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Fundamental Science and Engineering Questions in Planetary Cave Exploration

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Abstract Nearly half a century ago, two papers postulated the likelihood of lunar lava tube caves using mathematical models. Today, armed with an array of orbiting and fly-by satellites and survey instrumentation, we have now acquired cave data across our solar system—including the identification of potential cave entrances on the Moon, Mars, and at least nine other planetary bodies. These discoveries gave rise to the study of planetary caves. To help advance this field, we leveraged the expertise of an interdisciplinary group to identify a strategy to explore caves beyond Earth. Focusing primarily on astrobiology, the cave environment, geology, robotics, instrumentation, and human exploration, our goal was to produce a framework to guide this subdiscipline through at least the next decade. To do this, we first assembled a list of 198 science and engineering questions. Then, through a series of social surveys, 114 scientists and engineers winnowed down the list to the top 53 highest priority questions. This exercise resulted in identifying emerging and crucial research areas that require robust development to ultimately support a robotic mission to a planetary cave—principally the Moon and/or Mars. With the necessary financial investment and institutional support, the research and technological development required to achieