observed in all inner planets and some satellites of the solar system. In 1972, the discovery of what are now-known as fluvial channels or levees on Mars became the subject of heated debate, particularly in regards to the contribution of water in molding these structures. However, the newfound understandings of the fluvial nature of these levees have spawned a new onslaught of theories with respect to the origin, mechanism, and presence of oceanic bodies and hydrological processes. [3]

**Importance of Characterizing Levees:** Since lava tubes or levees were first identified on the Red Planet, there has been curiosity towards sampling cave minerals due to the potential for unraveling historical or current interplays between water and subsurface regolith. Drawing further, perhaps it can provide some of the first moves towards Martian habitability.

Akin to the Mauna Kea in the Hawaiian Islands on Earth, Olympus Mons is the consequence of numerous basaltic lava flows from volcanic vents. [4] Research in terrestrial analogues has indicated the presence of small mineralized nodes called coralloid speleothems in these tubes which have a postulated link with biofilm that forms in caves. As a plausible source/sink of microbial diversity and associated geomicrobiological interactions, the mineralization can provide an important historic time bank for Mars. [5]

**Use of polSAR in Terrestrial Classification Methods and Transfer to Martian Classification Methods:** polSAR data analysis has had a myriad of terrestrial applications, including but not limited to terrain and land use classification. Marapareddy *et al* [6] have described the use of polSAR in detecting anomalies on terrestrial levees. They report the high spatial resolution and soil penetration capabilities as important elements in identifying regions of interest.

Typically, SAR imagery relies on algorithms that must be extensively optimized for reliably modeling the images statistically. [7] However, fundamental to statistical modeling is an in-depth recognition of the terrain scattering mechanism. If we can train a machine learning algorithm to optimize edge detection of Martian levees, it could provide us a way to provide space agencies with the pinpointed longitudinal and latitudinal points for landing future spacecrafts.

**Conclusion:** Understanding that older flows are relatively less volatile and safer areas for unmanned probes to explore, the authors propose a mechanism for targeting sites of landing that has the potential to reap exciting developments to current understandings of Martian geomorphology. Note that this geomorphological identification is merely one of many considerations in site selection. Amongst these considerations are climatology, gravity, and radiative stresses on Mars.

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**MIRRORS FOR HARNESSING SOLAR ENERGY IN CAVE EXPLORATION AND OTHER LOW-LIGHT SETTINGS** J. C. Johnson[1,2,3], P. A. Johnson[1,3], and A. A. Mardon[2,3], [1]Faculty of Engineering, University of Alberta (email: jcj2@ualberta.ca ), [2]Faculty of Medicine and Dentistry, University of Alberta (email: paj1@ualberta.ca ) [3]Antarctic Institute of Canada (103, 11919-82 Str. NW, Edmonton, Alberta CANADA T5B 2W4; email: aamardon@yahoo.ca )

**Introduction:** Solar energy is an essential resource for both illumination and energy capture in space, especially in light-limited deep space geography such as caves. For the purposes of this abstract, we will be consider lunar caves. Existing models, such as space-based solar power (SBSP) for the harnessing of solar energy, utilize collecting satellites with solar panels in orbit. However, this conception is limited both conceptually and economically. Firstly, a phenomenon known as the sparse array curse may interfere with the transfer of energy from satellite to the surface. [1] Second, the conversion of photons to electrons and vice versa may result in significant energy loss and difficulty in management of overheating. Resources and costs associated with satellite launching, maintenance, and risk management must additionally be considered for. Here, we propose the integration of the SBSP model on the lunar surface with the use of mirrors on the Moon for solar energy capture for use in exploration and *in situ* resource utilization.

**Seasonal differences:** Seasonal differences, which exist on the lunar surface, are unlike that observed on the Earth. This is primarily due to the difference in the Moon's axial tilt in reference to the ecliptic being approximately 1.54°, in contrast to the Earth at 23.44°. [2] Solar irradiation is thus less variable on the Moon and as such depends more closely on variables such as topography, location, positioning, phasing and rotation of the Moon. Due to these variables and axial tilt, peaks of eternal light (PELs), which are theorized to always receive illumination, and craters of eternal darkness, which remain in permanent shadow never being exposed to sunlight, both exist on the lunar surface. For instance, PELs have been suggested on the Peary Crater at the lunar north pole, which is a high point receiving illumination for the full lunar day.

**Novel design:** Unlike the SBSP conception of placing solar panels on satellites within orbit to capture solar energy, we suggest the placement of specially designed mirrors at PELs on the lunar surface to reflect light towards solar panels on the lunar surface in order to obtain solar energy. By doing this, the sparse array curse would not be a concern. Additionally, the properties of the mirrors utilized can be designed and adjusted to accommodate varying degrees of concave angles, sizes and numbers, and reflective capacities, providing a suitable medium through which solar energy can be captured. This would ensure a nearly unlimited supply of solar energy and a single conversion process from photons to electrons, in contrast to SBSP where energy is lost due to multiple conversions. Furthermore, using mirrors enable the adjustment of light reaches solar panels eliminating the risk of overheating. Finally, the mirrors would also reduce cost and resource expenditure.

**Limitations:** While this technology may be theoretically sound, there is no proof-of-concept to demonstrate its feasibility. The strength and durability of mirrors during space travel and on the lunar surface is important to consider for. Space debris or lunar dust may interfere with the reflection. Additionally, the stabilization and maintenance of mirrors and mirror surface may require more resources. Furthermore, there is a need for a mirror positioning goniometer or similar device to measure and determine angles of light reflection.

**Conclusion:** While space-based solar power has conventionally used solar panels on satellites to harness light energy, here we suggest the innovative utilization of mirrors for this purpose. The existence of PELs can be used to our advantage in a novel design allowing for continuous, unlimited access to a light source. However, this has yet to be tested and this may prove to have further limitations in practice.

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**AUTOMATED DESIGN OF ROBOTIC PLATFORM FOR EXPLORATION OF PLANETARY CAVES, PITS AND LAVA TUBES.** H. Kalita[1] and J. Thangavelautham[2], [1]Aerospace and Mechanical Engineering, University of Arizona, 1130 N Mountain Ave., Tucson, AZ 85721; hkalita@email.arizona.edu, [2]Aerospace and Mechanical Engineering, University of Arizona, 1130 N Mountain Ave., Tucson, AZ 85721; jekan@email.arizona.edu.

**Introduction:** The next frontier in solar system exploration will be missions targeting extreme and rugged environments such as caves, pits, and lava tubes of the Moon and Mars [1]. Exploration of these environments will provide vital clues to the past and present habitability conditions. However, current landers and rovers are unable to access these areas of high interests due to limitations in precision landing, inability to traverse rugged terrains, and operations culture where risks are minimized at all costs. So, there is a need for small, low-cost platforms that can perform high-risk, high-reward science on these extreme environments [2].

With the rapid advancement in electronics, sensors, actuators, power supplies and instruments as a result of rise of interplanetary CubeSats, it is possible to develop robotic architectures that can take high exploration risks at low costs. Taking motivation from these advancements, we present an architecture of small, low-cost, modular spherical robot called SphereX that is designed for exploring planetary caves, pits, and lava tubes [3-5]. A large rover or lander may carry several of these SphereX robots that can be tactically deployed to explore and access these rugged environments inaccessible by it.

**SphereX Architecture:** SphereX consists of a mobility system to perform optimal exploration of these target environments. It also consists of space-grade electronics like computer board for command and data handling, power board for power management and radio transceiver for communicating among multiple robots. Moreover, it also consists of a power system for power generation/storage, multiple UHF/S-band antennas, a thermal and shielding system for survival, an outer shell for structural rigidity and accommodates payloads in the rest of the volume as shown in Fig. 1.

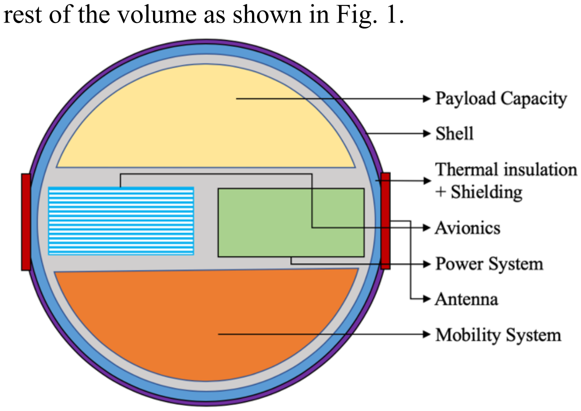


Fig. 1: SphereX Architecture.

However, the design of SphereX is a complex task that involves a large number of design variables and multiple engineering disciplines. It is a highly coupled problem between multiple disciplines and must balance payload objectives against its overall size, mass, power and control which affects its cost and operation. Moreover, each subsystem has multiple candidate options which give rise to complexity and discontinuity in the objective function and design space.

**Design Optimization:** Our approach to find optimal design solutions of SphereX involves using a hybrid optimization process where the search of the design space is performed with a Genetic Algorithm (GA) based multi-objective optimizer at the system level to find a set of Pareto-optimal results while using gradient-based techniques at the discipline level as shown in Fig. 2. The system level optimizer interacts with an inventory of Commercially-Off-The-Shelf (COTS) components and mathematical models of each subsystem to find pareto optimal solutions that meets predefined mission specifications in terms of exploration distance, exploration time, and target planetary body. The objective is to find optimal design of SphereX that minimizes its mass, volume and power requirements while maximizes available payload mass, volume and power [5, 6].

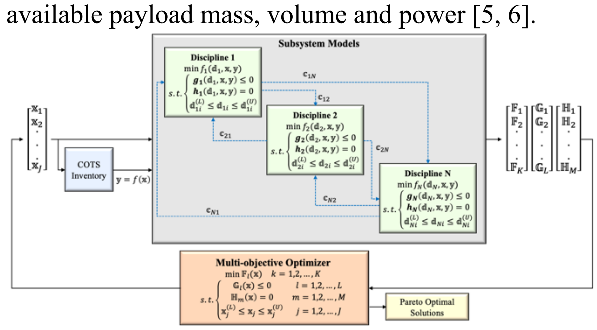


Fig. 2: Hybrid optimization approach for multidisciplinary optimization.

Moreover, the design of the robot takes into account environmental factors such as temperature, radiation, gravity and surface interaction to provide the optimal designs. Mathematical models of each subsystem are developed that include mobility system, power system, thermal system, shielding, communication system, avionics and shell. Three types of mobility system (hopping, rolling, wheeled) and two types of power system (Li-ion batteries, fuel cell) are used in the design process. The optimizer is capable of providing the optimal choice of mobility system type and power system type along with the optimal design of each subsystem based on the mission specifications.

**Results:** We performed a simulation to execute sub-surface exploration of Mare Tranquilitatis Pit on the Moon at 8.33°N 33.22°E. Lunar Reconnaissance Orbiter Camera (LROC) images reveal that the pit diameter ranges from 86 to 100m with a maximum depth from shadow measures of ~107m and that it opens into a sublunarean void of at least 20meters in extent [7, 8]. However, the sublunarean void might extend to a few kilometers in length and so mission specification is to explore 1000m of the sublunarean void. The con-ops for performing this mission is shown in Fig. 3. A lander carrying multiple SphereX robots would descent nearby Mare Tranquilitatis Pit and deploy the robots one by one. Each robot will have three phases 1. Surface operation to approach the pit entrance, 2. Pit entrance maneuver, and 3. Sub-surface operation to explore the pit. The mission target is to explore 2000m on the surface in 10 hours, 50m in 10 minutes to enter the pit and 1000m inside the pit in 5 hours as seen in Figure 16(Right).

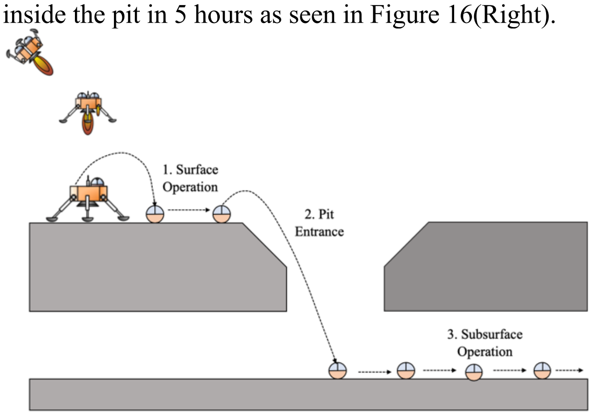


Fig. 3: Concept of Operations for exploring Lunar pits.

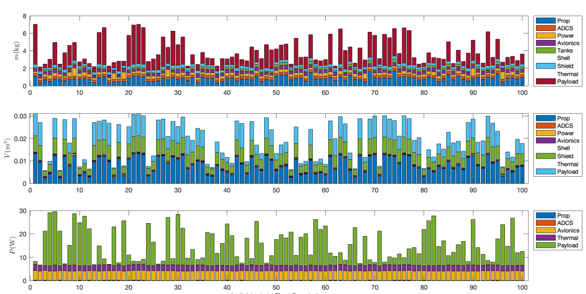


Fig. 4: Mass, volume and power budget of the 100 individuals in the pareto optimal front.

Fig. 4 shows the mass, volume, and power budget of the pareto-optimal solutions of SphereX for the above mission specifications. An important result found in the pareto front is propulsive hopping was selected as the optimal choice of mobility and Li-ion battery was selected as the optimal choice of power system for short duration missions while fuel cell was selected as the optimal choice of power system for long duration missions. Fig. 5 shows 3D visualization of a few selected designs from the pareto front developed using MATLAB VRML.

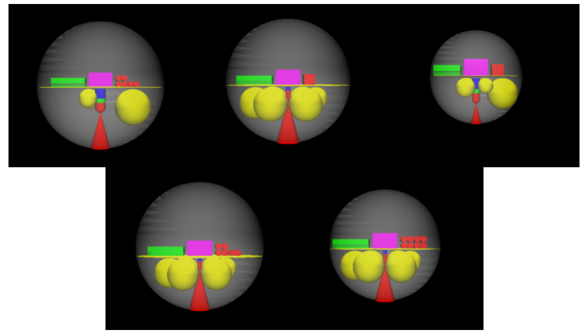

Fig. 5: 3D visualization of the designs in the pareto front.

**Conclusion:** We presented a robotic architecture for exploring planetary caves, pits and lava tubes. The design of complex systems like SphereX needs a multidisciplinary optimization approach because of involvement of multiple engineering disciplines. Our approach provides a system-level perspective of SphereX with sufficient depth to capture high-level trade-offs and reveal insights that are perhaps not obvious at the discipline level. The solution provides a geometric solution that is useful for ground development of SphereX taking into consideration its operational and exploration goals on a target environment.

**References:**

[1] Scientific Goals and Pathways for Exploration of the Outer Solar System (2006). [2] NASA Space Technology Roadmaps and Priorities Revisited (2016). [3] Thangavelautham J. et al. (2014) *2nd International Workshop on Instrumentation for Planetary Missions*. [4] Kalita H. et al. (2020) *IEEE Aerospace*. [5] Kalita H. et al. (2019) *70th IAC*. [6] Kalita H. et al. (2020) *AIAA SciTech*. [7] Wagner R. V. et al. (2014) *Icarus,* 237. [8] Robinson M. S. (2010) *Space Science Reviews,* 150 81-124.

**ROBOTIC EXPLORATION OF PLANETARY CAVES, PITS AND LAVA TUBES.** H. Kalita[1] and J. Thangavelautham[2], [1]Aerospace and Mechanical Engineering, University of Arizona, 1130 N Mountain Ave., Tucson, AZ 85721; hkalita@email.arizona.edu, [2]Aerospace and Mechanical Engineering, University of Arizona, 1130 N Mountain Ave., Tucson, AZ 85721; jekan@email.arizona.edu.

**Introduction:** Exploration of planetary caves, pits and lava tubes has been identified as one of the science goals by the Outer Planets Assessment Group (OPAG) under the theme Making Solar System [1]. Exploration of these environments has the potential to ascertain the range of conditions that can support life, and identify planetary processes that are responsible for generating and sustaining habitable worlds.

High resolution orbital imagery from the Lunar Reconnaissance Orbiter Camera (LROC) reveal evidence for subsurface voids and mare-pits on the lunar surface [2, 3]. Similar discoveries have been made with the HiRise camera onboard the Mars Reconnaissance Orbiter (MRO) observing the Martian surface. However, exploration of these extreme and rugged environments remains out of reach from current planetary rovers and landers; but the 2015 NASA Technology Roadmaps prioritizes the need for next-generation robotic and autonomous systems that can explore these extreme and rugged environments [4]. The challenges are three-fold and stem from limitations in precision landing, inability to traverse rugged terrains, and operations culture where risks are minimized at all costs.

One credible solution is to develop an architecture that permits taking high exploration risks that translates into high reward science but without compromising the rest of the mission. The wide adoption of CubeSats for Low Earth Orbit (LEO) missions has led to the rapid advancement in electronics, sensors, actuators, power supplies and instruments. Furthermore, with the rise of interplanetary CubeSats (INSPIRE, MarCo, LunaH-Map, Lunar Flashlight, Swirl, NEAScout, OMOTENASHI), radiation hardened version of these components are developing.

Taking motivation from these advancements, we present an architecture of small, low-cost, modular spherical robot called SphereX that is designed for exploring planetary caves, pits, and lava tubes [5-7]. A large rover or lander may carry several of these SphereX robots that can be tactically deployed to explore and access these rugged environments inaccessible by it.

**SphereX:** SphereX is a spherical robot of mass 1.5-4 kg and a diameter of 180-300 mm. Mobility for SphereX is achieved through a combined action of a miniaturized propulsion system and a 3-axis reaction wheel system in the form of combined ballistic hopping and rolling. It also consists of space-grade electronics like computer board for command and data handling, power board for power management and radio transceiver for communication among multiple robots. Moreover, it consists of a power system for power generation/storage, multiple UHF/S-band antennas and accommodates a payload in the rest of the volume. Possible instruments may include a pair of FPGA cameras for imaging, a 3D LiDAR scanner for mapping, navigation and localization, and an impedance spectroscopy instrument to determine water content, distribution, and phase in regolith inside the caves, pits and lava tubes. Fig. 1 shows a conceptual design of SphereX for exploring Lunar pits.

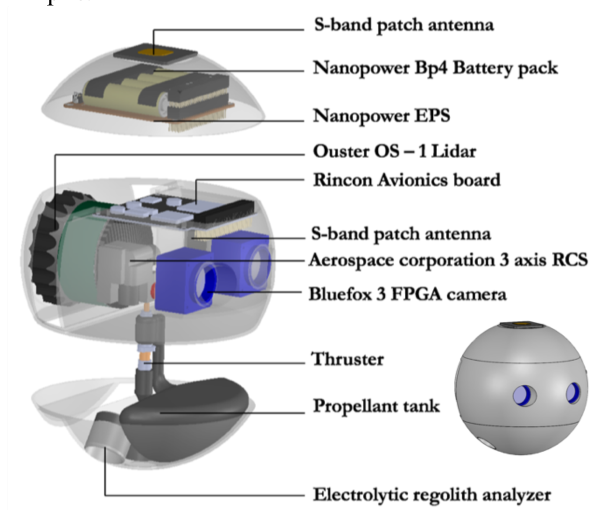

Fig. 1: Internal and external view of SphereX.

**Exploration Strategy:** A lander carrying multiple SphereX robots would land near a target planetary cave/pit/lava tube and deploy the robots one by one. Each robot will then approach the target, enter the target and explore by using mapping and navigation algorithms. Fig. 2 shows a particular strategy to explore Lunar pits where each robot after being deployed by the lander approach the pit and then enter the pit by performing a soft landing maneuver using the onboard propulsion and reaction wheel system. After entering the pit, each robot performs cooperative mapping and navigation using the onboard LiDAR and stereo camera sensors and then performs electrical impedance spectroscopy of the regolith inside. The robots will also be able to collect a few grams of sample, hop back to the lander and perform more detailed analysis using a VAPoR instrument onboard the lander using pyrolysis and mass spectroscopy.

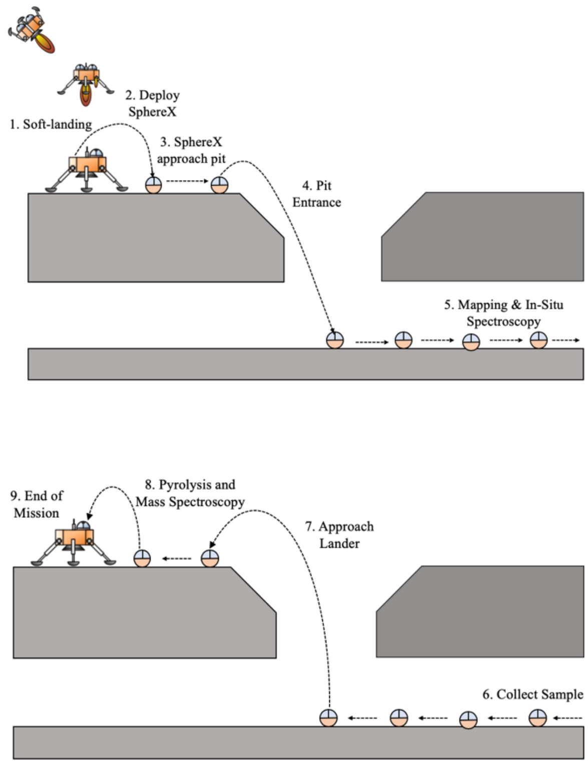


Fig. 2: Strategy for exploring planetary caves/pits/lava tubes using a CubeSat based lander and multiple SphereX robots.

Fig. 3 shows a conceptual 27U (54kg mass, 34cm x 35cm x 36cm dimensions) lander that can carry three SphereX robots and land near a pit on the Lunar surface from the proposed Lunar gateway [8, 9].

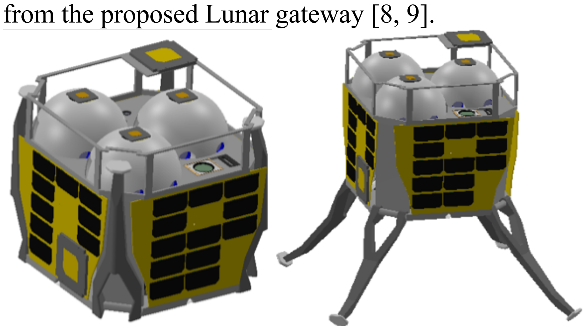

Fig. 3: Conceptual design of a CubeSat lander carrying three SphereX for exploring Lunar pits.

**SphereX Operations:** SphereX will be able to perform exploration through ballistic hopping and rolling mobility. Two modes of ballistic hopping mobility are identified for the robot: a) Energy efficient hard landing mode for exploring short distances, and b) Soft-landing mode for pit entrance and exploring long distances. Both these modes are achieved with the combined action of the propulsion and reaction wheel systems, while rolling mobility is achieved through the reaction wheel system.

For mapping and navigation the onboard 3D LiDAR is used to generate 3D point cloud maps which are registered and merged into one coordinate system using the point-to-plane iterative closest point (ICP) algorithm.

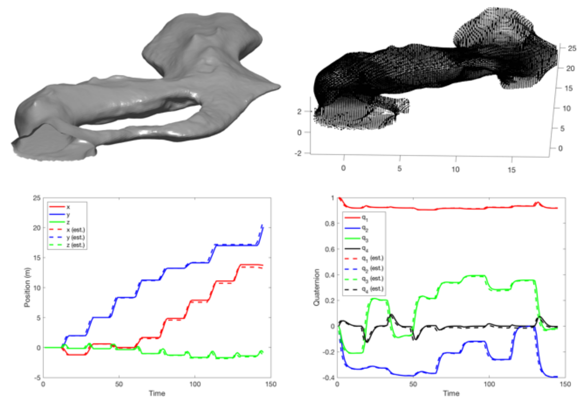

Figure 4: (Top-Left) 3D model generated for simulations, (Top-Right) 3D point cloud generated by registering successive scans by simulating the motion of SphereX, (Bottom-Left) True and estimated position of the robot, (Bottom-Right) True and estimated quaternions of the robot calculated using the ICP algorithm.

**Conclusion:** Detailed conceptual studies on the design of SphereX and accompanying lander are ongoing using a multidisciplinary design optimization approach. Although our results show feasibility of this design, significant challenges remain in the development of the propulsion system and integration of all the subsystems inside such a small volume.

**References:**

[1] Scientific Goals and Pathways for Exploration of the Outer Solar System (2006). [2] Wagner R. V. et al. (2014) *Icarus,* 237. [3] Robinson M. S. (2010) *Space Science Reviews,* 150 81-124. [4] NASA Space Technology Roadmaps and Priorities Revisited (2016). [5] Thangavelautham J. et al. (2014) *2nd International Workshop on Instrumentation for Planetary Missions*. [6] Kalita H. et al. (2020) *IEEE Aerospace*. [7] Kalita H. et al. (2019) *70th IAC*. [8] Kalita H. et al. (2019) *Advances in Astronautical Sciences*. [9] Kalita H. et al. (2020) *AIAA SciTech*.

**MOON DIVER: JOURNEY INTO THE ANCIENT LAVAS OF THE MOON.** L. Kerber[1] and the Moon Diver Team [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA (kerber@jpl.nasa.gov)

**Introduction:** In 2009, the Japanese spacecraft Kaguya discovered several holes in the surface of the Moon [1]. Some of these holes are more than 100 m deep, and open into large caverns extending an unknown distance beneath the lunar surface [2–3]. Hypothetical lunar lava tubes may provide beneficial locations for future habitation: the caves offer protection from radiation, a shield from micrometeorites, and, with a predicted constant temperature of ~20°C, they provide refuge from the extreme temperature swings of the lunar surface [4–5]. Scientifically, the treasure is found within the walls of the pits: the exposure of near-vertical cross-sections through the Moon's uppermost crust, extending from the top of the regolith, through the regolith/bedrock transition, and through up to 70 m of intact lunar mare bedrock layers [2–3].

The *Moon Diver* mission concept proposes to use the extreme terrain Axel rover [6] to descend into the lunar mare (**Figure 1**), using a pit in Mare Tranquillitatis as a natural drill hole with which to access an unprecedented exposure through the regolith and bedrock of the Moon's secondary crust. At the bottom of the pit wall, *Moon Diver* will peer into a lunar cavern, and become the first mission ever to venture beneath the surface of another world.

**Science Goals:** *Moon Diver's* science goals are to understand the formation and evolution of the Moon's secondary crust. The Moon provides an especially useful example of secondary crust formation since (unlike the Earth and Venus) it is one of the few places where resurfacing stopped before the primary crust was completely obscured—meaning that we can determine both the composition of the secondary crust as well as the composition of the original crust through which it was emplaced. The relative geological simplicity of the Moon means that the evidence of these processes can be exquisitely preserved for billions of years. *Moon Diver*'s science objectives, derived directly from community documents [7–8], are to: **(1)** Determine the extent to which the regolith is representative of the underlying bedrock. **(2)** Determine whether the mare basalts were emplaced massively in turbulent flows, or if they were emplaced incrementally in smaller, but more numerous complex or inflated flows. **(3)** Determine the composition(s) of the parental magmas of the exposed basalts and what they tells us about the magma source regions in the lunar interior.

**Figure 1. Representation of the Axel rover rappelling into a lunar pit (left) and exploring the cavity below (right) as part of the *Moon Diver* mission.**

These objectives will be met by scaling the cross-section exposed in the wall of a mare pit, where both the process of regolith formation and the sequence of mare lava formation can be understood in their full contexts. Required measurements include:

**(1)** Elemental and mineralogical assessment of the regolith and the underlying basalts.

**(2)** Macro- and microscale physical characterization of the regolith up to and including the transition to the first bedrock layers.

**(3)** Assessment of macroscale lava flow morphology and microscale flow textures, lava layer thicknesses, and lava composition in order to determine lava flow rates.

**(4)** Chemical, mineralogical, and textural characterization of lava layers to constrain their petrologic origins.

**Science Implementation:** *Moon Diver* combines classic measurement techniques with a novel mobility system to achieve its ambitious science objectives. To make the measurements described above, the rover carries a suite of three simple instruments: (a) a trio of high-resolution cameras (Mars 2020 EECAM heritage [9]) to capture the macroscale morphology of the regolith and near and far pit walls with 20 megapixel color stereo images, (b) an Alpha-particle X-ray Spectrometer (APXS; MSL heritage [10]) to measure the elemental composition of both regolith and lavas, and (c) a multi-spectral microscopic imager (MMI) that uses controlled LED lighting to characterize grain, vesicle, and crystal size as well as capturing spatially resolved mineralogy [11]. The rover also carries a surface preparation tool, which creates a fresh, flat surface for the instruments to examine when needed.

**Mission Implementation:** Access to the record exposed in the wall of the target pit is provided by two key technologies: pinpoint landing (allowing the delivery of the payload close to the pit) and extreme terrain mobility (allowing the delivery of the instruments to the cliff wall to make their measurements).

Pinpoint landing uses Terrain Relative Navigation, similar to Mars 2020, which allows the spacecraft to recognize landmarks on the surface and adjust its trajectory to land extremely accurately [12]. It is expected to be even more accurate on the Moon in the absence of an atmosphere.

The extreme terrain mobility is provided by the Axel rover, which descends from the lander, rolls across the surface, and rappels down into the pit [6]. The lander provides mechanical support, power, and communication with the rover through its tether. The rover houses a winch on board, which pays out the tether as Axel moves. The instruments are housed inside Axel’s wheel wells, where they are protected from the environment. The wheel wells rotate independently from the rover’s wheels, allowing the surface preparation tool, the MMI, and the APXS to be placed on the same target with a high degree of accuracy [6]. Axel's simple design protects its instruments and makes it robust to the challenges of navigating a steep wall of lava layers.

**Field Preparations:** To test the mission concept and develop procedures for operating the rover and instruments in a lunar pit environment, a prototype of the Axel rover was outfitted with a suite of representative instruments: commercial equivalents of the EECAMs and APXS and a brassboard version of the MMI. This integrated suite was deployed to a terrestrial analogue site: a steep-sided basaltic collapse pit in Arizona called "Devolites Pit" (**Figure 2**). The rover was driven from a remote “mission” control, navigating the flat, funnel, and wall portions of the pit and taking representative science measurements along the way. Another field test was conducted in September 2019, where Axel rappelled down a near-vertical basaltic cliff (**Figure 3**).

**Implications:** The terrestrial planets are dominated by secondary crust. Understanding the process of secondary crust formation on the Moon, where there are fewer unknown or confounding variables, can provide a keystone for understanding crustal formation on other bodies [13]. In particular, planetary flood basalt flow rates currently have an uncertainty of many orders of magnitude, ranging from slow, laminar flows to fully turbulent flows. The measurements taken by *Moon Diver*, such as accurate flow thicknesses, could reduce this uncertainty for lunar basalts by up to seven orders of magnitude.

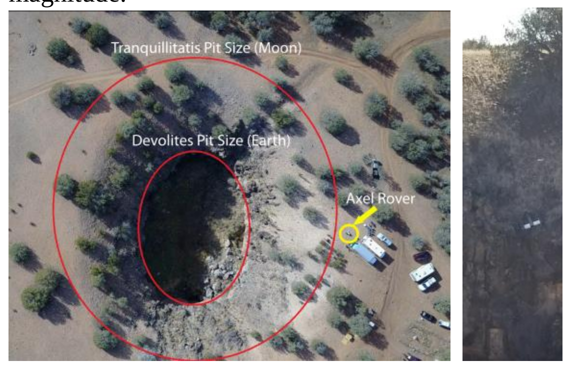


**Figure 2. Left: Field test site. Red circles show size of terrestrial versus lunar pits compared to the Axel rover (yellow). Right: The Axel rover on a vertical basalt wall.**

**Figure 3. Field test site at Fossil Falls, California. The Axel rover on a vertical basalt wall.**

Similarly, an examination of regolith formation and evolution from the surface to bedrock on the Moon, in concert with accumulated knowledge from *Apollo* and *Luna* samples, lunar meteorites, and remote sensing datasets, would help us interpret this process on other airless bodies where only remote datasets are available or where samples are available without contextual information.

**References:** [1] Haruyama, J., et al. (2009) *GRL 36*, L21206 [2] Robinson, M.S. et al. (2012) *PSS 69*, 18–27. [3] Wagner, R.V., Robinson, M.S. (2014) *Icarus 237*, 52–60. [4] Hörz, F. (1985) *Lunar Bases & Space Act. of the 21st Cent.*, pp. 405–412. [5] Haruyama, J. et al. (2012) *Moon*. [6] Nesnas, I., et al. (2012) *J. of Field Robotics 29*, 663– 685. [7] Abell et al., (2016) *Lunar Expl. Roadmap*. [8] NRC (2007) *Sci. Context for Expl. of the Moon*. [9] Singh, K., et al. (2017) *47th ICES* Abs. 212 [10] Gellert, R. et al. (2015) *Elements 11*, 39–44. [11] Nunez, J. et al. (2013) *Astrobiology 14*, 132–169. [12] Johnson, A. E., & Montgomery, J. F. (2008) *IEEE Aero.* (pp. 1–10). [13] Taylor, S.R. (1989) *Tectonophysics 161*, 147–156.

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**THE GEOLOGIC CONTEXT OF MAJOR LUNAR MARE PITS.** L. Kerber[1] L. M. Jozwiak[2], J. Whitten[3], R.V. Wagner[4], B.W. Denevi[2], , The Moon Diver Team. [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, 91109 (kerber@jpl.nasa.gov). [2]Johns Hopkins Applied Physics Laboratory, Laurel, MD, 20723, [3]Tulane University, New Orleans, LA, 70118, [4]Arizona State Univeristy, Tempe, AZ, 85287.

**Introduction:** In 2009, the Kaguya spacecraft discovered several large pits in the lunar surface [1]. Later Lunar Reconaissance Orbiter Camera (LROC) images captured these pits in greater detail, revealing that some of them expose tens of meters of in-situ lava bedrock cross-sections in their walls [2,3]. Such exposures offer tantalizing natural drill-holes through the regolith and into the lunar maria. In particular, the pits provide the opportunity to examine maria deposits from the top of the regolith, through the regolith/bedrock interface, and finally to exposed in-situ bedrock layers [4].The exploration of such an exposure would allow for the investigation of several key questions, including (1) how the regolith is generated from the original rocky surface [5], (2) how the mare lavas were emplaced (the true thickness of indivudual lava flow units and indications of their instantaneous flow velocities) [5], and (3) the effects of flow and in-situ fractionation on our understanding of the compositions and petrologic origins of the mare basalts [5].

While these three processes could be investigated at any mare pit having steep walls with exposed layering, the variation in exposure and geologic context among the pits means that each would provide additional, unique information about a specific region of the Moon. In this contribution, we discuss the geologic context for six of the larger pits, including pit geometry, regional geologic setting, and regional mare composition and expected exposure. We use this information to assess the exploration potential of each pit, and make suggestions about the potential contributions that each would offer to lunar science.

**Lunar Pits:** While analysis of the lunar surface has revealed 15 mare pits [3, 6] we focus here on six pits that show potential for significant cross-sectional exposure of mare layers: Lacus Mortis, Central Mare Fecunditatis, SW Mare Fecunditatis, Mare Ingenii, Marius Hills, and Mare Tranquillitatis (the pits do not presently have IAU approved names, and are instead canonically referred to using the name of the larger geologic region within which each pit is located [3]).

*Lacus Mortis*: The Lacus Mortis pit is the widest mare pit so far identified on the Moon, with dimensions of 140 x 110 m [3]. The north and south sides of the pit have a rounded regolith surface leading into exposures of layered wall units. The east and west sides of the pit are dominated by regolith slumping and talus features that extend into the pit, forming inclined surfaces [7]. It is unclear whether the pit leads to a subsurface void [3]. The pit is located a few kilometers to the west of the Rimae Burg graben, and could be related [7]. Compositionally, the pit is located in a deposit of low- to very low-Ti and high $Al_2O_3$ lavas that extend from Lacus Mortis across the larger Mare Frigoris region [8]. The Lacus Mortis region itself is a small, semi-circular mare deposit to the south of Mare Frigoris, and appears to be composed of a single basaltic unit [8]. The Lacus Mortis pit would provide access to 5-6 layers of undersampled Al-rich lavas [8]. While the layers may represent several flow events, they may not expose different flow compositions.

*Central Fecunditatis:* Mare Fecunditatis, a non-mascon pre-Nectarian impact basin [9], contains two mare pits, one in the central region of the basin and a second to the southwest. The basin contains predominantly low- to intermediate-Ti basalts [10].

The larger of the two Mare Fecunditatis pits has a similar geometry to the Lacus Mortis pit in that mare basalts are partly exposed in three-quarters of the pit walls while one quarter of the pit wall is dominated by a large slump of regolith material that extends from the surface regolith to the bottom of the pit. The pit itself is 130 x 110 m, while the outer funnel is 190 x 160 m. Shadow measurements indicate the pit has a total depth of ~45 m [3]. It does not lead to a sublunarean void. The surrounding region is relatively flat, almost equidistant between Messier B crater and a wrinkle ridge ~14 km to the east. The regolith surrounding the pit is likely contaminated by the ejecta of Messier and Messier B. The pit is located in a more Ti-rich region of the basin, with intermediate-Ti values.

*SW Fecunditatis:* While SW Fecunditatis is smaller, with a central pit opening of only 16 x 14 m, it is comparable in central pit depth (~35 m vs. ~30 m) to Central Fecunditatis. The total depth of the SW Fecunditatis pit (central pit and funnel) is closer to ~75 m. This pit is located on a large hummocky kipuka at the edge of Mare Fecunditatis, east of several large graben (e.g., Rimae Gloclenius). Available LROC imagery indicate that there is a void space ~7 m beyond the edge of the pit [3]. The upper walls of SW Fecunditatis are predominantly covered with regolith, obscuring any exposures of mare basalts in the pit walls and reducing the exploration potential of this pit. Based on the LROC $TiO_2$ map [10], the basalts of SW Fecunditatis are considered low-Ti basalts.

*Mare Ingenii:* The Mare Ingenii pit is located in southern Mare Ingenii in Thomson M Crater, on the far side of the Moon.. The pit is 100 x 68 m, 45-65 m deep, and exposes a very low-Ti unit [3, 10]. Three separate basalt units were mapped in Thomson M by [11], and it is unclear how many discrete units may be exposed by the pit. Additionally, the pit is located within a lunar swirl [12]. Lavas exposed at Ingenii would be a good exploration target for investigating farside magmas as well as the potential three dimensional structure of a lunar swirl. However, the pit's location on the far-side makes this pit a logistically difficult target.

*Marius Hills:* The Marius Hills pit is located in one of the most volcanologically diverse regions of the Moon. The pit is located in the bottom of a sinuous rille, which may have contained some of the most turbulent lavas on the Moon [13]. This sinuous rille is surrounded by volcanic domes, which may represent the most viscous lavas on the Moon [e.g., 14]. The pit is approximately 58 m x 49 m, and 40 m deep with approximately 23 m of lava layers exposed in the walls [3]. The pit is located in intermediate-Ti lavas comprising the oldest regional stratigraphic unit [15], and the further location within a sinuous rille make it possible that the entire exposed stratigraphy was emplaced during the same event as the sinuous rille. The Marius Hills pit leads to a void with a significant overhang (12 m; [3]), and has been the subject of several studies trying to determine the presence and extent of a large subsurface void [16-17]

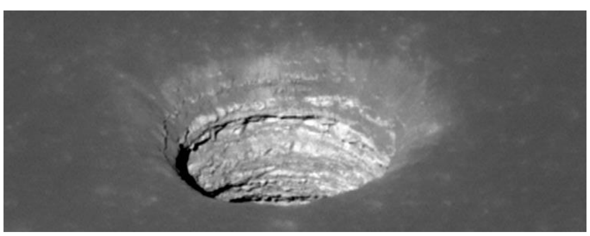

**Fig. 1.** An oblique view of the Mare Tranquillitatis Pit (100 x 88 m) showing the layers exposed (LROC image M144395745L)

*Mare Tranquillitatis:* The final pit is located in southeast central Mare Tranquillitatis (100 x 88 m and 105 m deep, with a ~20 m overhang; [3]). Mare Tranquillitatis is well known for titanium-rich lavas, sampled by Apollo 11 and Apollo 17 [17]. Multi-spectral analysis of the basin using Clementine data divided the basin lavas into four [19] or five [20] units, varying from low-Ti to very high Ti The pit is located right on a boundary where very high-Ti lava embays a kipuka of older, high-Ti lava. Because it is so close to the boundary, the pit should expose both units, which are compositionally distinct (high-Ti compared with very high-Ti) and significantly different in age (3.67 Ga compared with 3.85 Ga [19]). This age difference increases the likelihood that a paleoregolith layer would be encountered. The total depth of the lavas in this region of the basin was recently estimated to be ~200-400 m [21], meaning that a 111 m pit would sample a significant way through the total depth of the mare layers in this region.

**Analysis and Implications for Exploration:** Out of all of the pits, the Tranquillitatis pit provides the most compelling case for exploration. First, the surrounding flood basalts display a "classic" morphology, forming flat plains without clear flow boundaries or unusual morphologies. In this way the morphology can be considered "representative" of flood basalts broadly across the Moon. Second, the pit would provide a way to test theories of lateral regolith mixing, since it is distant from the highlands, but close to an internal mare boundary between two lava types. Third, since the pit it is located where one flow embays enother, the lateral location of the cross-section within the top flow is known, making interpretations of its morphology more straightforward. Finally, both of the pit's likely exposed lava types have been spectrally linked to basalt fragments in the Apollo 11 sample collection [19]. This means that as each lava was identified, it could be directly compared to an existing returned sample, multiplying the benefits of the in-situ payload by combining the original emplacement context of the lavas with the in-depth sample analysis done on the Apollo 11 samples [22].

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**BIOTIC INFLUENCE ON SPELEOTHEM MORPHOLOGY** C.A. Lakrout[1], E.J. Goldfarb[1], T.R.R. Bontognali[2,3,4], and N. Tisato[1] , [1]Jackson School of Geosciences; The University of Texas at Austin clakrout@utexas.edu. [2]Space Exploration Institute [3]Environmental Science Center; Qatar University. [4]Department of Environmental Sciences; University of Basel.

**Introduction:**

Researchers are interested in bio-mediated mineral formations in subterranean environments. Studying life in harsh conditions can provide information about habitability and mineral-life interactions in extreme environments. These can be analogues for life-related processes on other planets.

One example of such a harsh environment is a cave in France (Asperge), which contains mineral deposits (speleothems) called helictites (Figure 1A). Helictites grow in an area of Asperge with little water, no light, and heavy concentration of metals in the rocks. Such an environment would not appear to favor life.

Two specific helictites morphologies from Asperge are of interest for our research and are known as acicular and tubular. The former is made of aragonite with fibrous elongated crystals and is not hollow [1] (Figure 2A). The latter is composed of calcite crystals that form a relatively hollow tube with distinctive hexagonal crystals (Figure 2B). These formations are of interest because they are seemingly rare and, until 2015, the mechanism leading to their genesis was unclear.

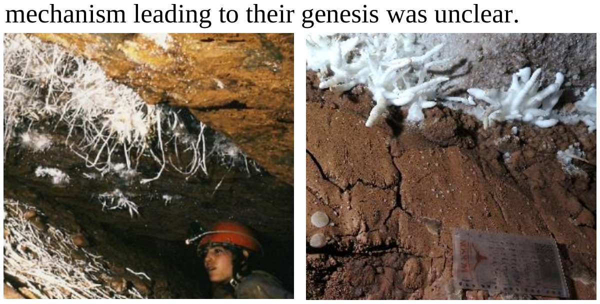

*Figure 1A (left): Speleothems in Asperge, France [2]. Figure 1B (right): Speleothems in Breezeway, Colorado. Notice the surrounding white dots in the soil.*

The Asperge speleothems were analyzed by Tisato et al. in 2015 who proposed that the formation of tubular concretions is orchestrated by life [2]. However, relatively little is known about the origin of these biologically-mediated deposits. Similar speleothems to those from Asperge have been observed in a cave in Colorado (Breezeway; Figure 1B). Proving a common nature for both the Breezeway and Asperge speleothems would provide a strong argument for the bio-mediated formation of helictites.

Here, we report analyses on speleothems from Breezeway. Such a cave has even less water than Asperge, no light, and the helictites appear to grow on a paleo-laterite, a paleo soil with a high concentration of iron and aluminum. We show that just like Asperge, Breezeway contains helictictes that are associated with distinctive bio signatures.

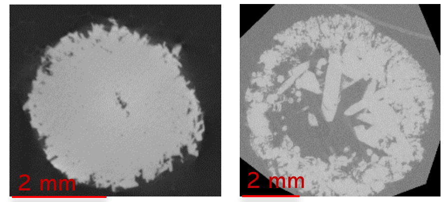


*Figure 2A (left): Acicular sample from Breezeway. Inside of the speleothem is filled in.*
*Figure 2B (Right): tubular sample from Breezeway. Inside is hollow.*

**Hypothesis:**

Due to the morphological similarity, we hypothesize that like the speleothems in Asperge, the mineral deposits from Breezeway have formed biotically. We can prove this by examining micro-computed tomography (micro-CT) scans, high resolution images, morphologies of our speleothems and analyzing for biotic films, textures, and chemical elements.

**Materials Methods:**

We collected 36 samples from Breezeway in May 2017. All samples were collected from the floor of the cave. On five of these samples we performed the following analyses:

1) X-ray diffraction to study mineralogy of the speleothems;
2) Micro-CT to study morphologies of speleothems;
3) Scanning Electron Microscopy (SEM) to investigate the presence of biofilms and biologically mediated structures;
4) SEM Energy Dispersive Scanning (SEM-EDX) to analyze the mineralogy of specific micrometric volumes of the samples.

Micro-CT scans were captured with a voltage of approximately 200 kV and a current of approximately 85 µA. Apparent voxel size is 18.5 microns per voxel. The scan was corrected for beam hardening. [3]

Sample mineralogy was measured from X-ray Diffraction (XRD). A few milligrams of an acicular and tubular sample were hand ground and placed on a tray and analyzed with a voltage of 45 kV and current of 40 mA. The sample patterns were recorded from 4° to 60° with a 0.02 stepsize.

Scanning Electron Microscope (SEM) analyses were performed with a Zeiss at the Bureau of Economic Geology UT Austin at multiple image scales, with EHT at 4 kV.

**Results:**

Visual inspection of in-situ concretions reveal the presence of millimetric bristled white dots (Figure 1B) covering the walls. Such dots, like in the case of Asperge, are present only in proximity of the speleothem site and have been identified as bio colonies [2].

XRD analyses indicate that acicular and tubular samples are composed of aragonite and calcite, respectively, similar to the Asperge speleothems.

The CT scans highlight the tubular and acicular nature of the speleothems. Given the large hole in the tubular concretions we can rule out that they formed abiotically [2]. On the other hand, acicular concretions present a micrometric center-tube supporting the hypothesis that acicular speleothems form abiotically [2]. In these scans, we can observe that calcite crystals of tubular concretions are covered by a "low-density" layer. Such a layer is tens of microns in thickness and was further investigated with SEM imaging.

SEM imaging of tubular samples revealed the presence of biofilms and mineral structures likely related to biological activity (Figure 3). Such features covering the calcite crystals are the "low-density" layer observed with the CT-scan. Few evidences of biological activity on acicular speleothems were also collected.

**Discussion:**

In the SEM images and EDX analyses of the tubular samples, we observe what we interpret as calcite "construction-sites" covering calcite crystals (Figure 4). It appears that crystals are in the process of growing by addition of calcite flakes. Small filaments create bridges between the calcite "flakes" within the "low-density" layer and the calcite crystals (Figure 3). Probably, these filaments are extracellular polymeric substances (EPS), which is a remnant of microbial life activity [4].

On most of the acicular sample surfaces no EPS was observed, and we see pristine aragonite needles. However, on an acicular sample, we observed what appears to be EPS. Such EPS is in the proximity of weathered Aragonite. We suggest that such EPS might represent the initial stages of the microbial colonization of an abiotic speleothem.

**Conclusion**

This research furthers the understanding that life exists in extreme environments. Understanding how life can thrive in these conditions is a starting point for the study of life on other planets. This research offers evidence of how life could manifest in the rock record. Given that caves are present on Mars and other planetary bodies, we suggest a potential way to search for past or present evidence of life in the geological record.

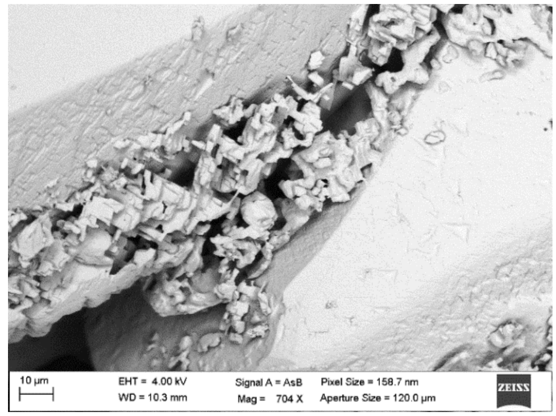


*Figure 3: SEM image of tubular Breezeway sample.*

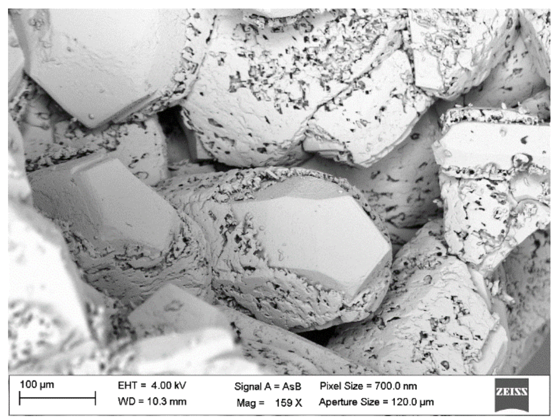


*Figure 4: SEM image of tubular Breezeway sample.*

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**ICE-RICH CAVES ON THE MOON AND MARS: PROSPECTS AND PRAGMATIC RECOMMENDATIONS FOR EXPLORATION.** Pascal Lee[1], [1]Mars Institute, [2]SETI Institute, [3]NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000, USA. E-mail: pascal.lee@marsinstitute.net.

**Summary:** We synthesize lessons learned from our recent studies of lava pits and caves on the Earth, Moon and Mars, and of promising technologies to explore these, and offer recommendations for the future.

**Pits/Caves & Lava Tubes on the Moon & Mars:** Over 300 pits have been identified on the Moon [17,35,36]. The USGS' Mars Global Cave Catalog lists over a thousand pits and candidate caves [12]. The vast majority of planetary pits are associated with lava cavities, mostly volcanic or impact melt lava tubes. Some pits on Mars are of volcano-tectonic origin [9,11]. None are likely from speleogenesis in karst.

Most pits and caves identified on the Moon are within 60° of the equator, a biased distribution reflecting an inherent limitation in the automated approach used to identify lunar pits [35]. While still geologically interesting, low latitude pits/caves are not expected to be cold enough to cold-trap $H_2O$ ice, mainly because their warm sunlit floors would radiate substantial heat into adjacent cave volume. However, we recently identified candidate impact melt lava tube skylights on the floor of Philolaus Crater (D~70km, 72.1°N,32.4°W), 800 km from the lunar North Pole [23,24]. If confirmed, these skylights would be high enough in latitude to have permanently shadowed floors as cold as the poles' Permanently Shadowed Regions (PSR).

**Terrestrial Analogs:** Lava tubes on Earth, including collapsed ones, are analogs for *sinuous rilles* and *pit crater chains* on the Moon and Mars [33,14,8,24]. To understand better if and where $H_2O$ ice might occur inside lava tubes on the Moon and Mars, and how it might be explored, we investigated the Lofthellir Lava Tube Ice Cave, Iceland, and mapped it in 3D with a drone-borne LiDAR [25,26] **(Fig. 1).**

**Water Ice in Lava Tubes:** Because subsurface cavities on planetary bodies offer shelter from ionizing radiation, meteoritic bombardment, drastic diurnal temperature variations, and surface dust transport, they represent environments radically different from the surface. Caves on Earth may be repositories of perennial $H_2O$ ice even if external conditions preclude stable surface ice year-round [1,16]. Analogously, some caves on the Moon and Mars might be volatile-rich.

Building on previous studies of thermal conditions inside planetary lava tubes [21], we find that for high latitude skylights on the Moon with permanently shadowed floors, the portion of the cave immediately below the skylight achieves the coldest temperatures (T~40-60K), as the open sky overhead maximizes radiative heat loss. If $H_2O$ is available in sufficient amounts, $H_2O$ ice will accrete immediately below the pit, forming a cap of ice over any existing debris pile on the pit floor **(Fig.2).** Over time, with continued $H_2O$ supply, cold-trapping of ice would expand laterally into the subsurface cavity beyond the skylight area.

At Lofthellir, where most of the $H_2O$ ice is exogenic, derived from atmospheric $H_2O$ either as water vapor or by meteoric precipitation followed by infiltration [25,26], there is ample supply of $H_2O$, and large ice masses occupy the cave. Our field study revealed that this ice is dynamic, forming micro-glaciers with accumulation, flow and ablation/melt zones, and moraines. The rockfall debris loads carried by some micro-glaciers qualify them as *micro- rock glaciers*.

On the Moon, it remains unknown if sufficient $H_2O$ ice mass would accumulate inside high-latitude lava tubes to allow it to creep under its own weight given the extremely low temperatures. The candidate pits in Philolaus and associated rilles are narrow (<50m across), implying small lava tube volumes and limited ice masses per unit section [25,26].

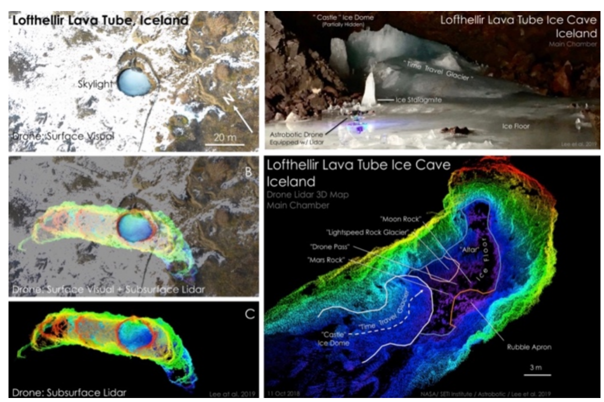


**Fig. 1:** Lofthellir Lava Tube Ice Cave, Iceland. **L**: Drone + LiDAR 3D mapping of skylight area. **R: Top**: Micro-glaciers. **Bot**: Main chamber LiDAR map [25,26].

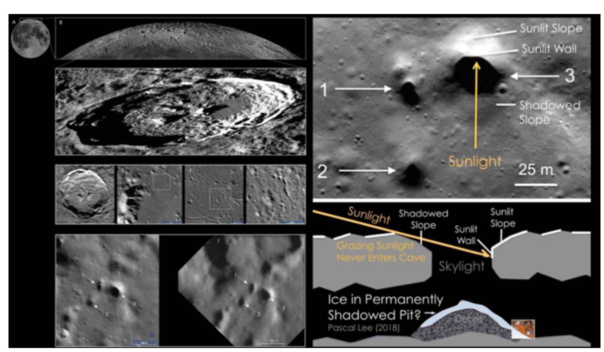


**Fig. 2.** Candidate permanently shadowed impact melt lava tube pits (skylights) in Philolaus Crater near the North Pole of the Moon. [23,24].

On Mars, the possibility of ice caves has also been proposed [e.g.37]. Because Mars has a substantial, $H_2O$-saturated atmosphere that provides an exogenous source of $H_2O$ [e.g.,22,2,3,30], and because its giant volcanoes might still be active and release endogenic $H_2O$ [e.g.,30], lava tubes on Mars, even at high altitude, are likely to harbor $H_2O$ ice. The protracted history of glaciation on Mars, including on Tharsis volcanoes, further raises chances that some Martian lava tubes may be long-term repositories of ice [18,32,34].

**Astrobiology Potential:** Lava tubes on Mars have significant astrobiological potential [e.g.,15,4,10,29]. The likely association of volatiles with these caves strengthens their potential for harboring biosignatures, including of extant life. Given the biocidal agents acting on Mars at present, the Martian surface is likely sterile, and the sheltered, warmer, wetter subsurface is a more likely place where extant life might be found. Finding extant life, more so than fossils, is critical to deciding whether any biosignature found is alien or not, as analysis of fresh genetic material must be performed in order to establish alien phylogeny. While lower mass and cost deep drilling technologies might one day be deployed on Mars [20], caves offer immediate ways of exploring the subsurface for alien life.

**Resources & Habitability of Lava Tubes:** The exploration of lava tubes should also be of high priority in the context of human exploration. Lunar circumpolar caves cold enough to cold-trap $H_2O$ ice would offer a valuable non-polar option for $H_2O$ ice ISRU.

Lava tubes have also been proposed as "ready-made" safe havens that humans could occupy for habitation and settlement [e.g.,19,7]. However, this prospect is likely not as realistic - because not as necessary -, as often assumed. On Earth, while humans have a long history of inhabiting caves, most caves used were in karst, not lava tubes. Lava tubes have rarely been used for extended stays, for three main reasons: i) There is often no source of liquid water nearby, in contrast to karst caves which, by definition, form *by* liquid water flow; ii) Lava tubes are significantly more hazardous than karst caves, as they are more prone to rockfalls, mainly because the formation of lava tubes involves drastic cooling and contraction of initially molten rock, which produce highly fractured walls and ceilings. Susceptibility to collapse is exacerbated by the fact that volcanic regions are generally also seismically active; iii) Because of their history of collapse, lava tube surfaces are often extremely rough and their floors difficult to traffic. Lava tubes with smooth, glassy walls, are uncommon.

The above three issues would persist on the Moon and Mars, where meteoritic impacts are an extra cause of continual fracturing and instability. If ice is present, a valuable resource would be on hand, but as we observed in Iceland, ice accretion increases gelifraction, which then promotes rockfalls. For ice-rich caves on Mars, acute planetary protection concerns also arise. More importantly, the main advantages of a planetary cave (shielding from ionizing radiation [13] and temperature swings) are easily and safely achieved by burial of habitat structures under regolith "sand bags".

**Robotic and Human Exploration:** Access and exploration of pits on the Moon and Mars pose an exciting challenge. Classical robotic mobility systems proposed for pit and cave exploration, such as autonomous rovers and walkers, direct landers, tethered robots, and danglebots, all involve substantial complexity and risk, including the need to interact carefully, and thus slowly, with ground and wall obstacles. Slow is not good, as access to lasting power and comms while caving are limited. Drones have been proposed (gas thrustered flyers or rotorcraft) as they offer the key advantages of being nimble, quick, and touchless [26]. However, as drones would still risk stirring up considerable dust, another promising approach is proposed with JPL's GlobeTrotter universal soft hopper concept [27,28] **(Fig.3)**. Given the multitude of caves on the Moon, Mars, and beyond, such a universal, low cost, robust robotic approach to exploring caves, with human follow-up as required, is recommended.

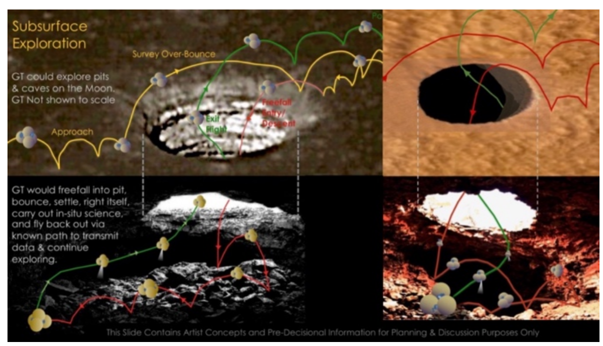


**Fig.3**: GlobeTrotter Soft Hopper Cave Explorer Concept.

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**MARTIAN CAVES AS SPECIAL REGION CANDIDATES.** Javier Martin-Torres[1,2], Patrik Olsson[1], Maria-Paz Zorzano[3,1], Anshuman Bhardwaj[1], Lydia Sam[1], and Shaktiman Singh[1]; [1]Division of Space Technology, Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Luleå, Sweden, [2]Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR), Armilla, Granada, Spain, [3] Centro de Astrobiologia (INTA-CSIC), Torrejon de Ardoz, Madrid, Spain

**Introduction:** Sub-surface lava tubes, cavities and caves have been found on Mars. Past volcanism and its gradual interactions with aeolian processes have played a vital role in Martian landscape evolution and possible cave formations. With the possibility that future Mars missions might be focussing more on the subsurface exploration, Martian lava fields and associated caves appear to be interesting targets for astrobiological, geomorphological, and in-situ resource utilization (ISRU) research. However, as their detection presently relies on multiple observations from orbiters, there is limited knowledge about their environmental conditions. At most, only the temperature and thermal inertia are the two vital environmental parameters which can be inferred from remote sensing observations. Furthermore, when the cave openings are small, their detection may not be possible due to the resolution limitation of visual camera observations. Their size, extension and structural durability is generally difficult to predict. However, caves are an interesting region for the future human exploration of Mars, as they provide a natural shelter from the very harsh UV, cosmic, and solar radiation. Thus caves display steady environmental, geophysical, and geochemical conditions supporting possible habitation in extreme extraterrestrial conditions.

**Caves as Special Region :**

The Committee on Space Research (COSPAR) Planetary Protection Panel has defined as Special Regions on Mars, those environments where the water activity may be above 0.5 and the Temperature above -25°C. These two environmental parameters are taken as reference to make large scale parametrizations on the planet and distinguish those regions where terrestrial microbial life may proliferate and thus where planetary protection measurements for landed missions should be more stringent. So far the environment of Martian subsurface caves has not been taken into account for these considerations. Given the perennially shaded character of subsurface caves their temperatures are expected to vary in a different way thus allowing for different relative humidity and temperature values. The relative humidity (RH%) is a critical environmental parameter, as in equilibrium, it defines the water activity of the regolith (a.w.=RH/100). Furthermore, the RH% is important to evaluate the potential of certain salts to hydrate or deliquesce and allow for brine formation.

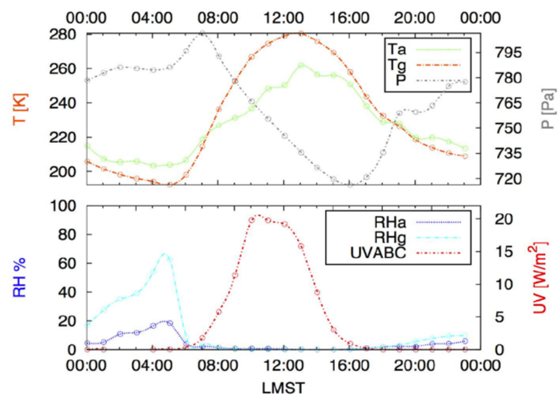


Figure 1. A typical Martin day on Mars as measured by the Rover Environmental and Monitoring Station (REMS) on the Curiosity rover. Ta: air temperature; Tg: grounf temperature: P: pressure; RHa: Air Relative Humidity; RHg: Ground Relative Humidity; UVABC: UV radiation [1].

**Main Results:** In the present work we present a study of the environmental conditions in Martian subsurface cavities such as caves and how it can be considered as Special Regions. For the calculations, we have used lava tubes observations made by Cushing and Titus [2] , and the environmental, near-surface observations of the Curiosity rover, at Gale crater (Fig. 1). Physical parameters considered in the model include size, shape, inclination, and composition of the walls of the caves.

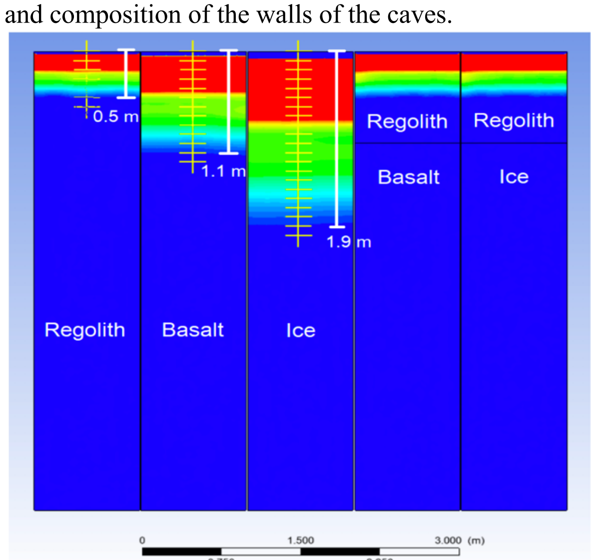


Figure 2. Computed Ground thermal wave penetration depth cross section for different materials inside the cave.

Some of the results are presented in Figures 2 and 3. One of the interesting results is that a cave roof with a thickness greater than 1-2 m reduces the amplitude of the ground temperature variation during the day and has a significant impact on the air temperature in the cave.

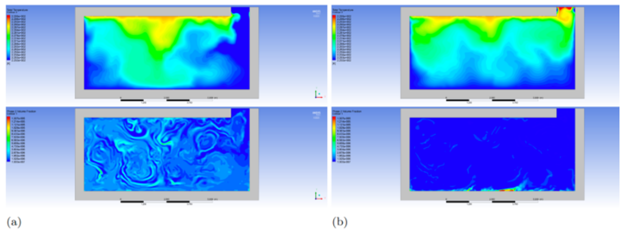

Figure 3. Top panels: Temperature; Lower panels: Relative Humidity at 3LMST (left) and 7LMST (right)

The average temperature and RH% throughout the entire models resulted in unfavorable conditions (relative humidity under 20% RH) to allow for brine formation. The most interesting results were found in smaller cave simulations where higher relative humidity was found for several hours during the same day. This happened at certain times during the day (LMST 7 and 17) when the inlet temperature surpassed the average temperature in the cave and resulted in relative humidity of up to 90% RH which potentially could allow Martian salts to form brines, or could at least keep them in a hydrated state throughout the day. On the other hand, while the low temperatures in today's Martian caves may be too harsh for life forms to exist, a previous warmer climate might have allowed for extremophiles to thrive in highly saline solutions within such caves, thus highlighting them as the potential astrobiological targets. As a future scope, we plan to model brine scenarios within caves using more combinations of environmental and physical parameters. The presence or absence of overlying dust or its thickness can also have significant effects on the subsurface environmental conditions and we plan to include this in future modelling attempts.

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**GEOMICROBIOLOGICAL FIELD RESEARCH IN A SUBSURFACE ANALOGUE ENVIRONMENT FOR FUTURE PLANETARY CAVES MISSIONS.** A. Z. Miller[1,2], J. L. Gonzalez-Pimentel[1,2], M. Maurer[3], S. Stahl[4], S. Castro-Wallace[5], L. Bessone[3], J. Martinez-Frias[6], F. Sauro[7], [1]HERCULES Laboratory, University of Évora, Portugal (anamiller@uevora.pt), [2]Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS-CSIC), Seville, Spain, [3]European Astronaut Centre (EAC), European Space Agency (ESA), Cologne, Germany, [4]JES TECH, Johnson Space Center (JSC), National Aeronautics and Space Administration (NASA), Houston, U.S.A., [5]Human Health and Performance Directorate, JSC, NASA, Houston, U.S.A., [6]Instituto de Geociencias, CSIC-Universidad Complutense de Madrid, Spain, [7]BIGEA, University of Bologna, Italy (cescosauro@gmail.com).

**Introduction:** A rapid expansion of interest in the geomicrobiology and exploration of subsurface environments, such as caves, has recently emerged to better understand origins of life on Earth and on other planets. Volcanic caves have lately received particular attention as similar cavities have been reported on the Moon and Mars [1]. Hence, caves on Earth are planetary analogue environments suitable for the training of astronauts, both from the science prospective and for technological testing, for future exploration missions to other planets.

In this sense, since 2011, the European Space Agency (ESA) holds astronaut training courses in caves, including the CAVES (Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills) and PANGAEA (Planetary ANalogue Geological and Astrobiological Exercise for Astronauts) programs.

Within the PANGAEA course, a geomicrobiology field training took place in 2017 in Lanzarote, Spain. This training involved the collection of microbiological samples in the Corona lava tube (one of the biggest volcanic caves known on Earth) and successive DNA-based analyses in the cave environment using fast and portable devices for DNA amplification and sequencing (Fig. 1).

**Advanced on-site DNA sequencing:** Samples of dark-colored microbial mats on the volcanic bedrock located in the twilight zone of the cave were collected by gently removing the microbial mat with sterile disposable scalpels and gathering it into sterile vials (Fig. 1A). Subsequently, DNA extraction was conducted using the DNeasy PowerSoil DNA extraction kit (Qiagen), followed by PCR amplification using the miniaturized and portable thermal cycler miniPCR (Amplyus), controlled from a laptop. Sequencing of the full-length 16S rRNA gene was conducted using the MinION (Oxford Nanopore Technologies - ONT) sequencer device attached to a laptop and using the operating software MinKNOW (ONT). Finally, taxonomic classification of generated reads was performed using the EPI2ME platform (ONT). These analyses took place in the module of the Lanzarote Geodynamic Laboratory (Fig. 1B,C) installed in the Corona lava tube, and currently managed by the Geopark of Lanzarote together with IGEO (CSIC-UCM).

A total of 9149 reads were obtained from the MinION sequencing and more than 8300 reads with the full-length of the 16S rRNA gene (approx. 1500 base pairs) were analyzed for microbial diversity. Proteobacteria dominated in this cave ecosystem. Most of the DNA sequences (>35%) were affiliated to *Salinisphaera halophila*, a moderately halophilic bacterium belonging to the Gammaproteobacteria class. Of note is the presence of abundant deposits of gypsum, halite and clay minerals associated with the dark-colored microbial mats, as revealed by in-situ V-NIR spectroscopy and laboratory XRD analyses [2].

**In-depth laboratory analyses:** Replicate samples of the dark-colored microbial mats were analyzed under laboratory conditions for comparison purposes. The extracted DNA was analyzed with next-generation sequencing (NGS) of the bacterial V3 and V4 regions

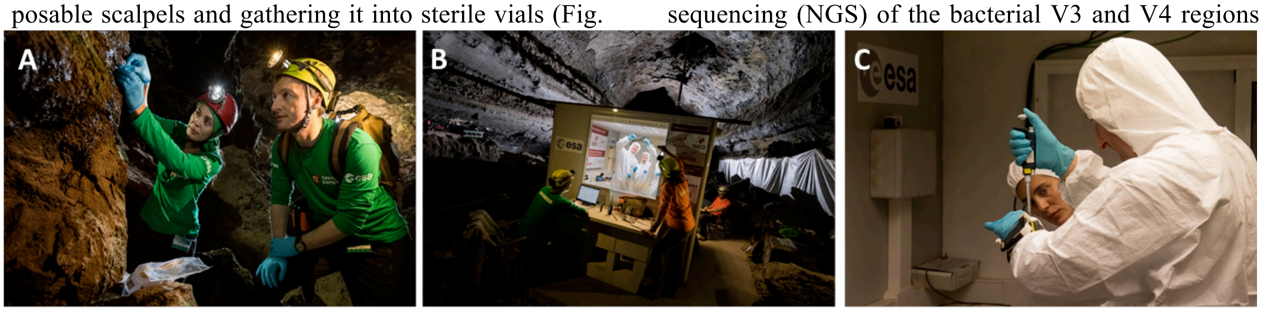


*Figure 1. Sampling of microbial mats (A) and in-situ DNA analysis in the Corona lava tube (B,C).*

of the 16S rRNA gene using the Illumina MiSeq platform by STAB Vida sequencing services (Portugal). Raw data was processed in Qiime2, which includes the DADA2 algorithm, for optimal quality control without clustering. Classification of the reads was based on the ARB-SILVA SSU database, and further analyzed and visualized using the online web-tool Calypso.

In addition, microbial mat samples were investigated by field emission scanning electron microscopy with energy dispersive X-ray spectroscopy (FESEM-EDS) using a FEI Teneo microscope equipped with an Ametek EDAX detector.

Phylogenetic analysis based on 16S rRNA gene sequences showed that the microbial mat samples are dominated by *Salinisphaera* sp., followed by *Halococcus*, a genus of extreme halophilic archaea. These results are in line with the in-situ DNA-based analysis and are consistent with the mineralogical composition of the rock substrate.

FESEM-EDS observations revealed abundant microbial cells, comprising short rods of approximately 1 μm long and 0.4-0.6 μm wide, and coccoid cells with less than 1 μm in diameter and septum formation (Fig. 2). Their size and morphology resemble those of *Salinisphaera halophile* [3], and Halocccus [4], respectively.


Figure 2. FESEM image of the dark-colored microbial mat sample depicting

**Conclusions:** Our field experiment revealed halophilic microorganisms associated with gypsum and halite, suggesting they are capable of adapting to this cave environment and to interact with secondary minerals. In addition, this study showed that subsurface environments in general and lava tubes from Lanzarote in particular offer one of the best possible terrestrial analogue sites to search for extremely specialized microbial life and to test new approaches to planetary science investigations, helping to understand the geological and potential microbial processes on Mars.

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**JPL R&D FOR DEEP EXTRATERRESTRIAL CAVE EXPLORATION.** K. L. Mitchell, L. Kerber, M. J. Malaska, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 183-601, 4800 Oak Grove Drive, Pasadena, CA 91109, Karl.L.Mitchell@jpl.nasa.gov.

**Overview:** The discovery of craters indicating the presence of lava tubes on Moon [1,2] and Mars [3] opens up a new frontier for exploration of benefit to both planetary science and human exploration. However, accessing their riches presents a series of technical challenges. A 2014 joint study between Jet Propulsion Laboratory (JPL) and New Mexico Tech (NMT) identified six areas of technological fidelity (see table 1) that would be required to reach a technology readiness level (TRL) of 6 before exploring deep inside an interplanetary cave. Significant advances against these areas have been achieved at JPL both in development of the Moon Diver mission [4] and in a series of individual projects funded both internally and via ROSES R&A programs, including NIAC and PSTAR. Activities continue, with increasing emphasis on demonstrating approaches in terrestrial caves and developing fully integrated resilient semi-autonomous robotic systems for deep cave exploration.

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**Additional Information:** This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. Government sponsorship is acknowledged, in the form of a JPL Center for Academic Partnerships grant. We are grateful to Penny Boston and her former team at NMT, and numerous JPL engineers, for fruitful discussions.

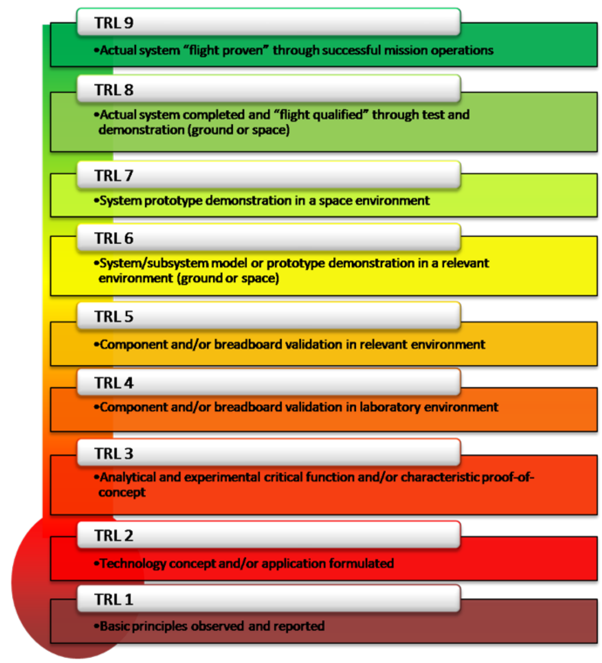


Fig. 1: NASA Technology Readiness Levels. Source: https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

Table 1: Extraterrestrial cave exploration requires advances in six key areas of technical fidelity.

| Area of technical fidelity | Challenges | Potential solutions |
|---|---|---|
| Access | Precision landing for limited-range/speed mobility solutions. Descent into a skylight. | Precision landing, large surface rovers carrying smaller devices, wheeled robots with tethers, e.g. Axel [5]. |
| Mobility | Deep cave entry over some unknown, probably rubbly/blocky surfaces. | Wheeled robots (problematic for rubble), hoppers, limbed robots (e.g. LEMUR [6]). |
| Power | Extended operation without sunlight. | Umbilical (powered tether), MMRTGs [7], beamed energy, reflected sunlight + solar [8], batteries, low power payloads (see instrumentation). |
| Communications | 2-way data transfer for operation and science return without line-of-sight to Earth. | Umbilical (powered tether), wireless relays (e.g. IEEE 802.11), electro- or magneto-quasistatics [9]. |
| Control | Navigation within a previously unmapped environment, automation of complex path planning and mobility activities, intelligent target selection. | Simultaneous autonomous localization, mapping and planning [10], joystick control (Moon-only), hydrid approaches (e.g. Moon Diver). |
| Instrumentation | Low/no light conditions, limited power, cave-specific conditions/materials. | Ongoing development of numerous instrument classes for planetary exploration (e.g. SHERLOCK [11]). |

**CRYOLAVA TUBES: A FEASIBILITY STUDY.** A. A. Morrison[1] and A. G. Whittington[1], [1]The University of Texas at San Antonio, San Antonio, TX.

**Introduction:** Lava tubes are a phenomenon familiar in terrestrial volcanology where channelized lava flows cool at the surface creating a roof or skin which insulates the interior allowing for transport over potentially long distances. Some of the longest flows on Earth (e.g. Hawaiian flows [1], Columbia River Basalts [2]) are thought to be tube fed flows. The processes that control lava tube formation are dominated by heat transport and thermomechanical erosion of the substrate. These processes can be expected to exist on the icy bodies of the outer solar system, albeit in drastically different temperature and compositional regimes.

**Heat Transport:** With such low surface and eruptive temperatures in [potential] cryovolcanic systems, radiative cooling is unlikely to control the heat loss during emplacement of cryolava flows. On icy bodies with little to no atmospheres (e.g. Ceres, Europa, or Enceladus), convective cooling by wind at the lava interface can also be neglected. In fact, this situation requires a carapace to form over extrusions in order for them to be insulated enough to transport instead of immediately evaporating in the low pressure environment. The roofing over of flows (or carapace formation) would likely be assisted by the density inversion of crystallizing water ice. Cryolavas are likely to be aqueous brines predominantly crystallizing water ice upon cooling below the liquidus. The density contrast between these crystals and the surrounding brine (e.g. seawater) coupled with the very low viscosity of the fluid will allow for fractionation/floatation via Stokes' Law. All crystallization that occurs is then likely to contribute to the roofing process making tube formation efficient. Convective cooling to the surrounding atmosphere may be more important on bodies like Titan, with a thick atmosphere, or Triton, with hypothesized winds [3]. Conduction of heat through the substrate/subsurface is likely the dominant mode of heat transport for potential cryolava tubes.

**Thermomechanical Erosion:** Thermomechanical erosion is the degradation of substrate material by both melting and physical removal. This has been suggested as a mechanism for the formation of the lunar sinuous rilles [4,5,6,7]. Calculations done for lunar sinuous rilles suggest that for low viscosity, turbulent lava with adequately high flow rates, thermal erosion into the substrate can be significant [4,5,8,9]. Analogous to the lunar sinuous rilles, cryolavas that are erupted near the liquidus will likely be very low viscosity (caveat: very compositionally dependent) allowing for turbulent flow during emplacement. This may allow conditions to be right for thermal erosion to take place on icy bodies as well. Thermal erosion rates can be increased by increasing the mass flux (i.e. effusion rate) or by superheating the lava [9].

**Approach:** Similar calculations [4,9] as those conducted for lunar rilles can be run for icy compositions relevant various bodies in the outer solar system. Results of these calculations should provide rates of thermal erosion which may suggest whether cryolava tubes result in the same morphologies as silicate-lava tubes.

**Implications:** Cryolava tubes, once drained and if they exist, may allow for vast cave-like networks to form on icy worlds. If exposed at the surface, these caves could provide passage into the subsurface of the cryosphere making high priority astrobiological and habitability targets.

This presumes a cryovolcanically active body where high volume, effusive (flood?) eruptions occur. This also presumes the preservation of cryolava tubes. Water ice, a dominant crustal component of many of the icy bodies, is much more ductile than the silicates of the terrestrial bodies and thus the relaxation time is much smaller. This suggests that only geologically recent tubes would be observed.

**Acknowledgments:** The authors would like to acknowledge Karl Mitchell for his helpful discussions of lava tubes and Alex Sehlke for additional support in conceptualizing the study.

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**THE ROLE OF PHOSPHOROUS IN MICROBIAL COLONIZATION OF LAVA TUBE CAVES** C. M. Phillips-Lander[1], Benjamin Jordan[2], Amanda M. Stockton[3], and M.E. Elwood Madden[2] [1]Southwest Research Institute, San Antonio, TX; charity.lander@gmail.com, [2]Department of Natural Sciences, Brigham Young University-Hawaii, Honolulu, HI, [3]School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA, [4]Department of Geosciences, University of Oklahoma, Norman, OK

**Introduction:** Lava tubes have been observed on Earth and in Hesperian to Amazonian terrains on Mars [1-5]. These lava caves have been identified as "special regions" [6,7] which may serve as past or current refugia on Mars because (a) they act as preferential conduits for water flow, even under semi-arid to arid conditions [8], (b) their insulating properties may maintain stable, habitable, environmental conditions over extended periods, which may be significantly different than surficial conditions [9], and (c) they provide UV protection, which would enhance the preservation of organic biosignatures [10]. Therefore, lava cave systems may preferentially preserve biosignatures indicative of past life on Mars.

This study documents and directly compares chemical and biological weathering and biosignature formation in 4 spatially co-located lava tubes of Craters of the Moon National Monument, Idaho (CROM) (43.2058° N, 113,5002°W). These caves, located within a 1.6 km area within the Grassy Flow (7,360±60 yr) [11] represent warm/dry (Screaming Jaws of Death Cave), warm/wet (Pond Cave), cold/wet (Ice Lake Cave) and cold/damp (Spongy Floor Cave) conditions respectively. Fresh, sterilized, high (0.5-0.75 wt.% P) and low (0.2 wt% P) glasses were incubated in each cave for 6 months. Results from this study will define a range of weathering, mineralogical, and trace element signatures that may be encountered during cave exploration on Mars.

**Methods:** We utilized coupled field and laboratory methods to determine the degree of chemical and microbially induced weathering in different lava cave environments present at CROM.

*Geochemistry* Tiny Tag TGP-4500 temperature and humidity sensors were deployed within the caves. Data from these sensors were compared to Western Regional Climate Center weatherstation at CROM to determine how internal cave climate was influenced by external temperature conditions.

Temperature and pH were measured in the field. We filtered water samples in the field using 0.2 µm polystyrene syringe filters. Samples for cation analysis were acidified with trace metal grade nitric acid. We allowed frozen samples to melt before filtration. Upon collection and filtration, we placed all samples on ice in a cooler, where they remained at or below 4°C during transport to the laboratory. Major and trace elements were analyzed using inductively coupled plasma mass spectrometer at Oklahoma State University. Filtered, unacidified samples for anion analysis were analyzed using a Microdrill Ion Chromatograph at KU. Alkalinity was determined in the laboratory using filtered unacidified samples.

*Microbial Colonization* We deployed field microcosm experiments, a modification of the buried slide technique [12-16] to determine the role of mineral-bound P in microbial colonization. We incubated 2.5 $cm^2$ billets of McKinney Basalt (0.5-0.75 wt% P) and Hawaii basalt (0.2 wt% P). Each billet was sterilized using UV and 70% ethanol in a sterile, UV hood. One of each type of billet was deployed in for 6 months in each cave to determine intial microbial colonization and weathering. Upon retrieval from the caves, basalt billets were immediately placed in sterile, wide-mouth HDPE bottles with 2.5% glutaraldehyde solution in order to fix samples and preserve fine-scale microbe-mineral interactions [17]. Billets were ethanol dehydrated and critically point dried prior to analysis with scanning electron microscopy (SEM).

We analyzed sample billets from microcosm experiments with SEM to determine the potential microbial influence on colonization, weathering, and secondary products.

**Results and Discussion:** *Temperature* Surface and internal cave temperatures co-vary in caves where the connection to the surface is large and the cave is not deep. Caves which had narrow, deep (~4.5 m) entrances maintained persistent 0°C temperatures (i.e Ice Lake and Spongy Floor).

*Aqueous Geochemistry* indicates water in the four caves derive from a similar source, as major anions and cations are similar between the Spongy Floor, Ice Lake, and Pond. Phosphate limited conditions occur in Spongy Floor (4.8 µM), Pond (4.4 µM), and Ice Lake ($2.44x10^{-2}$ µM) caves. No water sample was collected from Screaming Jaws of Death (SJD) due to low flow rates (damp wall conditions were observed).

*Microbial Colonization* Microbial population size is greatest in the twilight zone of Screaming Jaws of Death where photosynthetic microorganisms are present and decreases in the dark zone. Decreasing temperatures and phosphate availability correlate with decreased microbial population sizes between Pond and Ice Lake caves. In Ice Lake cave, microorganisms occur as individuals attached to basalt surfaces by large networks of nanowires (Figure 1) .

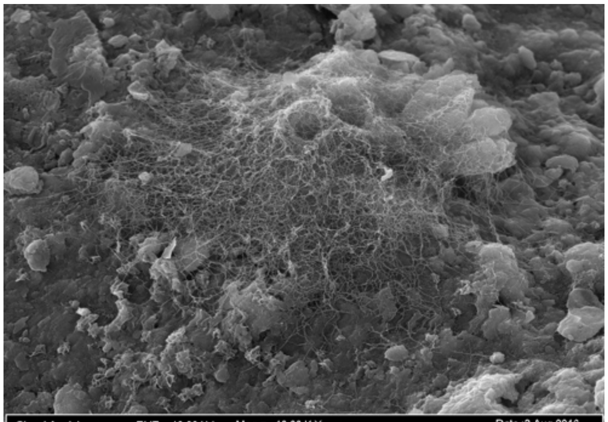

*Figure 1: Ice Lake Cave. Nanowires attached to rock surface. Depressions are where cocci were detached during sample preparation.*

**Mars Caves Mission Selection Criteria:**

*Cave Structure as a Habitability Selection Criteria* Because internal climate and water availability are influence by lava tube depth and structure, potential future lava tube cave missions should consider designs that maximize the potential to explore several co-located caves. This would increase our ability to assess the variation in habitability and increase our understanding of the subsurface geology of Mars.

*Phosphate as Astrobiological Selection Criteria* To reduce risk associated with astrobiologically focused exploration of the martian subsurface, we must develop methods to assess the habitability potential of the subsurface. While significant effort has been devoted to engineering selection criteria [18], significantly less work has been done to assess the geology of the Tharsis region to determine its habitability potential. Surficial analysis of different flow units associated with cave features could constrain the P content of lava flows in this region, which would provide insight into the best lava tube cave sites to examine for signs of present/past life.

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**Science Returns Expected from MACIE: Mars Astrobiological Caves and Internal Habitability Explorer (a New Frontiers Mission Concept).** C. M. Phillips-Lander[1], J. J. Wynne[2], A. Parness[3], K. Uckert[3], N. Chanover[4], T. N. Titus[5], K. Williams[5], C. Demirel-Floyd[6], E. Eshelman[7], A. Stockton[8], S. Johnson[9], D. Wyrick[1] [1]Space Science and Engineering Division, Southwest Research Institute, San Antonio, TX; clander@swri.edu, [2]Department of Biological Sciences, Northern Arizona University, Flagstaff, AZ, [3]NASA Jet Propulsion Laboratory, Pasadena, CA, [4] Department of Astronomy, New Mexico State University, Las Cruces NM, [5]Astrogeology Science Center, United States Geological Survey, Flagstaff, AZ, [6]School of Geosciences, University of Oklahoma, Norman, OK, [7]NASA Ames, Mountain View, CA [8]Department of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA, [9]Department of Biology, Georgetown University, Washington, DC

**Introduction:** Caves represent one of the best localities for finding evidence of life beyond Earth. These features offer subsurface access without the costs of a deep drilling payload [1] and and are ideal locations for potential human habitation. Mars has more than a thousand cave-like features [2], which formed from volcanic processes (e.g. lava tubes), tectonic processes (e.g. atypical pit crater chains), or both. Together, these features represent substantial void space in the subsurface. Numerical heat and mass-transfer modeling of the martian surface indicates equatorial martian caves may not only be shielded from cosmic radiation, but also host favorable conditions to maintain stable water-ice deposits [3]. Both factors would enhance the habitability and astrobiological potential of martian caves relative to surface environments. Therefore, these features represent ideal astrobiological targets on Mars.

**Objectives and Relevance:** We assessed the potential science returns for a New Frontiers (NF) Mars lava tube (cave) exploration mission. The Mars Astrobiological Caves and Internal habitability Explorer (MACIE), named after Macie Roberts NASA's first human computer [4], would address a key recommendation of the 2019 National Academies' Astrobiology Strategy, "NASA's programs and missions should reflect a dedicated focus on research and exploration of subsurface habitability in light of recent advances... [in our understanding of] the history and nature of subsurface fluids on Mars..." [5].

MACIE's Science Goals would address all four goals of the Mars Exploration Program, including (1) Determine whether life ever existed on Mars; (2) Characterize the climate of Mars; (3) Characterize the Geology of Mars; and (4) Prepare for human exploration [6]. MACIE also addresses Strategic Objective 1.1 by "Searching for Life Elsewhere" and Objective 2.2 by "leveraging scientific expertise for human exploration of the Solar System" [7]. If the MACIE did not detect evidence of past or present life, it would still provide significant habitability and geology science returns, and enable us to develop criteria for accessing lava tubes for future use as human astronaut shelters or bases.

**Science Goals:** MACIE's primary science goal would be to (1) Assess the astrobiological potential of the subsurface by determining the presence of extant/past life and life-related indicators. MACIE's other goals, including (2) Assessing habitability of the subsurface, and (3) Determining the geologic history would support interpretation of astrobiological data.

**Instrumentation:** A number of heritage instruments could be used to satisfy Objectives 1-3 as shown in the STM (**Table 1**). Payload selection will be driven in part by spacecraft architecture; however, the payload would emphasize instrumentation associated with assessing the astrobiological potential of Mars' subsurface. A possible strawman payload would include cameras for stereo imaging, a DUV/Vis Raman spectrograph and/or a mass spectrometer, a temperature (T) and relative humidity (T/RH) probe, and a Gamma ray or neutron spectrometer.

*Goal 1 Astrobiology:* Both Raman and Mass Spectrometry can be used to address Objective 1A (**Table 1**). However, a mass spectrometer would be required to quantify isotopic ratios (Obj 1A.2) and gas concentrations (Obj 1A.3). A microscope would be required to characterize morphological signatures of life Obj 1.B.

*Goal 2 Habitability:* Objective 2A and part of 2B could be addressed either by mass spectrometry or Raman. Quantifying atmospheric gases would require a mass spectrometer (Obj 2B.2). Cave climate would require an T/RH probe similar to Mars Science Laboratory's Remote Environmental Monitoring Station and Obj. 2C and 3B.1 would require a Gamma ray or neutron spectrometer.

*Goal 3 Geology:* Cameras required for robotic traverse of the cave can also provide data on the depth, structure, and extent of the cave. In particular stereophotogrammetry may provide a low mass alternative to LiDAR and address Obj 3A.2 and 3B.2. Raman or mass spectrometry can provide insight into Objective 3B.1 and 3B.3.

**Spacecraft Architectures:** There are three main robotic architectures that could support a NF Mars' Caves Mission, mainly a rock climbing robot (LEMUR; TRL 6) [8], a two-wheeled axial robot (i.e. similar to MoonDiver) [9], and unmanned aerial systems (SwRI drone; TRL 9 for Earth applications; TRL 4/5 for space). In all cases, the robotic architecture will consist of a surficial

Table 1: MACIE Science Traceability Matrix

| Goal | Objective | Science Objectives | Science Measurement Observables w/ Uncertainties |
|---|---|---|---|
| 1. Search for the presence of extant and/or extinct life | 1A. Detect and characterize chemical signatures of life/life-related processes | 1A.1 Determine the concentrations/abundances of organic compounds to differentiate life/life-related processes. | Relative concentrations of amino acids (0.1-10 ppb) |
| | | | Concentration of amino acids relative to glycine (±1 wt%) |
| | | | Chirality of amino acids, sugars, fatty acids, EPS |
| | | | Concentrations of individual sugars, fatty acids, EPS (at least 500 Da to ±0.1 wt%) |
| | | | RNA and DNA (≥0.2 ng/gram rock) |
| | | 1A.2 Determine whether stable isotopic signatures are indicative of biological activity | Measure δ13C and δ34S (≤5‰); would require 10 fmol $g^{-1}$ or better to measure δ13C in C1 compound |
| | | 1A.3 Determine the presence and concentration of inorganic signatures of life | Concentration of gases including $CH_4$, $O_2$, $N_2O$, $H_2S$ (1-5 ppb) |
| | | | Biominerals including $SiO_2$, carbonates, sulfates, Fe-oxides, R-250 |
| | 1B. Detect and characterize potential morphological signatures of life | 1B.1 Characterize any macroscale indicators of life | Textural evidence including biovermiculations (i.e. spatial pattterns of organics and crystals), mineral size and shape (10 μm-2.5 cm resolution) |
| | | 1B.2 Characterize microscale indicators of life | Morphological evidence of cells (1-750 μm resolution), colonies, aggregates, biofilms (10-200 μm resolution) |
| 2. Determine the past and present habitability of the cave environment | 2A. Determine whether the geochemical environment contains water, chemistry (CHNOPS+Fe) and chemical disequilibria essential to support past or present life | 2A.1 Determine the geochemistry (CHNOPS+Fe) of the system | Whole rock geochemistry and unaltered mineralogy (i.e. Ca, Mg, Fe, Si, Al, S, P (±0.1 wt% on a 10 cm scale) |
| | | 2A.2 Determine the alteration mineralogies (including evaporites, carbonates, oxides, and silicates) and textures that may influence distribution of CHNOPS+Fe | Quantify alteration minerals and geochemistry (CHNOPS+Fe, Ca, Mg, Si, Al (±0.1 wt% on a 10 cm scale) |
| | | 2A.3 Determine the geochemical resources (CHNOPS+Fe) available in the aqueous phase that could support life and activity of water | Quantify water chemistry (anions, cations, dissolved gases) (1 ug/l for trace elements; 1 mg/l major elements) |
| | 2B. Determine the physical and chemical properties of the atmosphere | 2B.1 Determine whether the cave climate is conducive to present/past habitability | Define cave climate (temperature (T=±1°C), wind speed, relative humidity ($R_H$±5%), barometric pressure). Measure T of air and cave wall. |
| | | 2B.2 Determine whether the atmosphere is suitable for human habitation | Quantify the atmospheric composition, including $CH_4$, $O_2$, $N_2O$, $H_2S$ at 1-5 ppb and isotopic ratios of the cave |
| | 2C. Determine the cave radiation environment | 2C.1 Determine the potential of the cave environment to shield past/present life from the surface environment | Identify radiation levels and sources within the cave Spectra gamma ray; data collection rate such that K, U, and Th gamma ray counts achieve rates required for precision; distance from the rock <20 cm; elemental abundances of obverburden above the lava tube |
| 3. Determine the geologic history of the cave | 3A. Characterize the geologic context of the cave | 3A.1 Determine the overburden roof thickness and geologic composition | |
| | | 3A.2 Determine cave depth, structural complexity, linear extent, and estimate volume | Imaging spectral resolution X, Y >1 mm; data collection along cave traverse in continuous coverage |
| | 3B. Define the physical composition and structure of the cave (i.e. speleogenesis processes) | 3B.1 Determine near surface geology | Whole rock geochemistry and mineralogy (unaltered) (i.e. Ca, Mg, Fe, Si, Al, S, P (±0.1 wt% on a 10 cm scale) |
| | | 3B.2 Determine the duration of emplacement processes | Visually measure any volcanic stratigraphy within the cave to create a cross-section; determine the geologic age(s) |
| | | 3B.3 Determine how cave formation processes differ on Mars and Earth | At various resolutions, examine mineralogy/geochemistry, size/shape of the cave and compare it to Earth analogs |

lander for communication, and a mobile unit for communication, and a mobile unit for exploration. Communication repeaters may also be used in the lava tube to enable deep exploration.

**Planetary Protection:** A lava tube cave mission would access an area designated as a "special region" [10] and require compliance with Planetary Protection Category IVc, which addresses special regions [11]. Accordingly, the mission would ensure a total bioburden level of $<1.5x10^{-4}$ spores.

**Discussion:** Advancement of several spacecraft architectures for use in lava tube cave exploration make the search for life in Mars subsurface feasible within the next decade. We recommend exploration of Mars' subsurface via cave access points for inclusion on the NF list for the upcoming Decadal Survey and recommend that a mission concept study be performed to determine the best payload(s) that could determine whether life existed in Mars' subsurface with different robotic architecture options.

**Acknowledgments:** We thank SwRI for their support of our efforts and the PI Launchpad program for helping us generate next steps.

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**MUON OVERBURDEN GAUGE FOR PLANETARY ANALOG STUDIES OF CAVE ICE STABILITY.**

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**Background:** Perennial ice is found in many terrestrial caves and ice may be present within caves on the Moon and Mars. The conditions for ice formation within caves are not completely understood. Why do some terrestrial caves have ice, while nearby caves do not? For example, El Malpais National Monument in New Mexico contains many caves that are adjacent to one another, some of which have seasonal ice, some have perennial ice, and others have little to no ice. Various processes could contribute to the formation and retention of ice, including cold trapping, wind-forced convection, thermal conduction, advection of water/heat, and percolation of water through the surrounding rock **(Fig. 1**) [1, 2]. For terrestrial and martian caves, we hypothesize that wind-forced convection produces the thermal conditions necessary for ice formation as well as delivering water vapor to the interior of the cave. To test this hypothesis, we are planning analog studies to fully characterize the mass/energy balance of ice caves using a combination of cave climate monitoring, geophysical surveys, and sampling.

**Overburden measurements:** Part of this work involves testing instrumentation that uses cosmic rays (muons) to constrain the density, porosity and permeability of the surrounding rock and to monitor percolation of water from the surface. The sensor technology enables rapid, cost-effective nondestructive characterization of caves, providing a powerful new tool for terrestrial and planetary cave research.

The column of rock above the cave, or "overburden" is expressed as the mass of rock per unit area and can be determined from measurements of atmospheric muons (**Figs. 1 & 2**). Relativistic muons are produced steadily by the collisions of galactic cosmic ray ions with nuclei in the upper atmosphere. They arrive at the surface of the Earth in large numbers (~10,000 muons/m$^2$/min) and can penetrate large distances through rock with minimal deflection. As such, they provide a stable source for probing the interior of large structures on or beneath the surface of the Earth [3-6]. See [7] for potential applications to planetary caves.

The bulk density of the cave ceiling (kg/m$^3$) can be determined from the mass overburden (kg/m$^2$) and the thickness of the ceiling (m). The latter can be found using a georeferenced lidar survey of the surface and interior of the cave. The macroporosity of the ceiling can be determined from the ceiling bulk density given the specific gravity of intact rocks. Inflow of meteoric water and exchange of air through the rock column is likely controlled by a macroscopic network of fractures in the rock. Overburden measurements provide bounds on the available volume for fluid flow.

In addition, the flow of liquid water through the ceiling and surrounding rock can be directly observed by monitoring temporal changes in the mass overburden with time (e.g. before and after rain showers).

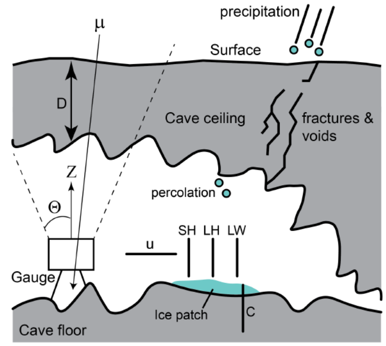


**Figure 1**. The energy balance for an ice mass on the floor of a cave. SH is the sensible heat flux, LH is the latent heat flux, C is conductive flux, u is horizontal wind speed and LW is the longwave (IR) flux. Sources of water include advection of water vapor and percolation of meteoric water. The mass overburden (D, kg/m$^2$) is determined using an upward looking cosmic ray detector (gauge) with restricted field of view (Θ), which measures the vertical flux of atmospheric muons (μ) that reach the interior of the cave.

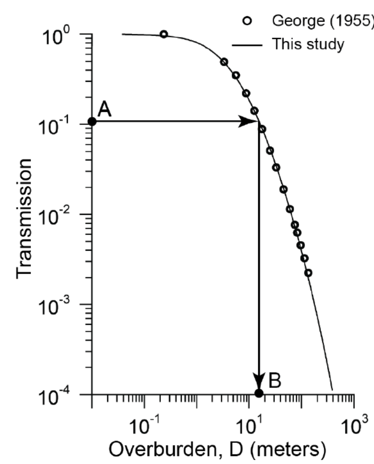


**Figure 2**. *Gauge principle* – Measurements of the transmission of the vertical flux of muons are related directly to overburden depth (A→B). Transmission is the ratio of counts measured in the cave to counts measured on the surface. Here, overburden is expressed in terms of equivalent meters of standard rock (ρ = 2650 kg/m$^3$). Our calibration curve is compared with a previous study [3].

When combined with surface rain gauge data and modeling, the temporal variations can be used to infer the permeability of the rock formation.

**Instrumentation**. Our goal is to implement affordable, low size-weight-and-power, battery operated instruments that can be deployed within the rocky terrain found in caves. To accomplish this, we use plastic scintillating "paddles" read out by compact photosensors to detect downward-going muons. Two methods can be used to determine the flux of muons arriving within a selected angle of zenith: *Electronic collimation* and *geometric collimation*. Electronic collimation, illustrated in **Fig. 3**, results in a very simple, compact instrument that we have tested in several caves (**Figs. 3 & 4**). A single paddle is read out by a silicon photomultiplier (SiPM), shaper and multichannel analyzer (MCA). The MCA records a pulse height spectrum that can be calibrated to give the spectrum of energy deposited by muons that pass through the paddle. Minimally ionizing muons produce a broad peak in the recorded pulse height spectrum that is well separated from the natural gamma-ray background. The energy deposited is roughly proportional to chord length traversed by the muon, such that vertical muons can be distinguished from those arriving at larger angles (**Fig. 3**). Geometric collimation (**Fig. 4a**), which records coincidence interactions between two paddles separated by a gap that defines the field of view, will be used to validate measurements by the single-paddle system.

**Initial Results**. Functional testing of the electronic collimator was carried out in caves in Hawaii, New Mexico, and Arizona. A preliminary study of the Lava River Cave (LRC), a lava tube in the San Francisco volcanic field near Flagstaff, was carried out using the single paddle system. Overburden measurements were made at 12 measurement locations spanning the length of the tube (**Fig. 4b**). The initial measurements (Day 1) are consistent with rough estimates of depth based on barometric pressure. These measurements were carried out during a soaking rain. The rain abated overnight. Replicate measurements made the next day (Day 2) yielded systematically lower overburdens. We hypothesize that this resulted from draining of water from the rock formation. To test this, we plan to make additional, temporal measurements to determine if overburden is correlated with precipitation. Macroporosity and permeability determined by combining overburden data with a georeferenced lidar survey will be validated using geotechnical data acquired at the cave.

**Acknowledgments:** Work in the LRC was carried out with permission from the U.S. Forest Service, Flagstaff Ranger District. Support was provided by the Planetary Science Institute and NASA programs, NIAC, PICASSO, and SSERVI/TREX.

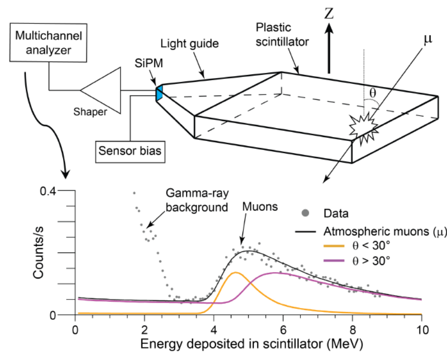


**Figure 3**. Block diagram and measured pulse height spectrum for electronic collimation (see text for details). Data are compared to Monte Carlo simulations of the interaction of atmospheric muons with the scintillator. The minimum ionization peak for muons can be decomposed into vertical (θ<30°) and large-angle (θ>30°) components. The vertical component is used to determine overburden.

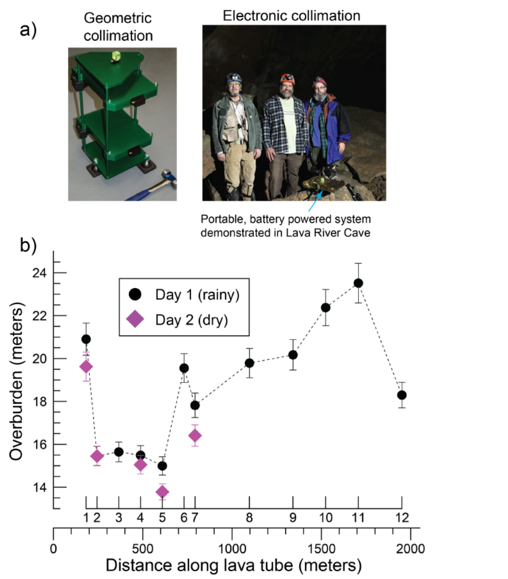


**Figure 4**. **a)** Photo of our two-paddle system for geometric collimation (left). Deployment of the single-paddle electronic collimator in the Lava River Cave (right). **b)** Measurements of overburden (eq. meters of standard rock) during Day 1 show systematic variations in rock column along the length of the cave. Replicate measurements were made at selected locations the following day. The observed decrease in overburden may result from draining of the rock formation following a soaking rain. The distances were determined using a laser range finder and have large uncertainties (~30%), motivating the need for a georeferenced lidar survey.

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**PASSIVE SOUNDING OF LUNAR LAVA TUBES.** A. Romero-Wolf[1,*], C. Devin[1], G. Franklin[1], D. Hawkins[1], M. Haynes[1], M. Lee[1], J. Lazio[1], J. Liu[1], K. Mitchell[1], S. Peters[2], D. Robison[1], D. Schroeder[2], [1]Jet Propulsion Laboratory, California Institute of Technology, [2]Stanford University, [*](Andrew.Romero-Wolf@jpl.nasa.gov).

**Introduction:** Lunar pit craters hint at massive lava tubes that could serve as potential sites for human bases [1,2]. A passive sounding technique has been developed at JPL to use radio emissions from the Sun, Jupiter, or Earth's Auroral Kilometric Radiation (AKR) as signals of opportunity to detect subsurface reflections from orbit [3, 4] or from the ground [5] using a lander or a rover. The technique was recently demonstrated using quiescent radio emission from the Sun [6]. Passive sounding does not require a transmitter and has significantly more relaxed requirements on the receiving antenna front-end. The inherently lower resource needs of this approach would enable low-cost smallsat or small rover missions aimed at revealing the Moon's subsurface lunar lava tubes. We present an instrument concept that can survey and characterize lunar lava tubes in the equatorial regions of the Moon. While focused on lunar exploration, the design can be applied to studies of subsurfaces elsewhere Solar System objects, exploiting the natural radio emissions from the Sun or Jupiter.

**Passive Sounding:** The technique works by recording the voltage waveforms from a single receiver and computing the autocorrelation of the signal as a function of delay (see Figure). A reflected signal appears as a delayed and attenuated peak in the autocorrelation. As in traditional radar measurements, the delay results from the propagation path of the signal and the magnitude of the peak is determined by the radar cross-section of the target. Provided the surface roughness is not so extreme as to completely scramble the reflected signal, the random phase of the source is not the main limitation since the correlation technique removes it, as is typically done in radio astronomical observations.

Previous low-resource concepts for lunar lava tube mapping rely on Earth-based transmitters and receivers [7]. The main challenge with this approach is obtaining the >3 MHz bandwidth at central frequencies < 40 MHz required to penetrate the lunar soil and resolve the lava tubes. Jupiter is a natural radio transmitter capable of producing strong bursts with these characteristics. The main difference between using man-made signals-of-opportunity and radio astronomical sources such as Jupiter is that the latter generally offer wide-band signals needed for depth resolution.

**Expected Sensitivity:** Jovian L-bursts occur at deeply penetrating frequencies 0.3 – 35 MHz and have a typical instantaneous bandwidth of ~3 MHz [8], which provides a depth resolution of ~50 m. Using a model of the Jovian flux, lunar surface roughness, and lunar soil dielectric properties including attenuation, it is expected

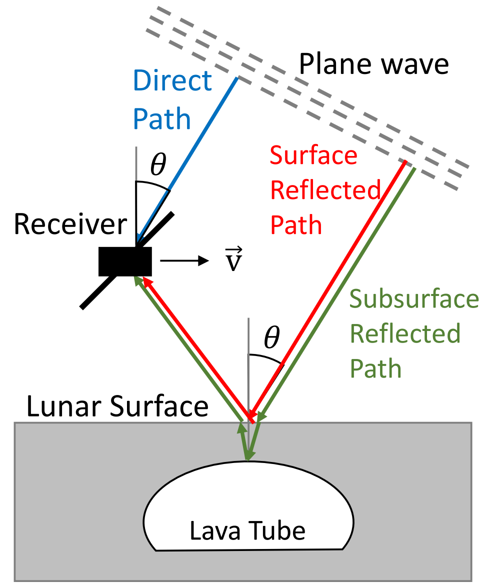


**Figure:** Passive sounding extracts the reflection coefficient and size of a reflector by delayed cross-correlations of the waveform from a single receiver.

that lunar lava tubes as deep as to 300 meters can be detected with signal-to-noise ratios of 10 dB or greater. The sensitivity is limited by the integration time allowed by the orbital motion of the spacecraft. A rover does not have this limitation which gives it the potential to observe lava tubes up to these depths with ~50 dB signal strength.

**Conclusions:** The instrument concept presented here has the potential to provide a low-resource survey for the presence, size, and orientations of lunar lava tubes from a smallsat. A lander or rover-based hosted implementation could then characterize these lava tubes in significantly greater detail to assess their potential to support human habitats on the Moon.

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**UAV IMAGING OF SMALL CAVES IN ICELANDIC LAVA FIELD AS POSSIBLE MARS ANALOGUES.**

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**Introduction:** Past volcanism and its gradual interactions with aeolian processes have played a vital role in Martian landscape evolution. With the possibility that future Mars missions might be focused more on subsurface exploration, Martian lava fields and associated caves appear to be interesting targets for astrobiological, geomorphological, and in-situ resource utilization (ISRU) research [1, 2]. Caves display steady environmental, geophysical, and geochemical conditions supporting habitation in extreme extraterrestrial conditions [3]. Several possible "skylights" of usually >100 m diameter have been reported in Martian lava fields. However, a possible prevalence of meter-scale features, about an order of magnitude smaller and difficult to identify even in HiRISE images, cannot be ruled out.

There are several constraints and facets of remote sensing-based research on Martian caves/lava tubes: (1) spotting and confirming caves in remote sensing images is difficult unless we have images from multiple view angles, 3D terrain profiles, thermal signatures, and subsurface RADAR profiles; (2) to project it as the site of future Mars exploration or settlements, determining the structural soundness and approachability of any cave is important, again requiring multiple data inputs; (3) the Martian equivalents of smaller terrestrial lava cave types can still be sufficiently large as exploratory targets, owing to lower Martian gravity. However, they can still be undetectable in available remote sensing images owing to their smaller dimensions.

The Icelandic volcanic-aeolian environment can serve as a good analogue site to study smaller lava caves such as inflationary caves, surface tubes, liftup caves, and conduits. Iceland has about 15,000 km$^2$ of active sandy deserts consisting of volcanic materials in a perfect aeolian setting [4]. These lava fields are known to harbor many huge lava tubes/caves and various types of small caves [5]. As explained above, detection and mapping of such cm-to-m-scale caves require extremely high-resolution photogrammetry possible only using an unmanned aerial vehicle (UAV) [6].

Use of UAVs for Mars analogue research is still in early stages [7]. The National Aeronautics and Space Administration (NASA) is sending the first UAV to Mars with Mars 2020 rover mission. We start this research with three main objectives: (1) UAV-based high-resolution imaging survey; (2) identification and characterization of small cave openings on UAV images; (3) high-resolution comparison between Icelandic and Martian lava flows.

**Study Area:**

Considering our focus on the small dimension caves, we selected a part of the Leirhnjúkur fissure volcano lava field, situated in Krafla Caldera in Iceland (Figure 1) as the study area. This lava field has numerous vent caves, formed by upwelling and withdrawing of the basalt lava directly from the magma chamber [5], with rather small (1-2 m wide) surface openings. These caves widen out towards the bottom reaching up to 4-5 m in dimensions.

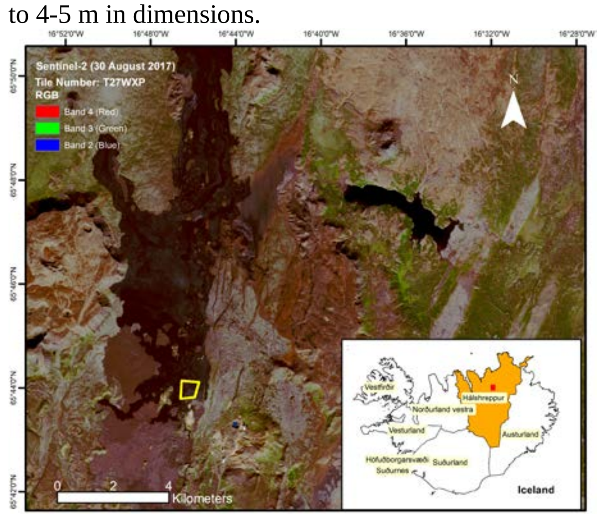


Figure 1. Location map of the study area. The red rectangle in the inset map shows the geographical location of the study site in Iceland. The yellow quadrilateral shows the relative position of the flight site.

**Main Results:** In the present work, we tried to explore the usability of UAV-derived images for characterizing a solidified lava flow and identifying possible small cave openings in it. In the mapped area of ~0.33 km$^2$, we were able to identify 81 small cave openings and five lava flow morphologies. The identified lava flow morphologies are: (1) shelly pahoehoe, (2) slabby pahoehoe, (3) spinny pahoehoe, (4) cauliflower aa, and (5) rubbly aa. Shelly pahoehoe consisted of the highest number of cave openings due to its extremely vesicular nature. The identified small cave morphologies are: (1) open vertical conduit, (2) collapsed lava tunnel, (3) tumulus cave off steep slope, (4) lava rise cave, and (5) rift or fissure caves. The results do not only show the usefulness of UAV imaging for such analogue research, but also highlight the possibility of widespread presence of similar small cave openings in Martian lava fields with significant astrobiological implications.

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**PATTERN EXTRACTION FROM CAVE IMAGES.** I. Sandjaja[1], K. E. Schubert[1], E. Gomez[2], and P. J. Boston[3] , [1] Department of Electrical and Computer Engineering, Baylor University, Waco, Tx 76798;keith_schuert@baylor.edu [2]School of Computer Science and Engineering, California State University, San Bernardino, San Bernardino, CA 92407; [3]NASA Ames Research Center Moffett Field, CA 94035.

**Search for Patterns of Life:** Biosignatures are fundamental to the search for life, but what comprises a biosignature and how do we tell what biosignatures are valid on planets that are not dominated by life, like earth? When a biosignature is selected to be used, how can we guarantee the quality of the measured value?

The first question is a hotly debated issue [1], though a number of potential candidates can be proposed. A potentially universal biosignature common to caves [2] is the characteristic patterned growth behavior of resource constrained life, such as extremophiles, referred to as “biovermiculations” or “bioverms” for short. Bioverms are common in many caves and are also interesting, as all that is needed is a good photograph to identify them. Histogram rule extraction [6], can then be used to attempt to distinguish patterns generated by biology from those generated abiologically.

The second question is more straightforward, but can still provide some unique challenges in cave environments. For example, in caves, light sources are extremely limited and often have a very narrow frequency bandwidth, making glare extremely hard to remove. The glare issue (Fig 1) is exacerbated by the often-moist surface of biofilms in caves, and the source of light is typically located right next to the sensor. A first challenge is thus to obtain clean images that can be used for analysis, which is the subject of this work.

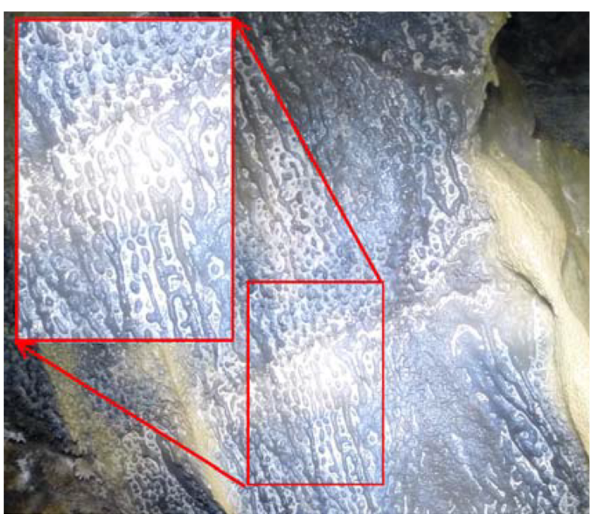

Figure 1: Photo of biovermiculations from Cueva de Villa Luz.

**Specular Removal:** A number of specular glare removal tools have been proposed [3], but many rely on a broad range of frequencies to distinguish reflections from just light colored areas. Since this not available in most cave environments, multiple image methods [4,5] were used to automatically remove specular glare by taking multiple pictures with variable light positions (Fig 2).

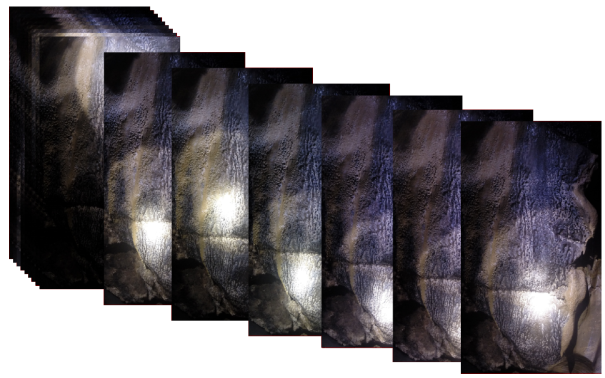

Figure 2: Multiple images of the same feature in Cueva de Villa Luz, with varying lighting used to remove glare.

We observed it took at least 10 images to get a good quality, glare free result (fig 3). This varied slightly, each new light source position had to not produce glare in at least 3 images to provide adequate removal. Flat images would could likely be done in 5 images, however, curved rock surfaces that provided many opportunities for reflection required about twice as much on average.

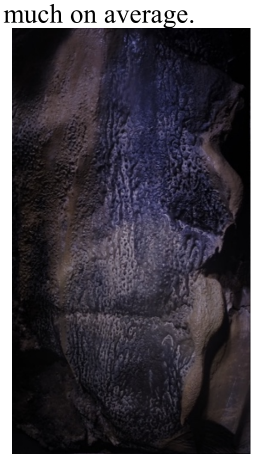

Figure 3: Bioverm pattern with glare removed.

Once glare is removed the image is converted into a three-color image: (red) not in a patterned region, (black) bioverm life, (white) bioverm no-life. The image must be filtered to smooth any noise in the image. A bilateral filter from the OpenCV library is used for this purpose. Image segmentation is augmented by edge detection in regions that are particularly flat to create local groups of pixels. Each pixel in a group is analyzed by examining the statistical variation of other pixels in its local region to determine if it is predominantly a two-colored region or not. Dynamic local thresholding then establishes which color group the pixel belongs to. Resulting images are then ready to have their patterns analyzed (fig 4).

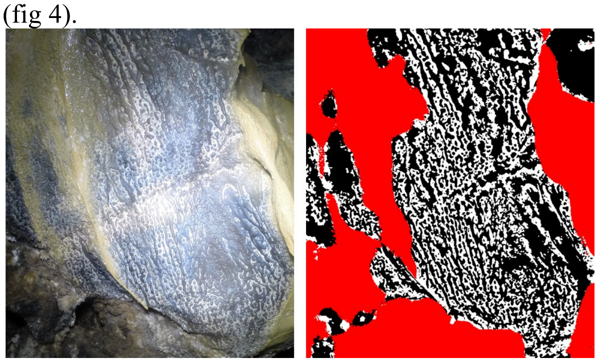

Figure 4: Biopattern converted to a three-color image.

**Conclusions:** Biopatterns are a potentially universal biosignature, but to utilize them images must be able to be automatically processed into a form that can be analyzed for the patterning. The removal of glare from cave images is a challenging part of this pre-processing, since many methods fail due to the limited light sources and narrow frequency range of the illuminating light. By utilizing multiple images and iterative glare removal, a successful image can be generated. Images can then be processed to separate patterned regions from non-patterned regions and the two colors of the pattern. A method that accomplishes this is presented.

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**LIFE IN SUBSURFACE VOIDS WITH GAS CHEMOCLINES - AN EARTHLY PROXY FOR EXTRATERRESTRIAL LIFE.** S.M. Sarbu[1], E.J. Fleming[1], K.H. Nealson[2], Casey Barr[2], J. Aerts[3], J-F. Flot[4], B.P. Onac[5], S. Tighe[6], D.L. Vellone[6] and R. Popa[7], [1]California State University, Chico (400 West 1st St, Chico CA, 95926-515 USA, serban.sarbu@yahoo.com enuester@csuchico.edu), [2]University of Southern California (3616, Trousdale Parkway, Allan Hancock Foundation, Los Angeles, CA, 90089, USA, knealson@usc.edu, caseyrba@usc.edu, rpopa@usc.edu), [3]Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands, j.w.aerts@vu.nl), [4]Université Libre de Bruxelles (Ave. F.D. Roosevelt 50, B-1050 Bruxelles, Belgium, jflot@ulb.ac.be), [5]University of South Florida (4202 E. Fowler Ave.,NES 107, Tampa FL 33620, USA, bonac@usf.edu), [6]University of Vermont Cancer Center (149 Beaumont Ave HSRF 303, Burlington Vermont USA 80265, USA, scott.tighe@uvm.edu, daniel.vellone@uvm.edu), [7]University of Craiova (Al.I.Cuza Str. 13, Craiova 200585, Romania, radu.o.popa@gmail.com).

**Introduction.** Underground voids vary in dimensions from human-explorable features (such as caves) to pore spaces (unfit for direct human exploration, but accommodating for microorganisms). Future extraterrestrial underground exploration will search for life from classical caves to pore spaces.

**Subsurface gas chemoclines.** From a habitability perspective, the energy in these environments may come from many sources. We focus on interconnected voids located in geological strata with high permeability, where life-usable energy is available at redox interfaces of gas chemoclines. We discuss earthly examples of such environments: caves and pore spaces in a volcanic area (Ciomadul Mountain, Romania). In this area, volcanic gas emissions fill subsurface voids to a depth level where a redox gas:gas interface forms. Here, methane ($CH_4$) and hydrogen sulfide ($H_2S$) are located below and atmospheric dioxygen ($O_2$) is present above. Water originates from vapor condensation and percolation. The pH is approximately 0.5-1.0.

**An earthly proxy for extraterrestrial life.** We show microbial biofilms colonizing a solfatara habitat in Smelly Cave, Romania [1]. In this ecosystem, the highest abundance of life occurs on the walls of the cave at the interface between oxidizing surface gasses (atmospheric air) and volcanic emissions. Differences in the density of the dominant gasses ($N_2$ from above and $CO_2$ from below) and little air turbulence in the deeper recesses of the cave result in a relatively steady gas gradient with a well-defined redox interface ($O_2$ above and $CH_4$/$H_2S$ below). Using 16S rDNA and metagenomic sequencing we found that this microbial community is dominated by bacteria (*Acidithiobacillus* and *Mycobacterium*) and archaea (*Ferroplasma* and *Thermoplasma*). SEM images also show extensive fiber-like structures resembling nanowires between cells, as well as between cells and sulfur crystals.

On Mars, such habitable environments that may carry biosignatures may be found in fumarole fields. We expect that some fumaroles on Mars are solfatara (i.e. fumaroles emitting reduced gasses such as $H_2S$). One example is the Tarsis province, where S-rich volcanic emissions have existed in the past. The Home Plate formation (Gusev Crater) is also suspected to be the eroded remains of an ancient and extinct fumarole. Sulfur-rich deposits were found by the Curiosity APXS instrument at Gusev, some of which are believed to be elemental sulfur.

Equipment that may be used for Mars exploration to analyze the presence, habitability and biosignature in such environments include: optical imaging with Visible/UV (MAHLI), RAMAN and DeepUV (e.g., SHERLOCK), ChemCam-LIBS, CheMin-XRD-XRF, and SAM-GC-MS. The Smelly Cave proxy from Romania offers an opportunity to test the appropriateness of such exploratory means in detecting underground habitability and biosignatures. Based on our work, we propose a strategy to investigate underground voids on Mars.

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# THE ESA PANGAEA-X TESTING CAMPAIGN IN THE CORONA LAVA TUBE (LANZAROTE, SPAIN) AS AN ANALOGUE FOR LUNAR CAVES EXPLORATION

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**Introduction:** On future planetary missions astronauts will probably explore complex environments such as lava tubes, canyon rills and rough surfaces. Training and technological testing on Earth in places with similar geological features and operational conditions will help the astronauts to perform better their tasks and to maintain a high situational awareness between themselves and the ground support during geological investigations in our Solar System. Potential near future missions to the Moon will take into account features such as lava-tube skylights, or extreme environmental settings like sub-polar regions, which were not taken into account during the Apollo missions. In this preparatory context ESA has included in the PANGAEA geological field training for astronauts [1] a traverse in the lava tube of La Corona in the volcanic island of Lanzarote, one of the best analogue for planetary lava tubes in Europe [2, 3]. This traverse is focused on teaching to the astronauts how to recognize specific lava tube morphologies, secondary mineralizations and potential spots for geomicrobiological research. Three editions of the training have been held in 2016, 2017 and 2018 with the participation of a total of 5 ESA astronauts, 1 Cosmonaut, engineers and mission designers. In addition to the astronaut field geology training purposes, one week after the training session, in November 2017 and 2018, ESA has decided to offer the PANGAEA framework to internal actors, partner agencies, and external investigators as an analogue test campaign (called PANGAEA-X), focussed on testing technologies and operational concepts for field geology and exploration. One of the main objectives identified for the 2017 campaign was testing of technologies for geo-microbiological sampling, exploration, mapping, navigation and communication in the Corona Lava Tube and other volcanic cavities of Lanzarote (Tinguaton volcanic gayser vents), as an analogue to planetary caves exploration.

**PANGAEA-X 2017 planetary cave-oriented objectives:** The PANGAEA 2017 eXtension campaign took place from 20th to 24th November 2017. For the 5 days of field trials, interrelated activities were combined to create more valuable tests and operational scenarios. The first two days were dedicated to tests of surface geological sampling and analytical instrumentation and operations, with human-robotics interaction, taking into account mobility constraints of lunar surface sorties. The last three days took place in subterranean environments and were focussed mainly on lava tube exploration and mapping. The following research projects linked to planetary caves have been implemented:

*Augmented field Geology and Geophysics for Planetary Analogues (AGPA):* a project of the Jacobs University Bremen and DLR with multiple experiments related to planetary geology investigation approaches and analytical tools. The AGPA team tested a geoelectric system searching subsurface features (cavities, lava tubes, Fig. 1), an innovative LIDAR mapping system inside of the lava tube, and a passive seismometer to study the subsurface. Drone photogrammetry was used for documenting and for 3D high-resolution reconstruction of the Tinguatón vents testing site.

*Pegasus backpack (PEGASUS LEICA)***:** Leica Geosystems (France) tested a combined SLAM/LIDAR systems embedded in a portable backpack for real-time mapping of lava tubes and rough terrains [4].

*Environment Modelling and Navigation for Robotic Space-Exploration (ENTERN)*: lead by the German Research Centre for Artificial Intelligence (DFKI), this research project focused on testing a rover system for exploration of rough terrain in lava tubes (Fig. 2); the rover ASGUARD was tested both autonomously and in tele-operation mode to evaluate critical constrains of the environment and efficiency of the different settings.

*Microbiological Sampling Sequence (MICSS) and DNA extraction (DNAX), with the support of the Mobile Procedure Viewer (MOBIPV)*: the "Instituto de Recursos Naturales y Agrobiología de Sevilla" and the NASA's Johnson Space Center provided specific instrumentation and procedures to perform microbiologic sampling and in situ DNA extraction and sequencing in a lava tube. The experiment was performed by an ESA astronaut within an operational relevant scenario, taking into account sampling protocols to avoid cross contamination, and with the support of the ESA mobIPV procedure viewer.

All these tests and experiments have been performed with the participation of European astronauts and the assistance of ESA experts with the aim of evaluating potential applications and developments for future

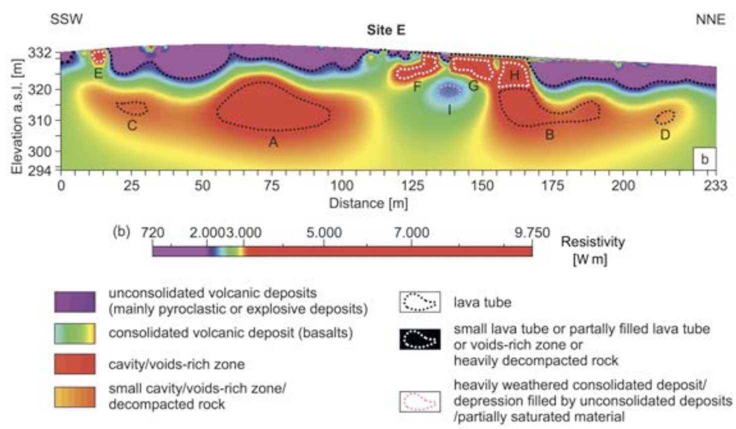


*Fig. 1. Example of results of the AGPA geoelctric experiment showing the section of the Corona Lava Tube (A) and of another uknown tube about one hundred meters to the NNE.*

*Fig. 2. ESA astronaut Matthias Maurer driving a rover of the ENTERN experiment in the Corona Lava Tube.*

missions and astronaut trainings. All experiments were documented with detailed reports and the results and data obtained by the different teams were presented at the European Geoscience Conference in March 2018. All participants deemed the campaign a really useful platform for validating concepts and instrumentation, mainly thanks to the integration in realistic operational scenarios and to the combination of field geology with surface and subsurface human and robotics operations

**Results:** All the different experiments have provided important data and lessons learned. As an example the stationary and mobile lidar mapping by LEICA, AGPA has provided, with the support of the company VIGEA, the longest centimetric resolution 3D model of a lava tube achieved so far (6.5 km), including high resolution models of the collapses through drone photogrammetry[4]. The MICSS experiment, performed by the ESA astronaut Matthias Maurer has shown the possibility of obtaining in situ an impressive amounts of data on the microbial diversity caracterizing the cave, with important implications for fast decision making in sampling protocols [5]. The AGPA geoelectric experiment has demonstrated the ability to identify a lava tube according to the 3D models, and also to discover additional parallel conduits not accessible to humans [6]. The ENTERN project has been able to test tele-operated and authonomous navigation of a rover in a lava tube environment, allowing to better define the robotic, communication and navigation approaches to lava tube exploration .

**Conclusions:** the synergies created by the PANGAEA-X campaign have demonstrated to be extremely useful for ESA in the framework of future human and precursor planetary missions since it allows testing and validation of complex operational concepts and testing of exploration technologies, scientitic methods and instrumentation. In addition, it fosters the exchange between research institutes, instrument developers and operational experts and thus boosts synergetically the use of novel portable analytical instrumentation and spin-in of new technologies and research into operations. Last but not least it provides a continuously increasingly relevant operational growth and novel scenarios for future ESA CAVES and PANGAEA training events.

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**VOLUME AND MORPHOLOGY OF MARTIAN AND LUNAR LAVA TUBES REVEALED BY COMPARATIVE PLANETOLOGY.** F. Sauro[1], R. Pozzobon[2], M. Massironi[2], P. De Bernardinis[1], T. Santagata[3], J. De Waele[1]. [1]Department of Biological, Geological and Environmental Sciences, University of Bologna (francesco.sauro2@unibo.it), [2]Department of Geosciences, University of Padova, [3]Virtual Geographic Agency, Italy.

**Introduction:** Aligned chains of collapses could represent the surface expression of lava tubes in the subsurface, being formed both during the genesis of the pyroduct through overpressure flow, or more commonly due to gravitational effects on the ceiling when the tube is finally drained. Lava tubes typically form sinuous chains of collapses mostly elongated along the direction of the tube. Between one collapse and the subsequent one the underground tunnel can be intact and accessible for exploration, mapping and utilization. Although the morphological similarities of sinuous lunar and martian collapse chains with terrestrial cases has been underlined by several authors[1-3], to date, a detailed morphometric comparison among them has not yet been performed. Given the direct genetic relationship between the collapse chains and the lava tube, morphometry can be used to estimate the dimension and general morphology of intact sections of the tube along the same pit chain line.

**Data and methods**: In this study examples of lava tube collapses on Earth were compared with a selected number of collapse chains with morphologies potentially related to lava tubes on Martian volcanoes and in the Lunar Maria [2, 4, 5]. The terrestrial examples analysed are Corona (Lanzarote, Spain), among the most voluminous tubes known on Earth[6], and Kazumura (Hawai'i, USA), the longest terrestrial lava tube[7] (78 collapses measured, through Lidar and terrestrial laser scanning data, and detailed topographic speleological surveys). In addition, in order to extend the dataset, we obtained from existing literature [8] additional information on the lava tube collapse chains of Undara (Northern Queensland, Australia), the longest - lava tube supported - lava flow on Earth. On Mars, a total of 98 collapses related to four chains along lava tube candidates were examined on Arsia, Olympus and Hadriaca volcanoes, through high-resolution stereo DTMs generated from CTX images. On the Moon a total of 27 collapses were analysed in three different collapse chains in Marius Hills and Gruithuisen through the Selene-Kaguya/LRO LOLA merged DTMs. In both cases, collapse chains have been carefully selected on CTX, HiRISE and LROC NAC image mosaics, looking for specific morphological characteristics that differentiate them from tectonic pit chains[9] .

**Morphometry:** Several morphometric parameters have been obtained to compare lava tube chains in the three planetary bodies (Table 1, Profiles in Figure 1)). The minor axis *W* of the collapses shows a relevant increasing trend from Earth (maximum few tens of m), to Mars (from 200 to 400 m), and to the Moon (500-900 m) (Table 1). The average linear volume of the

**Collapse chain parameters**

| | Lava tube | Collapses | N° Skylight | Vent | Ctl (km) | Si | CS (°) | Vr (m) |
|---|---|---|---|---|---|---|---|---|
| Earth | Kazumura | 53 | 48 | Yes | 32.1 | 1.3 | 1.9 | 1102 |
| | Corona | 25 | 1 | Yes | 6.1 | 1.1 | 2.91 | 240 |
| | Undara* | >40 | / | Yes | 41 | 1.24 | 0,7-1,4 | 377 |
| Mars | Arsia A | 24 | 1 | Yes | 56 | 1 | 1.1 | 1094 |
| | Arsia B | 18 | 1 | Yes | 30 | 1.23 | 0.01 | 315 |
| | Olympus | 27 | 0 | Yes | 29 | 1.1 | 5.2 | 2704 |
| | Hadriaca | 32 | 0 | No | 75.7 | 1.1 | 0.7 | 630 |
| Moon | Marius Hill A | 6 | 0 | Yes | 16.9 | 1 | 1.2 | 210 |
| | Marius Hill B | 3 | 1 | Yes | 8.5 | 1 | 0.01 | 60 |
| | Gruithuisen | 21 | 0 | Yes | 41 | 1.2 | 0.02 | 40 |

**Collapse morphometry**

| | Lava tube | Av. L (m) | σ L | Av. W (m) | σ W | Av. D (m) | σ D | Av. V (m3) | σ V | Av. V1 (m3) | σ V1 | Av. AR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Earth | Kazumura | 13.9 | 7.3 | 7.4 | 2.9 | 5.2 | 2.5 | / | / | 29.7 | 19 | 1.4 |
| | Corona | 62.2 | 32.8 | 37.6 | 12.1 | 9.8 | 4.4 | 9877 | 9099 | 305 | 182 | 3.8 |
| | Undara* | 250 | / | 68 | / | 5-15 | / | / | / | 270-800 | / | 5-12 |
| Mars | Arsia A | 369.1 | 164.4 | 283.3 | 83.7 | 25.3 | 16.7 | 13911961 | 62639821 | 6740 | 6330 | 11.2 |
| | Arsia B | 759.7 | 506.2 | 415.2 | 107.8 | 59.8 | 34 | 7324819 | 7079975 | 21514 | 14909 | 6.9 |
| | Olympus | 737.7 | 560.4 | 366.2 | 148.8 | 45 | 36.2 | 4549680 | 5714013 | 14970 | 17710 | 8.1 |
| | Hadriaca | 888.9 | 743.77 | 374.3 | 143.8 | 34.7 | 18.2 | 4648559 | 9511566 | 11700 | 10885 | 10.8 |
| Moon | Marius Hill A | 1070.3 | 374.5 | 573.9 | 141.5 | 87 | 32.9 | 16482675 | 13802402 | 41388 | 25543 | 6.6 |
| | Marius Hill B | 1358 | 802.6 | 527.4 | 197 | 95.8 | 30.2 | 21733653 | 22293270 | 42039 | 27341 | 5.5 |
| | Gruithuisen | 1333.7 | 629.4 | 858.5 | 322 | 189.9 | 83.54 | 81715413 | 78192450 | 141601 | 100929 | 4.5 |

Table 1. Main morphometric parameters of collapse chains (for Earth, Mars and Moon). Morphometric parameters acronyms are: Ctl – Chain total length; Si – Sinuosity index; CS – Chain Slope; Vr – Vertical range; Av. L – Average length of the collapses (major axis); σL - standard deviation of L; Av. W – Average width of the collapses (minor axis); σ W - σ standard deviation of W; Av. D – Average depth of the collapses; σD - standard deviation of D; Av. V – Average volume of the collapses; σV - standard deviation of V; Av.Vl – Average linear volume (along 1 meter thick cross section) of the collapses; $\sigma V_1$ - standard deviation of $V_1$; Av AR – Average asymmetry Ratio.

collapses follows the same trend in all three planetary bodies, being almost 80 times bigger on Mars than on Earth, and with the greatest magnitude on the Moon, which presents collapses from 300 to 700 times bigger than on Earth.

**Discussion:** Lava tube collapse chains on Earth share several common characters with those examined on Mars and the Moon, among them: a) most of the collapse chains here analysed are sinuous and hence not related to tectonic lineaments; b) the minor axes *W* and depths *D* of the collapses are comparable along each chain, with *W* perpendicular to the tube development line; c) the deeper depression at the beginning of the chain is most probably the feeding source of the tube; d) the presence of steeper overhanging and roundish skylights in the Martian chain in Arsia and in Marius Hills B on the Moon indicates that between one collapse and the other there should be an intact section of the pyroduct. All these morphological characters suggest that these collapse chains are genetically related and clearly different from pit chains formed along tectonic dilatational faults, grabens and dike swarms.

Our morphometric study shows that terrestrial lava tube collapse chains present striking morphological similarities with those proposed here as candidates on Mars and the Moon. However, dimensions and morphometric parameters like width/depth ratio *AR* have peculiar ranges each pertaining a different planetary body. Volumes of collapses and related conduits show increasing orders of magnitude from Earth, to Mars and to the Moon (Table 1). The size estimation indicates that on the Moon, the typical volume (linear tube volume=$V_l t$) and *AR* of lava tubes are not high enough to reach the roof instability threshold and cause collapse [10], as often happens on Earth and Mars. Indeed, on Mars intact sections of lava tubes surely exist, but they have more frequent collapses due to the higher width/depth ratio *AR*. Therefore, the Moon presents the highest potential for lava tube development and conservation. Most of its tubes are probably intact and stable along their full length exceeding a total volume of some billions of cubic meters each, but with few accessible entrances from the surface. These impressive volumetric values clearly show how future space missions devoted to the investigation of these voids could open a new era of subsurface lunar exploration.

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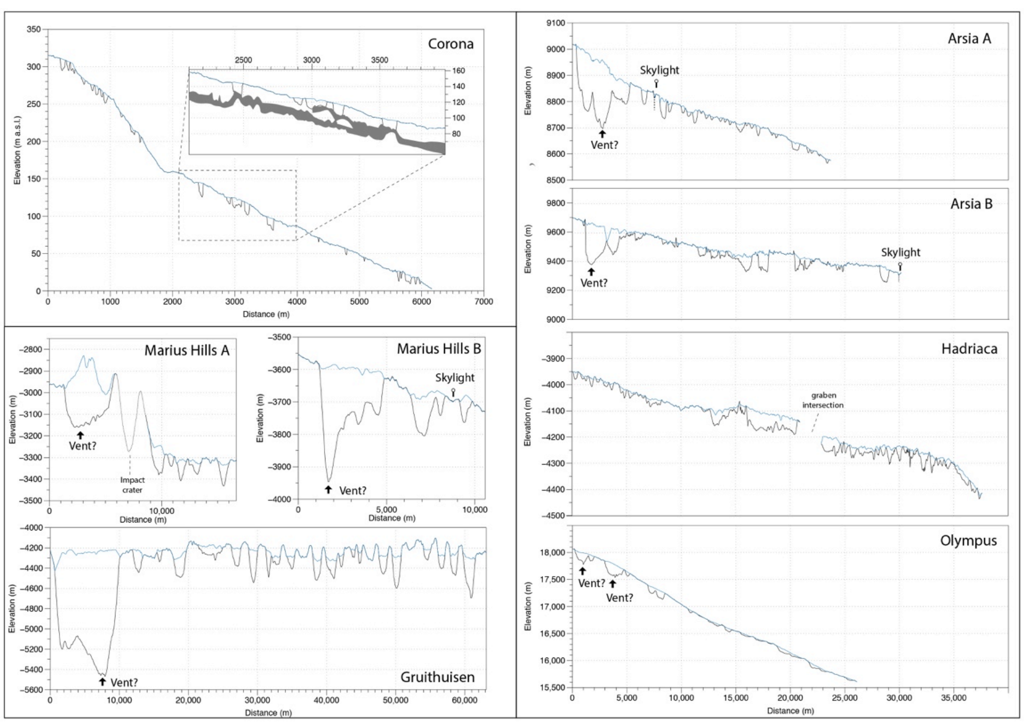


Figure 1. Profiles of tube collapse pit chains (black lines) with superposed the extrapolated intact topography on Earth, Mars and the Moon. For the Corona terrestrial lava tube the inset shows the relationship between the collapses and the tube surveyed with laser scanner.

# ROBOT AUTONOMY FOR ACQUIRING IMAGERY FOR PLANETARY PIT MODELLING.

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**Introduction:** Satellite imagery has provided concrete evidence for planetary caves, pits and lava tubes[1]. Lunar pits and lava tubes have caught the fancy of many space organizations as they plan to set-up a base on the moon for future space missions. Pits serve as a safe haven from the radiation, extreme temperature variations and probable micro-meteorite impacts. The inconsistent geometry and varying lighting conditions about the pit makes it challenging to obtain a high-resolution oblique views of the interior of the pit through satellites. This necessitates getting close to the edge of the pit. This abstract presents an autonomous robotic system which when released from the lander navigates to a lunar pit, avoiding obstacles and steep slopes on it's way. It then circumnavigates the pit, getting close to the edge of the pit at various vantage locations around the pit and captures the illuminated walls of the pit. These images can be used to generate a 3D model of the pit which would be of immense importance for future scientific missions. The entire mission is expected to be completed within a single lunar day devoid of human intervention. The major contributions of the work include novel algorithms to plan path around a lunar pit accounting for the changing illumination and validating the same in a simulated lunar environment.

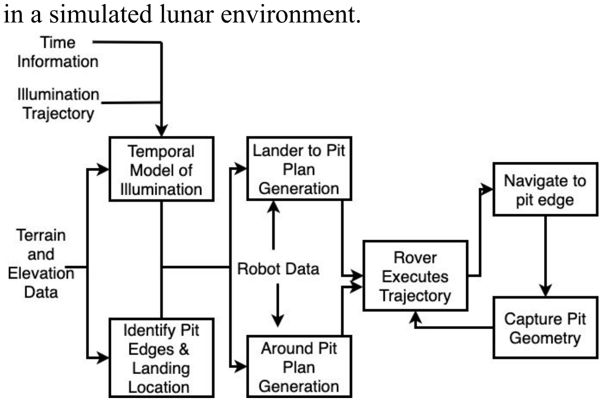


**Figure 1. Mission Process**

**Waypoint Generation:** The Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) provides images of the moon from an altitude of 50km at a nominal pixel scale of 0.5m[2][3]. The elevation map generated from the laser altimeter provides a high level notion of traversable areas and obstacles[4]. It also lays out a tentative location of the pit. An elevation gradient based approach is used to identify the edges and the interior of the pit. Waypoints can then be generated at any distance away from the pit edge based on the map digitization. To ensure appropriate pit coverage and waypoint navigability a two-pronged approach is followed. Untraversable waypoints are pruned off and suitably elevated waypoints are ensured around each quarter of the pit based on the variance of elevation of these waypoints.

**Illumination Modelling:** On the Moon, it is only possible to image surfaces that have been directly lit by an illumination source, primarily the Sun. It is essential to know the position of the Sun relative to the pit at all times to identify vantage points. For a pit with known coordinates and altitude information obtained by the LRO, it is possible to find the position of the Sun throughout the span of the day. The NASA tool CSPICE[5] provides the position vector of the Sun from the Moon. The tool also helps find the rotation of the Moon at the given time instants. With elementary vector arithmetic, the direction vector of the illumination of the Sun at the pit coordinates can be calculated.

Vantage points are defined as the possible waypoints the rover can be at a given time to capture a portion of the pit that is lit. The pit walls facing the illumination vectors are most likely to be illuminated, conditional to obstructions and local geometries. This is a fair assumption to obtain a sector of the pit that is likely to be illuminated. Previous work [6] has shown that the model of a pit generated from images is affected by the illumination angle relative to the surface. If the illumination is close to normally incident, images appear washed out; if too oblique, the surface is prone to shadowing; both resulting in images deficient of features. Generally circular pits will have a maximum depth illuminated towards the center of the sector. Waypoints that are facing these strongly lit points are classified as vantage points for that illumination direction. By modelling the illumination, at each vantage point, the sector of the pit optimally illuminated by the sun is estimated.

**Illumination Based Path Planning:** Capturing the illuminated sides of a lunar pit while ensuring complete coverage of the pit within a single lunar day is the prime goal of the planning algorithm. This necessitates a time based planning methodology which ensures that the rover captures the pit geometry when it is appropriately lit. At each time instant the algorithm evaluates each of the potential vantage points. Each vantage point is assessed for the cost to reach, time to reach, how centrally located is that particular vantage point compared to all the potential vantage point targets and the remaining time before the waypoint loses its vantage point status. A factor of pessimism is incorporated to take into consideration the increased time taken by the local planner to execute a collision free path. Doing this, we can ensure that the planner can be run offline and won't hog the on-board computational resources. Appropriate time is also allocated for capturing suitable images needed to create a 3D model of the pit later. The best vantage point is then selected. This ordered set of waypoints is then passed on to the local planner for traversal.

**Local Planning:** Local path planning is a mission-critical task as it has to take into account the local terrain, and define how the system will move on it. The presence of rocks, steep slopes, and craters make the problem onerous. Reliable perception is used to sense the environment, which enables the local planner to generate safe and feasible paths. The local planner has two major roles, namely, navigation between the globally generated vantage waypoints and navigation to the edge of the pit to take images of the interior of the pit.

The entire mission can be divided into three stages. The first is, traversal from the lander to a pit. The rover receives a set of ordered waypoints from the global planner which it tries to accomplish. The last waypoint of this global plan coincides with the first global vantage point around the pit. Once it is reached- the system transitions into the next state, which involves moving closer to the edge of the pit and capturing an image of the illuminated portion of the pit. If this step is successful, the system transitions into the third stage- which involves traversal around the pit from one vantage point to another. Once this is realized the system again cycles to the second stage and this process gets repeated till the entire pit is covered. The system shifts to achieve the next waypoint in case it fails to complete either of these transitions. The generated plan incorporates a dense collection of vantage points which have overlapping field of views. So missing a few vantage points would not impair pit coverage.

It is important to note that the pit edge generated from the LRO data is of low resolution. A low resolution map lacks information that is required to facilitate rover navigation to the edge of the pit. Navigation to the edge of the pit, from the given global waypoints, for capturing images of the inside of the pit, is handled by the local planner. It generates local waypoints which aid the rover to approach the edge of the pit while avoiding rocks and steep slopes on it's way and ensuring that it doesn't fall into the pit.

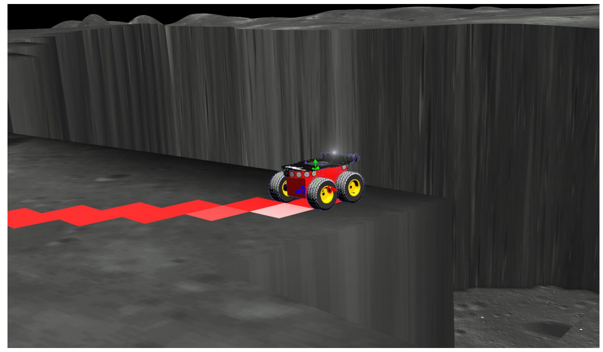

**Figure 2. Rover navigating autonomously to the edge of a pit in the simulated lunar environment**

Navigation to the edge of the pit requires defining what can be classified as the edge. The edge can be a vertical drop at certain regions or a gradual slope. The rover needs to be close to the edge of the pit while making sure that it does not fall inside. Going close to the edge of the pit demonstrates a risk-reward relationship. Going close to the edge of the pit increases the possibility of rover falling inside the pit, which would lead to mission failure but if done safely, it increases the depth of the coverage given the same field of view of the camera. This is achieved by using a perception system that can identify the edge of the pit using depth information generated from a stereo camera system, and an IMU which enables the robot to navigate to a safe angle of inclination.

**Conclusions:** The system was validated in a simulation environment with synthetically generated pits and illumination modelled at known coordinates of known lunar pits. The system was successfully able to generate plans for achieving complete coverage of the illuminated parts of the pit and traverse to the edge of the pit at the planned vantage points to image its interior. The images from the camera onboard the rover validate the capturing of the illuminated portions of the pit.

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**An astrobiology exploration strategy for Caves based on The Tony Grove Karst Region in Northern Utah.**

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**Introduction:** The Tony Grove lake area is a dolomitic karst region in the Bear River Range of the Middle Rocky Mountain Province (Hintze 1973, Wilson 1976). The 5 km study area (Figure 1) is strewn with boulders and consists of a combination of subsurface dissolution caves underlying the highly-eroded karst surface reminiscent of past glaciation. Traces of the dynamic mountain structure can be seen in faults, fractures, and folds with the largest being the Logan Syncline (Wilson, 1976) formed during the Sevier Orogeny. The Tony Grove area stratigraphy is dominated by the Ordovician (505 MYR) Fish Haven dolomite and Silurian (438 MYR) Laketown dolomite units topped with some Devonian (406 MYR) aged inter-bedded quartzite, shale, and dolostone from the Water Canyon Formation (Morgan 1992, Spangler 2001). The 5 km study area contains over 90 karst features formed through vadose water flow due to the alpine proximity. The development and exhumation of these features have been greatly influenced over time by plate tectonics and water. We investigate cave formation and sediments as an indicator of past water flow and watershed dynamics.

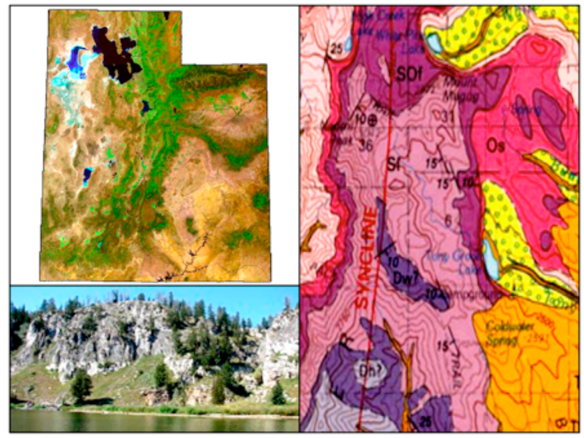

Figure 1: The Tony Grove Karst Region


Figure 2. Features in Thundershower Cave indicating water flow regimes.

**MINERAL BIOMARKERS FOR EXTRATERRESTRIAL CAVES** M. N. Spilde[1], J. J. Medley[2], D. E. Northup[2], and P. J. Boston[3]. [1]Institute of Meteoritics, MSC03-2050, 1 University of New Mexico, Albuquerque, NM 87131, mspilde@unm.edu; [2]Dept. of Biology, MSC03-2020, 1 University of New Mexico, Albuquerque, NM 87131; [3]NASA Ames Research Center, Moffett Field, CA 94035.

**Introduction:** Lava tubes, pit craters and skylights observed by Mars-orbiting spacecraft provide strong evidence of caves on Mars. Likewise similar features have been spotted on the Moon. Caves, modified into underground Moon or Mars bases, would provide shelter from radiation for human habitation. On Mars at least, lava caves may provide locations where water or ice are present, along with protection from radiation, conditions suitable for extant or past life.

For more than a decade, we have investigated the idea that the subsurface of Mars is the most likely place to find life or its traces. We have conducted extensive geomicrobiological, mineralogical, and geological fieldwork in a variety of lava caves in tropical to arid conditions. All the caves that we have sampled show evidence of microbially induced or precipitated minerals through SEM examination and DNA analysis [1]. Many microbial communities we have sampled are unique to the subsurface and represent countless novel strains [2].

**Minerals in phase change caves (lava caves).**

*Cu and V minerals.* Ephemeral minerals may be present in lava caves, largely related to fumarolic activity, including Cu-V oxides such as mcbirneyite [$Cu_3(VO_4)_2$] or ziestite [$Cu_2V_2O_7$] [3]. We have observed yellow and golden yellow V-bearing minerals in two cold, high altitude caves on Mauna Loa, Hawaii. SEM-EDS analysis revealed microbial evidence in the form of filaments, carbon-rich biofilm and putative cells closely associated with these minerals. We have observed other Cu minerals in lava caves in both Hawaii and New Mexico, also closely associated with evidence of microbial activity. These include reticulated filaments intermingled with Cu-Al silicate identified as chrysocolla by XRD in Maelstrom Cave on the flank of Mauna Loa. Unidentified Bi minerals associated with putative microbial cells in a greenish mineral coating were also found in this cave (Figure 1). Other, as yet unidentified, blue-green mineral deposits are present in lava caves at El Malpias National Monument in New Mexico.

Bismuth and V exhibit moderate volatility in volcanic systems. As fumarolic sublimates, Bi and V fall more or less midrange between volatile (e.g. S) and non-volatile elements (e.g. U) in fumarole deposition experiments [4]. Copper occurs slightly more toward the volatile side, similar to Zn in order of sublimation. Thus Cu-Bi-V minerals may be present as the result of degassing of the lava and crystallization after the tube drains. However, all the sites that we have examined show evidence of microbial filaments, slime, and cells within the minerals. This microbial evidence poses a question: are these unusual mineral deposits the result of abiotic sublimation which are then utilized by microbial communities or are they biotic in nature and the microbial community has enriched low levels of metals from the lava as a result of life processes.

*Sulfates and carbonates.* Both calcite and gypsum are common in lava caves as crusts, protrusions, and stalactites. These minerals may be present as moonmilk, a coagulation of disordered micro-sized individual crystals, plastic in nature, and containing up to 80% water as a paste (or as a crust when dry). Moonmilk may be of biogenic origin, chemogenic or of mixed origin [5].

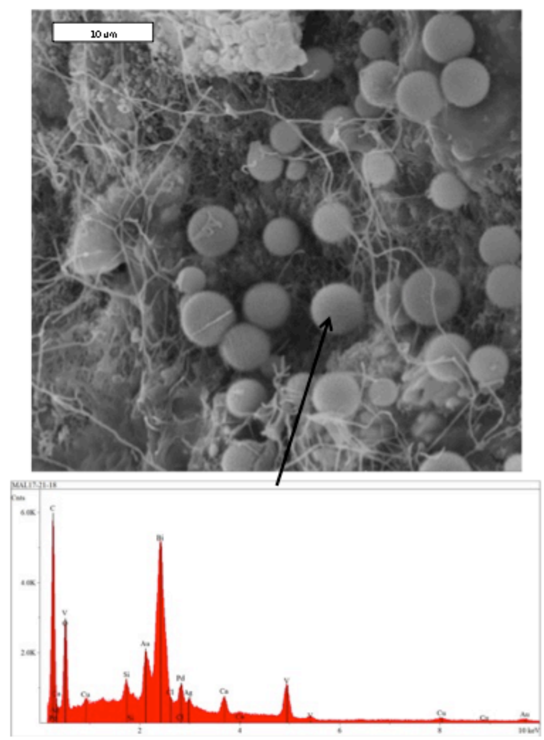


Fig. 1. Bismuth-vanadium oxide associated with microbial filaments and putative cells from a greenish mineral crust in a Hawaiian lava cave.

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**CAVE BREATHING IN A TERRESTRIAL ANALOG ATYPICAL PIT CRATER– INSOLATION INDUCED CONVECTIVE COOLING.** T. N. Titus[1], K. E. Williams[1], G. E. Cushing[1] and C. H. Okubo[1], [1]U.S. Geological Survey Astrogeology Science Center (ttitus@usgs.gov.

**Introduction:** Caves are subterranean voids that provide access to both surface and sub-surface geology [e.g. 1], as well as unique microclimates that are often exceptionally stable and benign relative to surface conditions. It has been proposed that Martian caves may preserve evidence of past life or currently harbor extant life [e.g. 2,3]. Caves may provide shelter for future human Mars explorers, protecting them from extreme temperatures and radiation [e.g. 4-6]. Caves may provide access to resources necessary for human exploration, especially water ice [5]. The suitability of caves for the preservation of past life, evidence of extant life, or human exploration and utilization will greatly depend on the cave's microclimate. Many factors can influence cave microclimates such as thermal conduction of geothermal heat, cave breathing (the exchange of inside and outside air), cold-trapping and evaporation/condensation of volatiles within the cave. This abstract focuses on one component that may contribute to cave breathing when the cave entrance is located in an Atypical Pit Crater (APC).

**APCs:** Atypical Pit Craters (APCs) exhibit a distinctive set of morphologies and thermal characteristics that set them apart from the commonly observed bowl-shaped pit craters. Instead of bowls, APCs interiors are cylindrical or bell-shaped with vertical to overhanging walls that extend down to their floors without forming substantial talus slopes. APCs are generally circular in plan view, and their maximum diameters are over an order of magnitude smaller than those of bowl-shaped pits [7]. Most APCs (~70%) have depth to diameter (d/D) ratios of >0.5, and several exceed d/D ratios of 1.5. Bowl-shaped pit craters often form in chains, and only a handful of these chains (both regionally and globally) contain APCs. Roughly 25% of all currently identified APCs formed within chains of bowl-shaped pit craters. APC diameters are usually less than a quarter of their bowl-shaped neighbors but tend to have comparable depths. It is important to note that although most pit chains on Mars formed along faults and/or in the floors of fault-bounded grabens [8], the pit chains that contain APCs consistently lack apparent spatial associations with grabens or normal faults. Most APCs are solitary, without accompanying pit chains, and are usually kilometers away from other collapse features. An example of a Mars APC with a possible cave entrance is shown in Fig. 1.

**Analog Site:** The Big Island of Hawai'i has a few terrestrial analogs for APCs. One of these, Owl Pit (also known as Wood Valley Pit Crater (WVPC) cave), formed above a dike located along Kīlauea's southwest rift zone on the island of Hawai'i [9]. Access to the dike is through a ~50 m deep collapse pit followed by an additional 50 m of scrambling through a connecting cave network. Dikes, unlike lava tubes which form near the surface, are usually inaccessible for study. This cave is unique in that its entrance is located at the bottom of a collapse pit (or Atypical Pit Crater) similar to some features observed on Mars [e.g., 7-8,10-11].

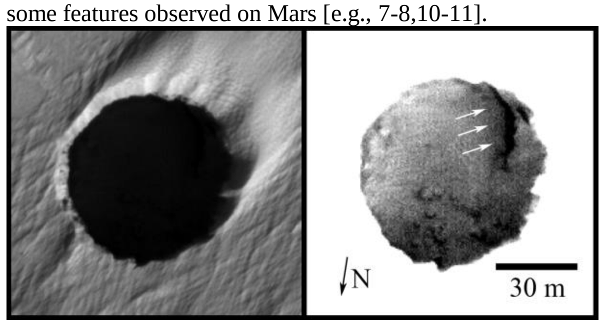


***Figure 1: HiRISE Image ESP_016622_1660. Top: A view of the APC without stretching. Bottom: A view of the APC floor where the arrow points at a possible cave entrance. Modified from [7] Credit: NASA/University of Arizona.***

**Data Collected:** We collected temperature (rock and air), humidity, and pressure data at the cave entrance (located at the bottom of the pit) (Fig. 1) and throughout the cave network (Fig. 2). An entire year of data was collected for the upper portion of the cave and ~six months for the lower portion of the cave, which included the dike. Unfortunately, we did not collect wind data from either inside the cave or near the entrance.

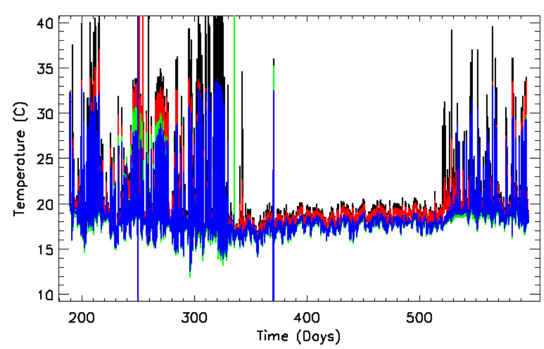


***Figure 2: Four surface temperature profile at the bottom of Owl Pit near the cave entrance. The period of low temperature variation occurs when the entrance is completely shadowed from the sun by the pit rim. Each color corresponds to a different sensor.***

**Data Analysis:** We analyzed data collected from Owl Pit cave. During the winter months, the pit wall around the cave entrance (north wall) is in direct sunlight and heat up during the day. During the summer months (Days ~ 350 to 550), the wall around the cave entrance is shadowed by the pit rim and therefore the wall remains at a near-constant temperature. (See Fig 1.)

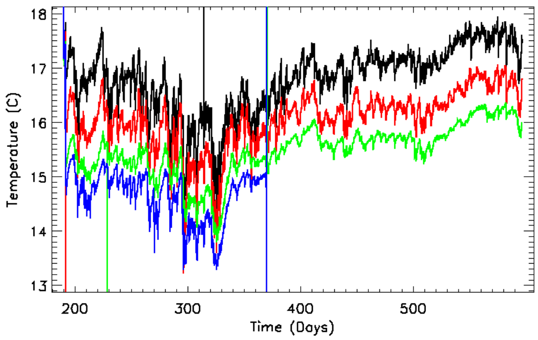


***Figure 3: Cave temperatures in descending order: black, red, green and blue.***

Over this same period of time, we see two distinct temperature behaviors in the upper part of the cave: (1) During the winter the upper portion of the cave is generally cooling and (2) during the summer this same portion of the cave is slowly warming. While these temperature trends are what one might expect for these seasons at mid-latitudes, this cave is located in the tropics. Also, the change in trends does not occur at a seasonal boundary (transition from winter wet season to summer dry season occurs ~ Day 370 from Figs 2 & 3), but rather when the cave entrance falls into or out of shadow (as indicated by the wall temperatures).

**Hypothesis:** We suggest that the wintertime cooling is caused by solar heating of the pit wall above the cave entrance. This heating causes convection to occur within the APC, thus causing air to circulate above the cave entrance. This causes a drop in air pressure at the cave entrance, thus drawing air out of the cave. Cooler air deeper in the cave is then drawn into the upper part of the cave, thus cooling it.

**The Conceptual Model:** A simplified description of the mass airflow from the cave to the pit is as follows. The Bernoulli equation may be used to characterize energy along a given streamline (say, pictured in Fig. 4 within the pit) with velocity $V_1$, initial pressure $P_0$ (in this case 101,325 Pa)

$$\frac{1}{2}\rho v_1^2 + \rho g h + P_0 + C = 0 \quad (1)$$

where C is a constant particular to the given streamline, h is a distance above some datum (e.g. the floor of the pit), ρ is air density (1.225 kg/m$^3$) and g is gravity. Assume that the air starts at rest somewhere in the floor of the pit (so $V_1$=0). For a given datum (e.g. h=10m), we may then calculate C= -101445.05.

If we assume a convective updraft velocity of 2 m/s along the warm sidewall and using the previous value of C, we find that the expected pressure drop of $|\Delta P|$ = 233 Pa. Substituting this value into the Darcy-Weisbach equation in order to estimate the mass airflow (Q, in kg s$^{-1}$) coming from the cave at the foot of Owl Pit: $Q=(|\Delta P|/R)^{½}$, where R is an empirically-determined "aeraulic resistance". Common values of R for rough conduits (such as the cave passageway) are from 0.01 to 0.5 kg$^{-1}$ m$^{-1}$ for 1 m conduits [12]. The cave passageway in Owl Pit is rough-walled with some additional boulders choking the way, hence we estimate the R value to be closer to 0.5 kg$^{-1}$ m$^{-1}$. The calculated airflow is then Q=22 kg s$^{-1}$, or 18 m$^3$ s$^{-1}$.

The flow rate described here is clearly an upper limit, (especially given that there will be inflow from sources other than the cave passageway) but it indicates that a source of cool cave air (as the temperature within the cave is much cooler than the ambient air at the surface) may be flowing up into the bottom of Owl Pit. We refer to this effect as a "convective cooling effect".

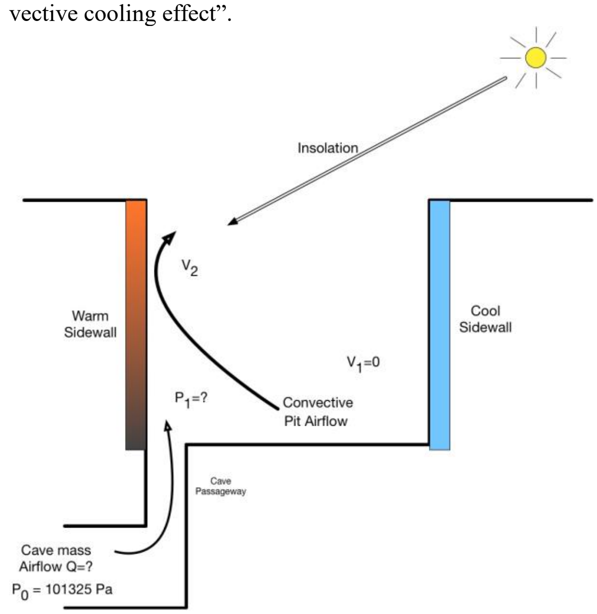


***Figure 4: Owl Pit diagram, showing expected airflow patterns due to convection.***

**Summary:** Insolation-induced convective cooling could be an important component for cave breathing where the cave entrance is at the bottom of an APC. One should also note that this affect is of the same order as expected from solar tides[13].

**Acknowledgments:** This project was partially funded through the NASA Exobiology Program. We would also like to thank G. Favre and his team for having discovered this cave and their assistance in accessing the cave.

**References:** [1] Rodriguez J. A. P. et al. (2005) Icarus, 175, 36-57. [2] Boston P. J. et al. (2006) GeCAS, 70, A60. [3] Boston, P. J. et al. (2001) aSbIO [4] Levelle R. J. and Datta S. (2010) PSS, 58, 592–598. [5] Williams K. E. et al. (2010) Icarus, 358–368. [6] Wynne J. J. et al.,2008, EPSL, 272, 240-250. [7] Cushing et al., 2015, JGR, 120(6) 1023-1043. [8] Wyrick et al., 2004, JGR, 109(E6) CiteID E06005 [9] Favre G. (2014) Stalactite, 64, 14–25. [10] Cushing G. E. (2012) J. Cave Karst Stud., 74, 33–47. [11] Okubo et al. (2015) 2IPCC, Abstract #9005 [12] Luetscher M. & Jeannin P.-Y., (2004) *Terra Nova*, 16(6), 344–350. [13] Sondag F. et al. (2003) JHyd., 273, 103-118.

**DEPLOYMENT OF AN INSTRUMENT PAYLOAD ON A ROCK-CLIMBING ROBOT FOR SUBSURFACE LIFE DETECTION INVESTIGATIONS.** K. Uckert[1], A. Parness[1], and N. Chanover[2], [1]Jet Propulsion Laboratory, California Institute of Technology. 4800 Oak Grove Dr., Pasadena, CA 91109 (kyle.uckert@jpl.nasa.gov), [2]New Mexico State University, Department of Astronomy, Las Cruces, NM 88003

**Introduction:** High value astrobiology targets on other planetary surfaces may be located in extreme environments which could be inaccessible to conventional wheeled-rovers [1]. We integrated a suite of instruments with the LEMUR 3 rock-climbing robot (Figure 1) to detect the presence of biologic activity on a vertical surface in a lava tube cave and to demonstrate autonomous climbing operations within a subsurface environment to mature this robotic platform for potential future exploration of caves and other extreme terrain on planetary surfaces [2].

**Figure 1:** *LEMUR 3 climbing autonomously at the Sweeney Granite Mountains Desert Research Center.*

**Astrobiology Payload:** The LEMUR 3 instrument suite (Figure 2) builds on the Mars 2020 rover payload for astrobiology investigations:

*X-Ray Fluorescence Spectrometer.* The Advanced PIXL Experiment (APE) instrument, based on the Mars 2020 Planetary Instrument for X-ray Lithochemistry (PIXL), measures the X-Ray fluorescence of a 100 µm diameter target following irradiation by an X-Ray source [3]. The resulting hyperspectral elemental composition maps reveal chemical variability across a sampling area and boundaries associated with geologic or biomineralized features.

*Raman/Fluorescence Spectrometer.* The Geobiology with UV Raman Imaging and Laser induced Autofluorescence (GURILA) instrument is a deep-UV Raman/fluorescence spectrometer based on the Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals (SHERLOC) instrument for Mars 2020 [4]. DUV Raman and fluorescence spectroscopy can assess a sample's habitability potential and detect the presence of biosignatures preserved in rocks by classifying organics and minerals on a surface.

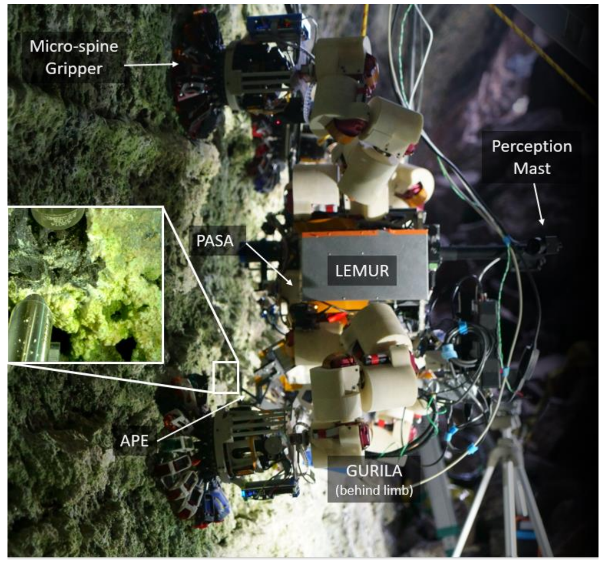


**Figure 2:** *Measuring a cyanobacteria microbial mat with instruments on LEMUR in Four Windows Cave, El Malpais National Monument.*

Unlike the Mars 2020 proximity science instruments, which are mounted to a turret, GURILA and APE are a confocal system, interrogating the same 100 µm spot on a target to produce a hyperspectral map that combines Raman/fluorescence, XRF, and context imagery. Coincident measurements of a target allow for direct comparisons between points without the need for interpolation within a hyperspectral map or requiring instrument-specific positioning systems. LEMUR does not need to prepare a surface for interrogation with a rock-abrasion tool, but instead employs a context image focus merge algorithm to autonomously move the instrument stage to the ideal focus position at each point within a mapping observation [5].

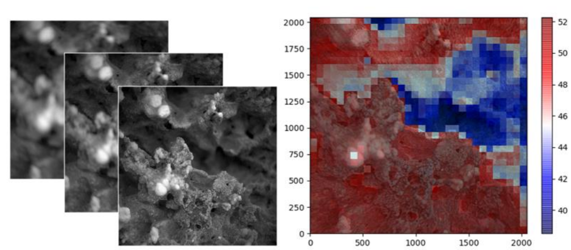

**Figure 3:** *The LEMUR 3 targeting focus merge algorithm collects a series of z-stacked images (left) and determines the distance to the focus point (right) at each position.*

*IR Point Spectrometer.* The Portable AOTF Spectrometer for Astrobiology (PASA) is an active illumination IR point spectrometer that operates in the 1.6-3.6 µm range, overlapping with the fundamental vibrational modes of hydrocarbons (C-H), hydroxyls (-OH), and other hydrogen bonded molecules [6].

**Operations:** The LEMUR 3 limbed prototype robot is a quadruped with seven joints (degrees of freedom) per limb, equipped with swappable grippers allowing the robot to climb a variety of terrains including rocky cliff faces, man-made surfaces like the exteriors of satellites, and icy environments [7-10]. The microspine gripper end effectors used in this field demonstration array hundreds of sharp hooks on compliant mechanisms that allow the gripper to conform to the shape and roughness of the rock's surface at the cm and mm scales [11].

LEMUR 3's perception system generates context imagery and three-dimensional point cloud maps of the surface (with sub-cm resolution at 10 m range) to provide input to gripper placement decisions. A machine learning algorithm identifies the safest route to a designated target based on properties of the surface, including its texture and the success of previous climbs on similar surfaces. During typical operations, LEMUR 3 generates an initial map of the area and an operator directs the robot to a point of scientific interest. LEMUR 3 chooses the safest path to this target and climbs autonomously, beginning scientific investigations upon arrival.

**Four Windows Cave:** In October 2017, we fielded LEMUR 3 with an integrated instrument payload in Four Windows Cave (El Malpais National Monument) to measure a cyanobacteria-rich basalt wall to characterize the biosignature detection capabilities of the instrument suite in an analog environment and assess the potential of this platform to acquire coincident hyperspectral maps of targets in subsurface environments.

Measurements of the cyanobacteria-rich microbial mat and the underlying basalt (shown in Figure 2) are presented in Figure 4. NIR spectra of the microbial mat are consistent with a calcite deposition overlying a basalt host rock. The low atomic weight hydrocarbon-rich cyanobacterial mat is not detected by APE, which instead reveals the calcium associated with the biological calcite precipitate that underlies the microbial mat. XRF measurements of the basalt wall show strong Ti, Mn, Fe, and Ni peaks relative to the calcified deposit, which contains a higher percentage of S and Ca. Strong organic and bound water Raman signatures associated with the microbial mat are observed, demonstrating the ability of Raman spectroscopy to identify microbial mats observed in a lava tube cave. Multivariate statistical analyses applied to these hyperspectral maps reveal further distinctions between the bare basalt wall and the organic-rich microbial community.

Performing integrated field tests at the system level forced science, instrumentation, and engineering to come together, benefiting future extraterrestrial rovers and revealing details of the concept not observable at the subsystem level. Future work will improve the reliability of LEMUR 3, mature the instrument subsytems, and investigate additional cave and astrobiologically relevant field sites.

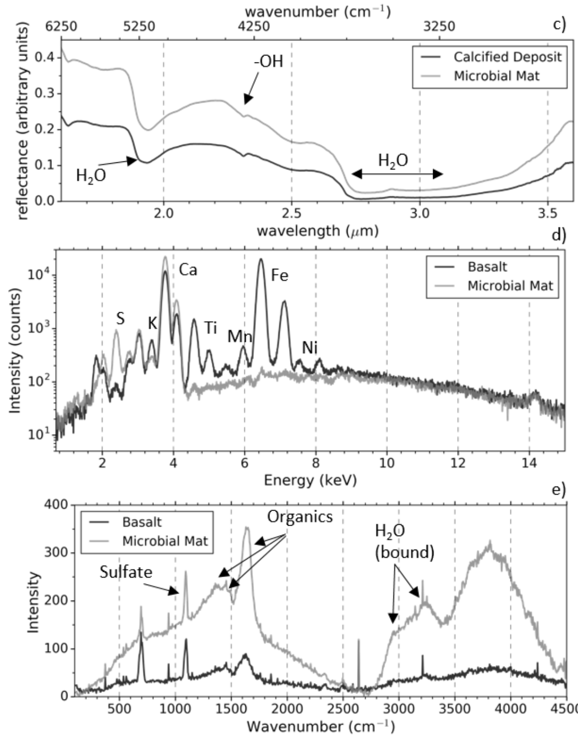


**Figure 4**: *Measurements of the cyanobacteria microbial mat in Four Windows Cave from PASA (top), APE (middle), and a laboratory Raman/Fluorescence spectrometer (bottom).*

**Acknowledgments:** This work was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). Government sponsorship acknowledged. The authors thank the NASA Planetary Science and Technology through Analog Research for funding under NNH14ZDA001N.

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**WHAT TO EXPECT IN LUNAR PITS.** R. V. Wagner and M. S. Robinson. School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-3603 (rvwagner@asu.edu).

**Introduction:** Lunar pits are an unusual negative relief landform characterized by near-vertical walls with inward-sloping rims, hypothesized to be formed by collapse into a pre-existing tectonically- or volcanically-derived subsurface void space [**1**,**2**]. There are currently 17 known pits in the lunar maria, only two of which have any apparent relation to each other, along with almost 300 pits in crater impact melt ponds, and three pits in the lunar highlands unassociated with any impact craters [**1**,**2**,**3**,**4**,**5**]. This work focuses on mare pits, as they expose cross-sections through the lunar maria, rather than simply through a likely-uniform impact melt unit.

**Data/Methods:** We used oblique Narrow Angle Camera images from the Lunar Reconnaissance Orbiter Camera with pixel scales ranging from 0.5 to 2 m [**6**] to investigate the walls of mare pits. Where multiple viewing angles were available with similar lighting, we produced stereo models of the walls to get 3D models of the pit walls and floors, along with accurate 3D locations of layer exposures [**5**].

**Morphology:** Mare pits show a sequence of morphologies, from extremely crisp features, steep funnels, and vertical or overhung walls, to rounded edges, wide shallow funnels, and significant infilling (**Fig. 1A-D**).

The pits with the largest exposures of vertical walls tend to be similar to **Figs. 1B** and **1F**, with vertical to slightly-overhung walls and a funnel that smoothly increases in slope from flat surrounding terrain to approximately the angle of repose near the pit rim (**Fig. 2**).

*Overhangs.* Our pit interior 3D models show floor extending 10 m under the east rim of the Mare Tranquillitatis pit (MTP), and 15 m under the southwest rim of the Mare Ingenii pit (MIP). In both cases, the floor slopes downward under the overhang, indicating that debris may not have fully filled in the original void space. The Marius Hills pit (MHP) and Lacus Mortis pit (LMP), by contrast, do not have significant overhangs on the modelled walls and have flat or upward-sloping floors at the wall, suggesting a more complete infilling. At MHP, the rim shows no evidence of extensive mass wasting to produce that infill, suggesting that either the original void space was very small or that the as-yet-unimaged west wall should have a significant opening.

**Layer Exposure:** Layers of apparently coherent rock do not appear in pits until near the bottom of the funnel, usually as thin exposures sticking out of angle-of-repose regolith slopes (**Fig. 2**, far left edge). It is unlikely that any exposed layers can be reached with an untethered rover due to the need to traverse unstable slopes. The main exception is LMP, where one wall has collapsed to form a ~23° slope from rim to floor, which may be traversable and would provide access to exposed bedrock on the north and south walls (**Fig. 1H**).

*Layer thickness.* We've found horizontal morphologic features, interpreted as outcrops, with a spacing of ~3.7±1.3 m at the two pits with completed models (MTP and MIP) [**5**]. These findings are in line with previous work that has found layer thicknesses exposed in impact crater walls of 2-14 m [**7**] and 15±5 m [**8**]. It should be noted that based on Earth analog studies, these morphologic layers may include multiple flow units, and are an upper limit on how thick individual flows can be [**9**].

*Inter-layer disruptions.* MTP has a >8 m deep recess on the west, north, and possibly east walls at 40 m depth, suggesting a strength discontinuity- possibly

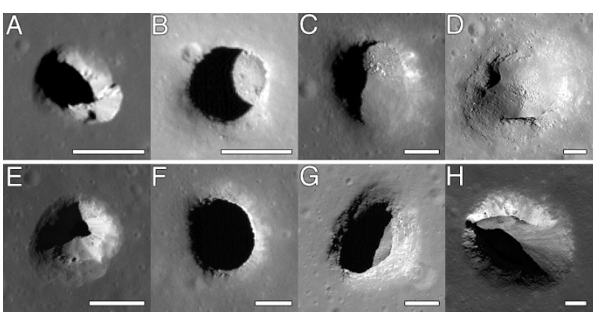


**Figure 1:** *A-D)* Examples of mare pits exhibiting a range of degradation states, from nearly pristine (*A*) to highly degraded (*D*). *E-H*) Other pits mentioned in this abstract. *A)* Schlüter. *B)* Marius Hills. *C)* Central Fecunditatis. *D)* Insularum. *E)* Southwest Fecunditatis. *F)* Tranquillitatis. *G)* Ingenii. *H)* Lacus Mortis. Scale bars are 50 m, all panels have similar incidence angles.

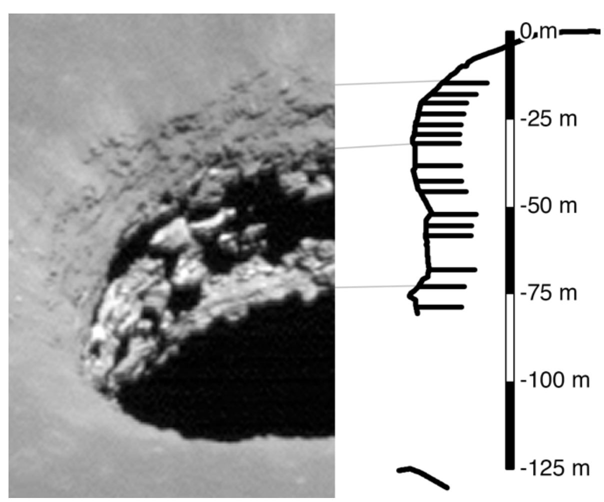


**Figure 2:** Mare Tranquillitatis pit, oblique view of east wall (*left*) and cross-section of 3D model (*right*).

evidence of a buried layer of unconsolidated material, the most likely candidates for which would be a layer of pyroclastic material, a paleoregolith that developed between mare flows, or ejecta from a nearby impact crater.

**Potential *in-situ* observations:** *In-situ* observations of mare pit walls could constrain the timing, volume, and flow rate of the individual eruptions that formed the lunar maria, without any complicating alterations by impact processes as would be found by traversing one of the crater wall layer sequences from [**7**] or [**8**]. A good instrument suite would constrain all of those factors, as well as allow correlation between flow units in the wall and samples or orbital observations from elsewhere on the Moon.

*Instrumentation.* A minimal sensor suite to discriminate flow thicknesses and mineralogies from the rim or floor would include a high-resolution monochrome camera and a visible/NIR spectrometer with a narrow field of view and high spectral resolution to determine the mineralogy of individual layers, and in particular to discriminate the orthopyroxene/clinopyroxene ratios.

Surficial coatings of fine-grained material may be a concern with spectral observations, especially for the upper layers. In MTP, the albedo of the wall changes abruptly at ~40 m depth, where there is an overhang which may shield the lower (brighter) wall from infalling debris (**Fig. 2**). This albedo boundary is not obvious at the other large pit with an overhung wall (MIP), but that may be due to illumination angle effects, as the only wall seen so far below the MIP overhang is facing downward, away from the Sun, whereas MTP has vertical walls both above and below the overhang.

With a tethered robot capable of rappelling down the wall (e.g. [**10**]), spectral analysis could be supplemented with contact elemental abundance instruments (such as APXS or Mössbauer spectrometers), as well as microscopic imagers to determine crystal size and thus cooling rate. Contact would also allow a surface preparation tool, like the Rock Abrasion Tool on the Mars Exploration Rovers, to remove any problematic dust coatings.

Collection of samples from a pit wall would allow precise age dating of individual flows and more detailed analysis of how the source magma or magmas for the flows evolved over time, and might allow analysis of exotic materials such as ancient solar wind particles emplaced between flows.

**Human Habitability:** We also made preliminary estimates of the amount of radiation exposure within lunar pits in the absence of any caves or overhangs, using simplified geometric models [**3**]. We found that ~15% of impact melt pits and six mare pits (**Figs. 1A, B, E, F, G, H**) reduced annual radiation exposure (ignoring solar flares) to levels allowed for civilian radiation workers. We found access to the interiors highly-shielding pits to be the most difficult aspect of using them for shelter; of the mare pits, only the floors of LMP and possibly MIP could be accessed without a long free-hanging descent below a loose debris slope.

**Conclusion:** Between pits and crater wall exposures it is now certain that significant portions of lunar mare were emplaced as relatively thin flows. Lunar mare pits expose up to ~100 meters of mare flow units, and could provide a detailed look into the history of the flows that created the maria, with >30 m exposures in at least six different maria allowing for comparative studies. The biggest outstanding question about pits themselves is the source of the original void space into which mare pits collapsed. Current orbital evidence is insufficient to distinguish between collapsed lava tubes, magma chambers, or tectonically-formed voids.

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**Appendix A: New mare pit:** Since our last publication ([**5**]), we have located one new mare pit, in Mare Serenitatis (**Fig. 3**). Located at 35.104°N, 17.402°E, the pit is ~25×17 m across, not including the funnel, and at least 22 m deep from the top of the funnel (the floor has not yet been imaged). The pit is located a few hundred meters from a kilometer-wide, ~150 m deep elliptical depression that may be a volcanic vent.

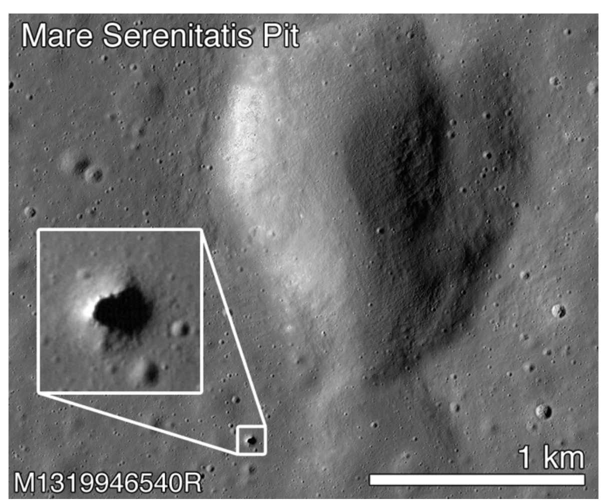


**Figure 3:** Newly-discovered pit in Mare Serenitatis.

**MICRO-ROVER EXPLORATION OF LUNAR PITS DEPLOYABLE BY COMMERCIAL LANDER.** W.L. Whittaker[1], H.L. Jones[1], U. Wong[2], J.S. Ford[1], W.C. Whittaker[1], N. Khera[1], and A. Horchler[3], [1]Carnegie Mellon University (5000 Forbes Ave, Pittsburgh, PA 15213; {red|heatherljones}@cmu.edu), [2]NASA Ames Research Center (uland.wong@nasa.gov), [3]Astrobotic (andrew.horchler@astrobotic.com).

**Introduction:** Commercial moon landers have, for the first time, made regular, affordable, lunar surface missions realities. However, since their payloads are currently limited in mass, volume and bandwidth, these constraints beg the question of whether such missions can possibly achieve purposeful, high-return pit exploration. This paper conceives high-return pit explorations achievable by the technologies of our time that can be delivered by these commercial landers and economical missions.

Former and current counterparts to the "Skylight" missions presented here include descending into or landing directly onto pit floors. Our own earliest concept envisioned a heavier lander as a flyover explorer, then landing to deploy a rover for modeling from the pit's rim [1,2,3,4]. The missions presented here embrace the small but existing landers of our day and smaller micro-rovers that they can deploy. Subsequent concepts by others have a spacecraft land directly in a pit [5], or land hardware massive enough to anchor for tethered pit descent [6]. These mission concepts require significant precision landing capability and landers that do not exist. They also rely on robot developments and technology maturation that are beyond immediate timeframe.

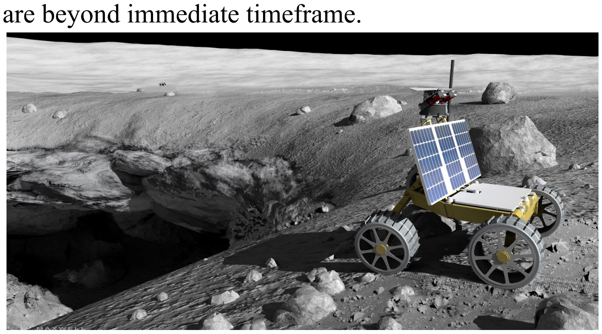

**Figure 1. Pit exploration mission concept**

**Purposeful Near-Term Missions:** We conceive "Skylight" missions to explore and model lunar pits. We constrain to landers, rovers and technologies that exist or are underway in current maturation programs. The missions seek to map pits and discover caves with merits advantageous to human presence. Beyond cave discovery, Skylight missions will determine pit morphology, rim geomechanics, the unique issues of rim navigability, rim terramechanics, and the existence of overlooks and rappel routes for future initiatives. The primary science products from which the studies and observations derive will be vast, high-fidelity, high-coverage models of pits and their surrounding terrains as viewed by rover from the rim. Additionally, the missions will evaluate and evolve performance of the landings, micro-rovers, exploration autonomy and pit modeling technologies that make the missions possible.

Skylight missions compute pit models from imagery acquired by micro-rovers while circumnavigating lunar pits. The landers and rovers of these missions are solar-powered without isotopes to survive a night. Hence, robot traverse and model computation must proceed at high cadence to complete operations within a single lunar illumination period. The mission elements and their technologies include precision landing, micro-roving, pit exploration autonomy, in-situ pit modeling, and the aggregate of all these to complete mission-in-a-week..

**Peregrine Lander:** Peregrine is characteristic of commercial landers that are tracking for first lunar touchdowns in 2021, then repeated landings thereafter. Although small, Peregrine is capable of deploying one or more pit exploration micro-rovers per mission. Pit missions are distinct from all rover missions to date that target regions versus a point feature. Pit missions require some degree of precision. Precision landing capability is under development for landing Peregrine reasonably near lunar pits, but without the ultra-precision suggested for landing in or exactly on the rim per alternate scenarios. Reasonable pit proximity is advantageous for minimizing rover driving distance and comm range rover-to- pit.

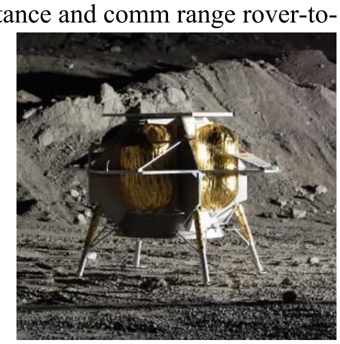

**Figure 2. Peregrine Lander**

**Pitranger Micro-Rover:** PitRanger is under development as a small, fast, autonomous solar rover. It must be small by virtue of lander volume and mass constraints. Such a small rover cannot carry or power a direct-to-Earth radio, so that compels autonomy when out of wireless comm range for data downlink via the lander. Since these "missions-in-a-week" limit time, and this class of pit modeling requires substantial driving range. For such range, these rovers must exhibit unprecedented speed and cadence relative to priors. Prior rovers are myopic to view for safeguard and navigation. PitRangers must additionally provide telescopic optics to acquire long cross-pit and down-pit views for modeling. These rovers must feature large tipover stability margins and high egress mobility for acquiring plunging views from precipitous pit rims.

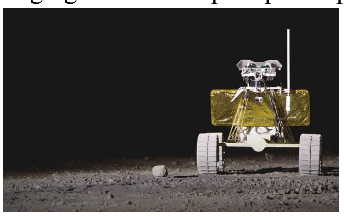

**Figure 3. PitRanger Micro rover prototype**

**Pit Exploration Autonomy:** Pit exploration autonomy consists of the behaviors and intentions to occupy vantage points, acquire imagery essential for pit modeling, scallop and encircle a pit, and make judgements like tradeoff of detail for coverage. This is achieved by layering methodologies like next-best-view planning, energy-maximizing sun-synchrony, brinkmanship precipice approach and exposure bracketing over conventional robotic sense-plan-act navigation.

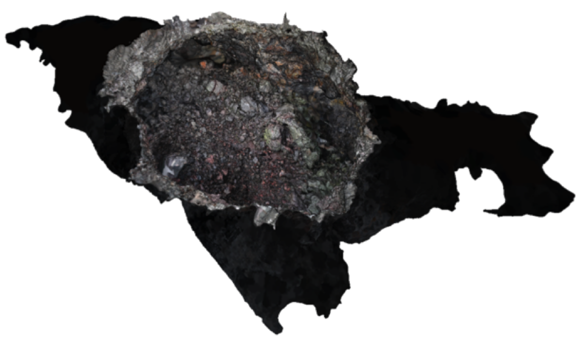

**Figure 4. 3D reconstruction of a terrestrial skylight using images taken from pit rim [7].**

**In-situ Pit Modeling:** Pit modeling processes imagery with structure-from-motion and simultaneous localization and mapping to generate vast, high-fidelity, highly three-dimensional pit models. The technology concurrently determines the poses from which each image was acquired and performs multi-pose stereo to model the geometry. The process is extremely process-intensive. For that reason this computation is performed aboard the lander. The raw imagery is massive data and couldn't possibly be conveyed to Earth by this class of lander during the short duration of these missions. The model resulting from the vast data and computation is, however, compact and viable for Earth transmission along with many raw images.

**Mission economy and way forward:** Skylight is presented as a class of micro-rover pit exploration that is deployable by lander, precision landing, rover, autonomy and modeling technologies that are all exist, are in flight development or are underway in technical maturation programs. The paper sets forth the scenario in which these can be combined serendipitously to accomplish highly-economical, high-value, near term missions. There is no representation that such mission or missions are chartered or commissioned.

**Support, Maturation and Acknowledgments:** Lander development of Peregrine and counterpart landers have been public-private initiatives supported by CATALYST and CLPS in addition to private resources. Precision landing is supported by Tipping Point. Micro-roving is supported by NIAC Ph III with complement to the MoonRanger LSITP flight program. The mission concept, pit exploration autonomy and pit modeling are funded by a NASA Innovative Advanced Concepts Phase III maturation project.

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**TUBULAR HELLS: NEW MEASUREMENTS OF LUNAR MAGMA RHEOLOGY AND THERMAL PROPERTIES APPLIED TO THERMAL EROSION AND LAVA TUBE FORMATION**

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**Introduction:** Lava tubes are potential sites for habitation on the Moon and other bodies, as long as their roofs are intact. Tubes form where surface flows develop solidified insulating roofs, allowing long-distance transport [1,2], and frequently erode down into their substrate [3,4]. There are more than 200 sinuous rilles on the Moon, thought to be channelized lava flows, and thermal erosion was probably the dominant incision mechanism in over 75% of these [5]. While the vast majority of rilles are associated with the lunar mare and Procellarum-KREEP terrane, some emerge from the anorthositic highlands and flow into the mare [5]. Potential lava tubes have also been identified by the presence of pits interpreted as skylights in an impact melt sheet associated with the crater Philolaus near the lunar north pole [6], although most pits in impact melts may result from collapse into voids formed during protracted cooling of a stationary melt sheet [7].

**Controls on Thermal Erosion:** The efficiency of thermal erosion depends strongly on magma physical properties including viscosity and density, thermal properties including heat capacity, thermal conductivity, and enthalpy of crystallization, and on environmental factors including ground slope and substrate composition [8]. The physical and thermal properties depend strongly on magma composition [9, 10, 11], which on the Moon include several subgroups of lunar mare basalt, and KREEP basalt.

Once lavas begin to crystallize, their rheology depends on strain rate as well as the shape- and size-distribution of the crystal cargo [9]. Models require increasingly large and tenuous extrapolation, and the best approach is direct measurement.

**An example using KREEP:** We studied the rheological evolution of a crystallizing lunar KREEP analog by concentric cylinder viscometry. At the liquidus temperature of 1220 ℃, liquid viscosity is ~50 Pas, similar to Hawaiian lavas [10]. At successively lower temperatures, crystal fraction and effective viscosity both increased (Fig. 2). By 1177˚C the crystal fraction was ~17 volume %, and the viscosity had increased to >1000 Pas.

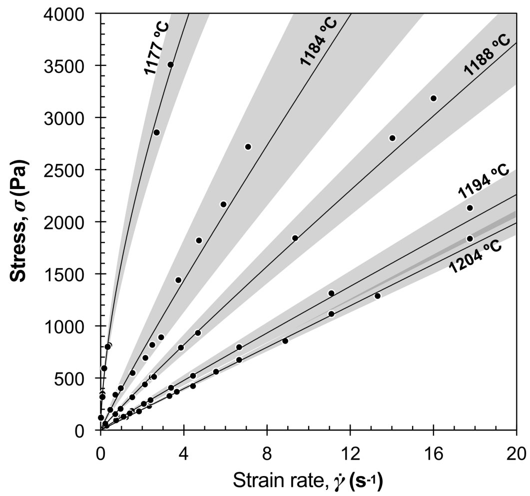


**Figure 1. Rheological data and best-fit flow curves**. Note non-Newtonian behavior (shear-thinning) at lower temperatures and higher crystal fractions.

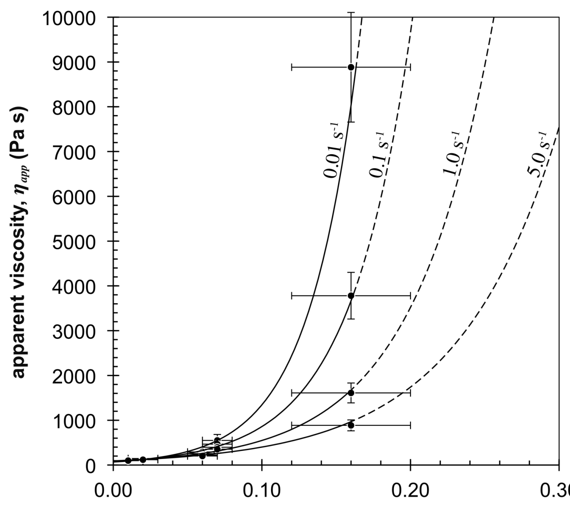


**Figure 2. Apparent viscosity vs crystal fraction**. Note the rapid increase in viscosity and importance of strain rate in determining apparent viscosity.

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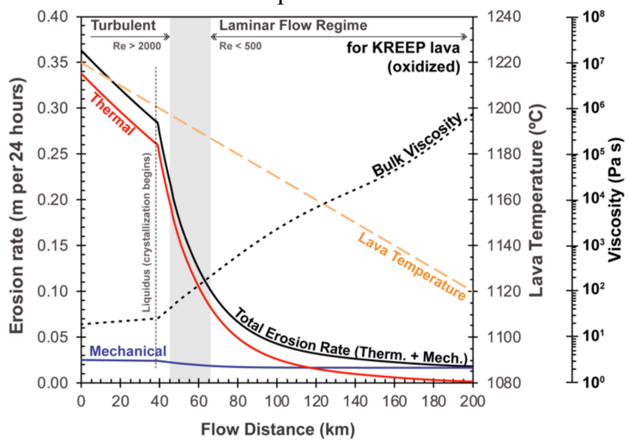


**Figure 3. Temperature, bulk viscosity, flow regime, and erosion potential of KREEP lavas**..

Example calculations are shown in Figure 3, for thermo- mechanical erosion rate as a function of flow distance for a KREEP analog basalt erupted on the lunar surface with a continuous channel width of 480 m and lava thickness of 10 meter on a slope of 0.2˚. Erosion rate quickly diminishes upon cooling below the liquidus due to increasing viscosity (in turn lower flow velocity and strain rate). Viscosity calculations include yield strength of the lava. The gray band indicates transition from turbulent to laminar flow regimes shortly after lava cools below the liquidus. This basic model assumes a constant cooling rate of the lava erupting about 20 ˚C above the liquidus temperature.

**Future work:** The possibility of lava tubes forming in impact melt sheets opens up a much wider array of compositions (from anorthosite liquid through the mare liquid, and everything in between) for study [12]. In addition, these superheated lavas may be much more effective at forming lava tubes than normal volcaniclava flows.

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**Innovating Lunar ISRU Technologies for Long-Term Exploration and Habitation.** A. D. Whizin[1], P. Metzger[2], C. Dreyer[3], C. Phillips-Lander[1], C. Asquith[1], R. Focia[1], and K. Retherford[1]. [1]Southwest Research Institute (6220 Culebra Rd., San Antonio, TX, 78238), [2]University of Central Florida, [3]Colorado School of Mines. (author contact: awhizin@swri.edu)

**Introduction:** We are developing an instrument-level architecture for *magnetic induction additive manufacturing*, which when applied to off-world applications, is a potentially revolutionary technique for the ISRU of lunar feedstocks. Additive construciton (AC) is the use of printers or extruders to build up three-dimensional objects layer by layer (e.g. 3D printing). Generally, this is done by heating a feedstock material and producing shapes or layers. In this case, this is accomplished through Magnetic Induction (MI) heating (a common method in industrial metallurgy), where the feedstock is melted in a metal vessel inside an oscillating magnetic field. AC could revolutionize the robotic construction of lunar bases (see Figure 1), create landing pads, roads, and other structures to increase mobility, accessibility, and enable exploration of caves and other potentially useful or resource rich sites on the lunar surface. This project involves studying MI AC of lunar soils by making regolith products and determining their efficiency for lunar surface applications (by measuring power requirements and mechanical strengths) and beginning work on a new resource extraction device integrated into the MI print head (Figure 2).

*Lunar Resources* – It is now known that lunar surface materials can provide numerous resources if properly excavated and utilized. Analyses of both Highlands and Mare Apollo samples demonstrated that either type of lunar regolith contains usable volatiles such as OH, $H_2O$, $H_2S$, $CO_2$, $NH_3$, $SO_2$, and CO, which are released by heating to 1200°C [1, 2]. Water has been detected in the LCROSS impact-induced plume in Cabeus crater [3, 4, 5, 6], and over much of the lunar surface at levels of hundreds of ppm [7, 8, 9]. The lunar regolith, comprised of iron- and titanium-bearing silicates [10], is highly valuable as a construction material for building habitats, roads, berms, walls, and other support structures, including astronaut habitats, which could be built in or in close association with cave-like features which offer stable temperatures of ~-13ºC at Tranquililitatis pit [11].

**Figure 1:** Concept of Autonomous AM on the Moon.

*Lunar Geologic Features* – There is a great deal of speculation about the possibility of lunar caves, pit craters, and exposed bedrock providing not only valuable resource deposits, but scientific insight into the geologic past of the Moon, including volatile budgets and transport, the timing of magmatic events, faulting, weathering, and the relationship to between the transition from regolith to bedrock [11].

**Additive Manufacturing on the Moon:** The use of lunar regolith in AM has been an active area of research for many years, focusing on laser/solar heating and sintering, polymer binders, resistive heating, and microwave sintering ([12, 13, 14, 15, 16, 17, 18]; and many references therein). MI heating and sintering has never been applied to additive manufacturing of lunar regolith and has the potential to address some of the shortfalls of the other methods. This project aims to advance the MI for ISRU concept by addressing unanswered questions about the operation, engineering, and efficacy of this application to off-world problems.

**Figure 2:** A steel crucible containing lunar regolith simulant heated to 1500ºC.

MI heating and sintering works by applying an alternating current through loops of copper coils wrapped around a ferrous metal crucible (i.e., a bored iron cylinder or vessel). The oscillating magnetic field from the coils (solenoid) induces a magnetic field in the crucible, which, based on Lenz's law ($E = -N\partial\Phi B/\partial t$), produces an electromotive force in the opposite direction for *N* loops resisting each subsequent change in the applied field, producing eddy-currents in the metal. This current-induced "friction" rapidly heats the metal, and the lunar regolith that will be placed inside. MI printing is fast, simple, can function in a vacuum, and low-cost, and potentially a game-changing technology for lunar base-construction.

Different types of induction sintering are possible with this methodology. Our goal is to apply it in three ways to the building and paving on the lunar surface: 1) 3D printing through extrusion, 2) brick making, and 3) contact-less sintering/paving of the surface.

**Experimental Approach:** The basic operating procedures and thermal responses to lunar regolith are being characterized by placing regolith into a crucible that is surrounded by copper tubing (Figure 2). As a controlled A/C current from a power source is passed through the wires, the crucible and regolith heat up due to eddy currents. Conduction between the crucible and regolith heats the sample until molten. The print head then extrudes the desired molten cylindrical product at a rate controlled by the composition of the sample, input power, packing density, and possibly atmospheric pressure (examples of induction prototype shown in Figure 3).

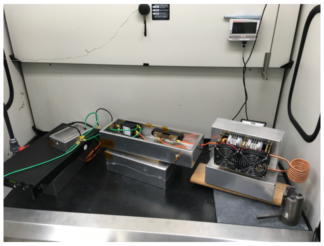
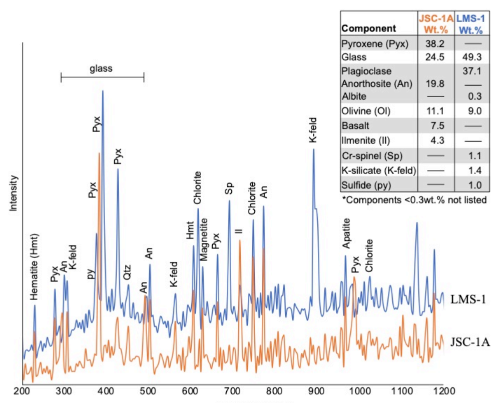


**Figure 3:** Breadboard level prototyping of the 30-amp magnetic induction heating circuit.

*Advancing Lunar Volatile Capture Technology* – The magnetic induction printing technology is also able to incorporate volatile capture of released gases from the heating of the soil. We are working to study the integration of this advantageous ISRU technology. Based on the types and abundances seen in remote sensing and in the LCROSS impact, there appears to be a strong case for implementing this type of gaseous volatile capture.




| Component | JSC-1A Wt.% | LMS-1 Wt.% |
|---|---|---|
| Pyroxene (Pyx) | 38.2 | — |
| Glass | 24.5 | 49.3 |
| Plagioclase | | 37.1 |
| Anorthosite (An) | 19.8 | — |
| Albite | — | 0.3 |
| Olivine (Ol) | 11.1 | 9.0 |
| Basalt | 7.5 | — |
| Ilmenite (Il) | 4.3 | — |
| Cr-spinel (Sp) | — | 1.1 |
| K-silicate (K-feld) | — | 1.4 |
| Sulfide (py) | — | 1.0 |

*Components <0.3wt.% not listed

**Figure 4:** Raman spectra of lunar regolith simulants.

*Raman Characterization of Lunar Simulants* – We are using a novel cavity raman spectroscopy technique to study the compositions and mineralogy of various lunar simulants we plan to use in the MI printing (Figure 4). By analyzing the differences in composition coupled with the result form the sintering tests, we can better understand which types of regolith are better suited for induction sintering, and better tailor the induction system to handle unknown regolith materials that a rover may encounter while construction an outpost on the Moon.

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**AIRBORNE RECONNAISSANCE MISSION CONCEPT FOR ORGANICS IN A MARTIAN CAVE.** R.C. Wiens[1], P. Gasda[1], A. Misra[2], L.H. Matthies[3], W. Johnson[4], L.A. Young[4], S. Clegg[1], and S. Maurice[5], [1]LANL (rwiens@lanl.gov), [2]U. HI, [3]JPL, [4]ARC, [5]IRAP.

**Introduction:** The search for life on Mars has followed milestones of finding evidence of water from orbit [1], to showing that long-lived freshwater lakes existed [2], to finding organic molecules [e.g., 3] and long-chain organics [4]. Still, given the radiation and cold surface environment, more habitable abodes for life are likely underground. Lava-tube caves exist on Mars [e.g., 5 & refs. therein], and are the "easiest" access to the martian subsurface. Such access is still not easy, as most cave entrances have vertical drops of tens to >100 m. Porting organic-detection hardware to the floor of a Mars cave is a daunting task. Here we present an organic-searching Mars cave mission concept that is feasible with current technology. This mission would be a "first look" into a Mars cave to reveal its environment.

**Mobility:** Entrance into Mars "skylight caves" (lava tubes with holes to the surface) may be most feasible with a drone. The 2020 Mars Helicopter Technology Demonstrator [6] is a coaxial helicopter with a rotor diameter of 1.2 m and a total mass of ~ 2 kg, capable of flying a few hundred meters per sol in ~ 90 s flights at the elevation of Jezero Crater (~ -2.5 km), carrying a cell phone camera as payload. Recent scalability studies have analyzed larger coaxial and hexacopter multi-rotor designs, aiming to increase payload to several kilograms, range to several km, and flight endurance to several min., depending on elevation and other factors. One class of concepts is a hexacopter with total deployed diameter on the order of 4 m that folds for interplanetary cruise to fit in the volume of the legacy aeroshell.

Most feasible Mars caves are atypical pit craters (APCs), which may have accessible passage at the base of the entrance pit [5]. Most occur at relatively high elevations, but some are in the -1 km to -2 km range NW of Elysium Mons, where it appears that a hexacopter in the total mass range of ~ 20 to 30 kg could carry payload on order of 5 kg for several minutes and a few kilometers per sol. A few APCs on the southeast flank of Elysium Mons and in the Tharsis region occur at elevations of +2 to 2.4 km, which may allow payload on the order of 2 kg for flights on the order of 1 km.

**Payload:** We propose an ultralight-weight payload that does not require a (risky) landing in the cave itself.

*Imaging.* The current Mars 2020 helicopter is already equipped for imaging (necessary for auto navigation). Lighting in the cave will be provided by either the OrganiCam laser (below) or a pulsed LED.

*Surface Organics* are identifiable via time-resolved fluorescence imaging. The Biofinder [7], a COTS instrument developed by U. HI, demonstrated that such an imager a) can clearly distinguish organic fluorescing materials from mineral fluorescence via ns time resolution and b) has detection limits in the ppb range at several m. A more flight-like prototype, OrganiCam, is under assembly at LANL (Fig. 1) using flight-qualified SuperCam technology. A 5 ns Nd:YAG laser beam is dispersed over the region of interest (several $m^2$). A camera with a filter to remove returned laser light passes the fluorescence images through a time-gated intensifier to a CCD. OrganiCam also contains a spectrometer using the same detector. It is very light-weight (0.7 kg w/o electronics, before mass reduction for flight) and uses rad-hard lenses.

*Atmospheric Sensing:* We propose a volatile organic carbon (VOC) sensor as the third instrument. VOC sensors are highly miniaturized and highly sensitive. Specifics of this payload element are still open.

**The Mission:** In response to a call for Mars mission concepts, LIFE COVE (Laser-Induced Fluorescence Exploration of Caves for Organics and Volatiles using an Elevated platform) was submitted. A Mars drone with a payload capability of 4 kg lands within 50 km of the cave and uses multiple flights to arrive at the entrance. There it hovers over the skylight entrance for initial imaging and VOC assays. On next flights it enters the cave for imaging & organic surveys. It never needs to land in the cave, instead exiting to recharge.

**Required Technology:** Caves are at higher elevations than previous landed missions and occur in terrain that is likely to be challenging for safe landing. This will require advances in Mars entry, descent, and landing (EDL) capability to land safely and precisely at these elevations (e.g. ~ -2 to +2.4 km). Autonomous navigation for drones is progressing rapidly on Earth, including for cave-like scenarios, powered by miniaturized sensors and powerful onboard processors from the smartphone industry. The OrganiCam prototype is currently being assembled, and should provide solid detection limits, expected at the level of organics detected by the SAM instrument (10s-100s ppb range). A VOC analyzer should be very feasible at Mars pressures.

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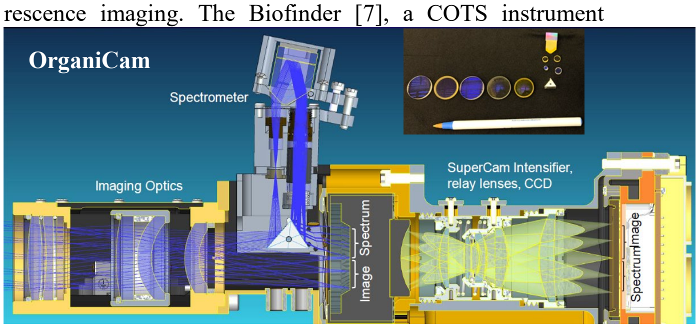


Figure: Prototype OrganiCam time-resolved laser-induced fluorescence imager and spectrometer capable of uniquely imaging organic materials to ppb abundances. The gated image intensifier and detector (right side) are Mars 2020 SuperCam heritage. The inset shows the size of the camera lenses with a pen for scale. Laser and electronics are not shown. The unit is currently being assembled. It is capable of 100 ns intensified images and spectra.

**PROPOSED MISSION ARCHITECTURE AND TECHNOLOGY REQUIREMENTS FOR ROBOTIC AND HUMAN EXPLORATION OF MARTIAN CAVES.** J. J. Wynne[1], C. M. Phillips-Lander[2], and T. N. Titus[3]; [1]Department of Biological Sciences, Merriam-Powell Center for Environmental Research, Northern Arizona University, Flagstaff, AZ, jut.wynne@nau.edu; [2]Space Science & Engineering Division, Southwest Research Institute, San Antonio, TX; and, [3]Astrogeology Science Center, U.S. Geological Survey, Flagstaff, AZ.

**Introduction:** Since the identification of atypical pit craters in 2007[1], the number of cave-like features resolved on Mars has steadily increased. To date, at least 1,035 features have been cataloged[2]; most of these features occurred within regions identified, via thermal inertia and numerical modeling, as capable of maintaining stable water ice deposits underground[3] (**Fig. 1**). In addition to serving as veritable laboratories to investigate numerous questions related to planetary geology, martian caves: (1) represent one of the best locations to search for evidence of life, (2) may provide access to water ice deposits for human use, and (3) are the safest places for human habitation.

However, beyond their locations and elementary entrance characteristics, we know little about these potential access points to the martian subsurface. How do we identify the most important candidates for astrobiology research versus human use? Importantly, how can we evaluate and rank these features? Moreover, what are the key planning elements to include in robotic and human missions? Here we briefly describe a mission architecture for robotic and human cave missions, while identifying critical lacunas in technologies that must be addressed to make such missions viable, as well as to help ensure mission success.

**Mission Architecture:** We propose a simplified process to advance martian speleology from a rudimentary understanding to acquiring the data required to evaluate and select the best candidates for astrobiological investigations and human outposts (**Fig. 2**).

*I. Remote Detection.* ***Development Status (DS):*** Combining thermal and visible imagery is a useful approach for detecting terrestrial[4-6] and martian[1,2,7] cave entrances, while gravimetry has been applied to estimate the subterranean extent of lunar caves[8]. ***Technology Requirements (TR):*** A multispectral approach will be most effective to most accurately identify and examine martian caves of interest; this

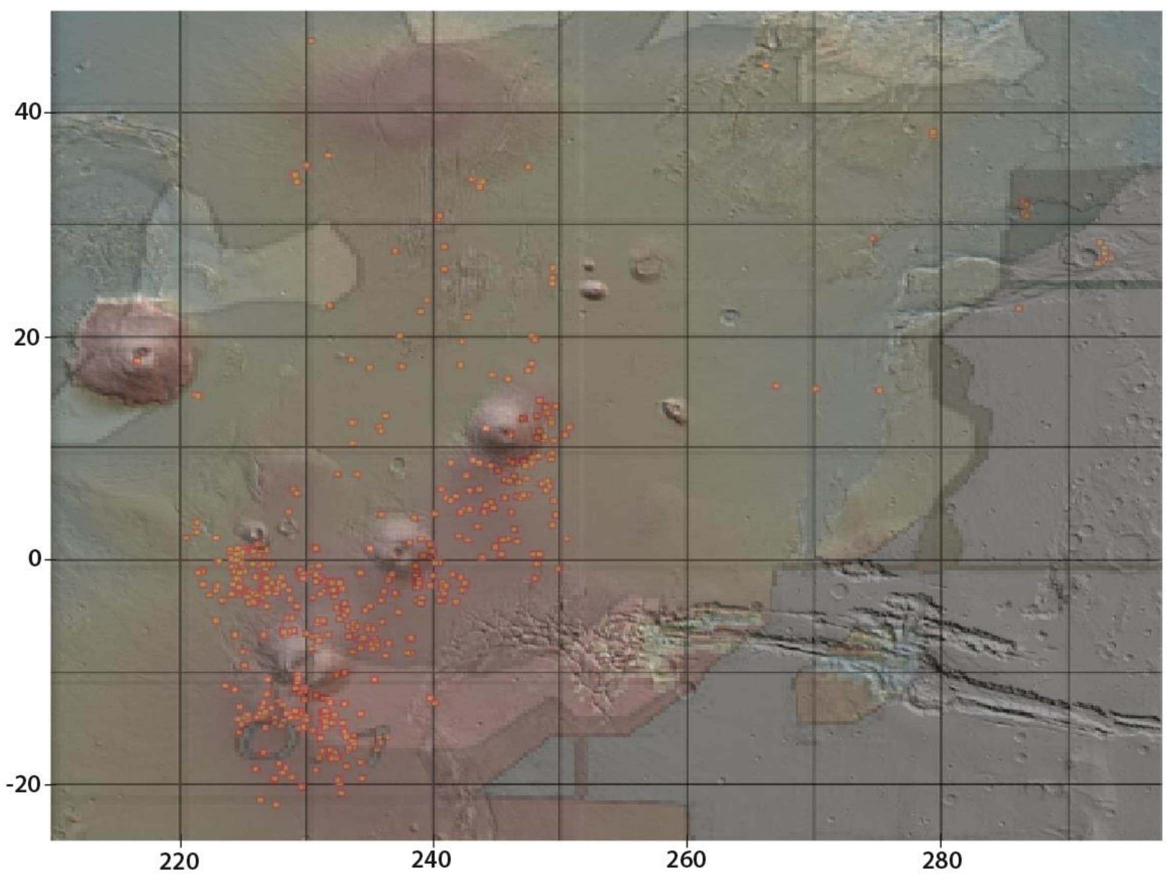


**Fig. 1. Global Mars. Map overlay of cave locations (red and yellow dots)[1] primarily in the Tharis Rise (red), which is an area modeled to support water ice within caves[3].**

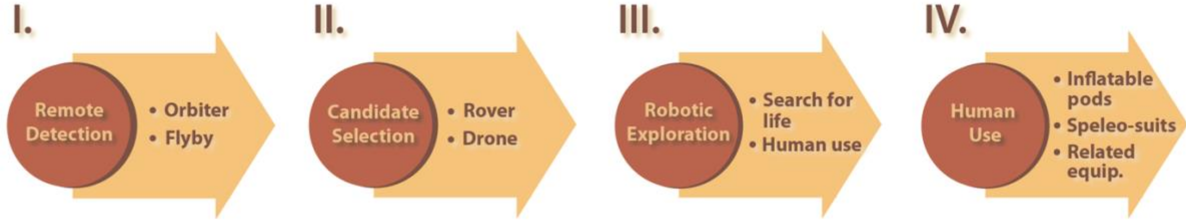


**Fig. 2. Proposed architecture for robotic and human exploration missions to martian caves. Development status (DS) and technology requirements (TR), for each of the four steps, are discussed.**

should include the addition of LiDAR and gravimetry data. In concert with thermal and visible imagery, LiDAR should be assessed for initial detection analysis, and the limitations of gravimetry need to be evaluated. Once entrances have been confirmed using thermal, visible and LiDAR data, gravimetry may ultimately be applied to differentiate large passages and rooms (conducive to human habitation) from deeper, more expansive caves (those likely to score highest as astrobiology targets).

*II. Candidate Selection.* In addition to the techniques elucidated in 'step I', these criteria (i.e., characteristics of regolith and local terrain; landing, power, and traversablity considerations for robotics; and, co-location of multiple high priority candidates) may be used to down-select the +1000 caves to a manageable number. Subsequently, either rovers or rotorcraft drone systems could then conduct a more detailed analysis to further pare down the number of suitable candidates. ***DS:*** Rovers currently used in Mars missions may be an effective tool for surveying entrance characteristics. Importantly, the Mars 2020 rover will include a small rotorcraft scout as part of its payload[9]. ***TR:*** Post-Mars 2020, NASA will have 'flight proven' Mars helicopter technology, which could be further refined and used to examine cave entrances.

*III. Robotic Exploration.* Given that most cave floors are littered with breakdown (cave ceiling material resting on the cave floor), dual-axel rovers will be unsuitable for most cave environments. ***DS:*** Currently, one of the best technologies to overcome this hurdle is the Limbed Excursion Mechanical Utility Robot (LEMUR) 3. Once fully developed, the world's first rock-climbing robot will be able to independently identify the most suitable travel route through a cave's entire 3D interior. This platform may be used to acquire, process, and analyze samples to search for evidence of life, as well as assess the structural stability of cave interiors for human habitation. ***TR:*** Currently, LEMUR 3 is rated at a technical readiness level (TRL) of 6. Substantial advancements (through adequate funding) will be necessary before the LEMUR platform can be elevated to 'flight qualified' status (TRL=8).

*IV. Human Use.* ***DS:*** Prototypes for inflatable and hybrid inflatable-rigid[10] human habitats are in the proof-of-concept stage and have been successfully tested in computer simulations. Current spacesuit technology, which has been largely unchanged since the Apollo program and is currently used for EVAs on the International Space Station, will be unfit for use underground – due to restricted mobility and the high risk of suit breech. BioSuit technology[11] is a svelte-fitting alternative that offers significant improvements to traditional spacesuits. These suits, and associated donning and doffing technologies, are still at the proof-of-concept stage[12]. To be used in caves, BioSuits must be extremely ruggedized to become puncture and abrasion resistant. Finally, technical climbing and work equipment for conducting science operations in spacesuits does not exist for underground use, nor have there been any studies to inspect the feasibility of such technologies for extraterrestrial cave applications. ***TR:*** All of these technologies need to either be developed and/or evolve from proof-of-concept to 'flight qualified' status (i.e., TRL=8) before we can safely enter, work, and live in the martian subterranean realm.

**Conclusion:** Through fully developing the analytical techniques and robotic technologies to down-select to the highest priority targets (steps I & II), and ultimately the technologies to support subterranean robotic and human missions (discussed in steps III & IV), then we will be poised to embark upon scientific exploration of the caves on Mars.

**Acknowledgements:** Special thanks to Melanie Gregory, Glen Cushing, and Anna Ross who provided comments leading to the improvement of this abstract.

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**PIT CRATER CHAINS: EVIDENCE FOR SUBTERRANEAN TECTONIC CAVES.** D. Y. Wyrick[1] and D. L. Buczkowski[2], [1]Southwest Research Institute, San Antonio, TX, USA (danielle.wyrick@swri.org), [2]Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA (Debra.Buczkowski@jhuapl.edu).

**Introduction:** Pit crater chains are surface features comprised of linear assemblages of collapsed depressions that are identified on several solid bodies throughout the Solar System. On Earth, they have been observed to form when dilational motion on normal faults causes the overlying materials to collapse into the dilating segment of the buried fault [1, 2]. It has been hypothesized that pit crater chains observed on Mars [1], Enceladus [3], and various asteroids [e.g. 4: *See Buczkowski and Wyrick, this meeting*] formed by the same process. Dilational fault movement can also create subsurface permeability pathways for fluid/volatile transport and trapping [5,6,7], thus studying pit crater chains and tectonic caves on planetary bodies has implications for both in situ resource utilization and astrobiology, and should be consider as a potential driver for determining exploration targets.

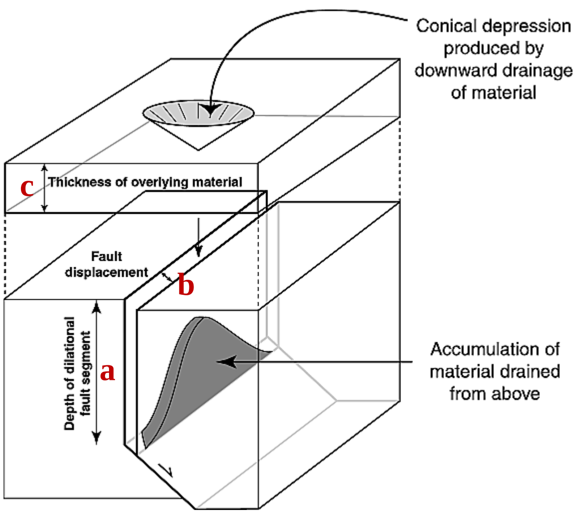


*Figure 1. Schematic illustration from [1] demonstrating dilational faulting. Pit volume is a function of (**a**) depth of the dilational fault segment, (**b**) increased displacement along the fault, or (**c**) the thickness of the overlying unconsolidated material.*

**Dilational Faulting and Pit Crater Chains:** Dilational faulting can occur on normal faults that traverse mechanically strong stratigraphic layers, or where hybrid mode failure (Mode I opening combined with either Mode II sliding and/or Mode III tearing) occurs under low differential stress [8]. Where the stratigraphy varies from mechanically strong rock to mechanically weak layers, the fault dip will also vary, creating steep vertical fault segments. Under such conditions, a void is produced in the subsurface, into which overlying unconsolidated or mechanically weak material can drain (Fig. 1) producing chains of pit craters [1]. The pit volume is a function of several factors, including the depth of the dilational fault segment, the degree of fault displacement along the fault, and the thickness of the overlying weaker stratigraphic layers. Subterranean void space can be estimated by calculating the volume of the overlying pit crater chain volume [1], as this represents the minimum volume of subsurface void space that must be available to accommodate the collapsed material. (Fig. 1).

**Dilational Fault "Caves":** Pit crater chains on Earth have been observed forming over dilational normal faults (Figs 2,3), illustrating the large volume of void space that exists in the subsurface beneath these surface features. These same terrestrial dilational faults become permeability pathways for groundwater flow and storage (Fig 2), suggesting that similar features observed on other planetary bodies may also provide volatile and fluid transport and potential reservoirs. On Mars for example, outflow channels have been mapped directly emanating from pit crater chains, which are interpreted to have been structurally controlling the groundwater in the region [9]. Understanding these structural controls on groundwater (and other volatiles) is critical toward understanding what resources may be available both for astrobiology and future human exploration. Very few endogenic geologic processes operate across-the-board on such a wide variety of planetary bodies with disparate lithologies and geologic histories. The identification of pit chains on these wide ranging bodies – from small asteroids to icy moons to large terrestrial planets – raises important questions regarding the near-surface crustal properties of solid bodies in our solar system and their capacity to store vital resources. The ubiquitous nature of pit crater chains makes them an easily identifiable target on many planetary bodies that may provide a peek into the subsurface.

**Implications:** Understanding the relationship between pit crater chains, dilational faulting and subsurface voids space will be critical in future solar system exploration. Dilational faulting, and the tectonics caves they can produce, have direct implications for the transport and storage of volatiles and fluids in the lithosphere on Earth. Pit crater chains on Mars appear to have also provided permeability pathways for groundwater, and may be regions of ground ice storage. Similarly, pit crater chain identification on the moon and other small bodies suggest that there may be significant subsurface void space to sequester volatiles and ices. Because pit crater chains are a more easily observed surface feature, they can serve as good proxy indicators of subterranean cavernous voids. With better constraints on the relationship between these features, we will gain a better understand of where to pursue in situ resources and look for habitable zones in the solar system.

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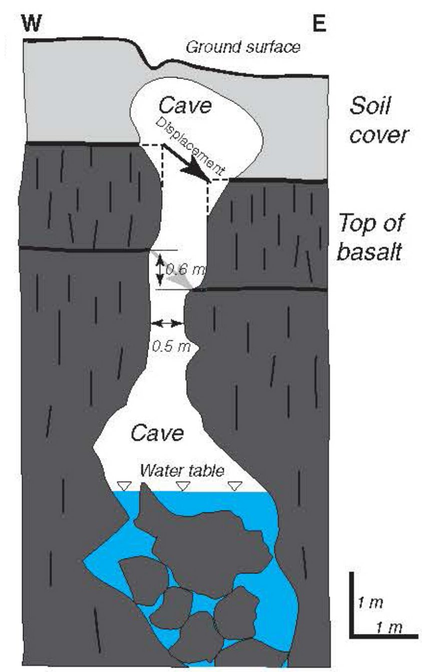


*Figure 2. Schematic cross-section of a tectonic cave associated with a dilational fault segment as shown in figure 3 (from [1]).*

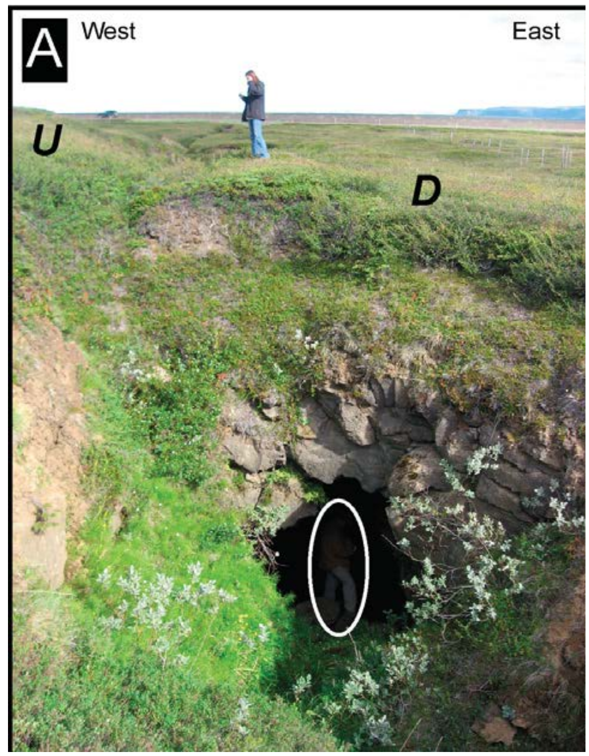


*Figure 3. Image from [1] showing a pit crater chain in Iceland. Note person at surface mapping pit crater while person (white oval) maps the subsurface dilational fault segment.*

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**LUNAR CAVES ANALOG TEST SITES FOR SPACE-STEM ENGAGEMENT.**
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**Introduction:** Inspiring the next generation of space explorers is a major objective for the scientists, engineers, and educators of today. To improve Space-STEM teaching and student comprehension, we have created the Lunar Caves Analog Test Sites (LCATS) program for science investigations, space exploration mission operations, technology development, and habitability system architectures. The LCATS program environment incorporates a pipeline of motivated middle and high school students to assist professionals in solving real-world challenges in space-exploration technology. Critical thinking, problem solving skills, teamwork, and mentoring enhance the student experience. Learning performance benefits from the use of robotic technologies, terrestrial analogs for testing technology projects and operational processes in a mission context. Local Texas caves in the area and region are utilized as analog environments for fielding student experiments and technology challenges through simulated missions.

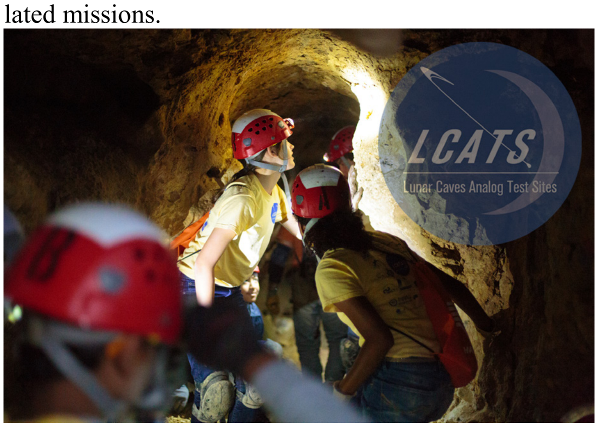

**Figure 2. LCATS Student Field Trips to Local Caves**

Investigations of In Situ Resource Utilization (ISRU) technologies, e.g., regolith simulant research and 3D printed manufacturing for habitat design and planetary construction are incorporated into project curriculum.

Student teams (cohorts) from the San Antonio area school districts are guided by subject matter experts in their development of innovative hands-on applications that provide practical solutions for lunar mission exploration and architecture challenges. LCATS goals include preparing and encouraging underrepresented minorities, female and economically disadvantaged students to pursue higher education and careers in human space exploration.

**Framework:** LCATS works within the framework of a larger lunar site development program known as LEAP2 (Lunar Ecosystem and Architectural Prototype). LEAP2 is a commercial lunar site development program being developed by an international consortium of aerospace industry organizations investigating technologies for lunar settlement. The LEAP2 international consortium is loosely organized for collaboration with industry, academia, and government organizations. LEAP2 addresses space architecture research in lunar exploration, economic development, mining, and sustainability at a specific lunar site identified as the Marius Hills Skylight. The skylight is located within an area of volcanic domes in the Marius Hills region of Oceanus Procellarum at 14.2°N, 303.3°E [1]. It is a large pit subsurface feature believed to be the opening to a lunar lava tube cave useful for eventual human habitation.

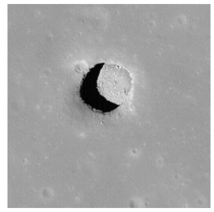
**Fig 1. MH Pit**
NASA/GSFC/ASU

The LEAP2 consortium uses the Marius Hills Pit as a case study for determining required technology development needed to access these type of geologic features for exploration and eventual human settlement. Projects within the LEAP2 program address various technology solutions and missions for achieving multi-generational program goals to develop the lunar site for eventual human settlement.

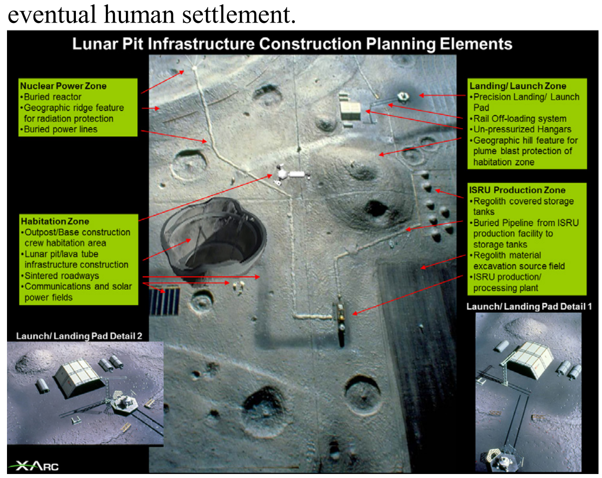

**Figure 3. LEAP2 Lunar Infrastructure**

**Project-based Learning:** LCATS is a NASA funded program administered by the non-profit WEX Foundation [2]. LCATS provides real-world context for students to assist aerospace professionals with solving actual space exploration technology development challenges using project-based curricula. The benefit of project-based educational programs is quite established [3][4]. Project-based learning, a teaching methodology that utilizes student-centered projects to facilitate student learning, is touted as superior to traditional teaching methods in improving problem solving and thinking skills, and engaging students in their learning [5][6].


**Figure 4. Lunar Surface/Subsurface Robotics Testbed**

Student projects and curricula of the LCATS program are attached to actual technology, engineering and science investigation challenges associated with the growth phases of human settlement at the Marius Hills Skylight. The LEAP2 commercial lunar site development program provides a framework for LCATS project-based curricula development to be aligned with the goals of the commercial venture for actual development of the lunar site [7].

**Figure 5. Robotics Field Test in Cave Environment**

The differentiator with the LCATS/LEAP2 education initiative is the specificity of its technology research and development projects. For project-based learning, all consortium sponsored curricula initiatives are focused on their application to advancing the body of knowledge for site development of planetary pits and lava tubes, in particular, development of the Marius Hills Skylight as a commercial prototype for understanding how to use these planetary features to the benefit of human settlement on distant planets.

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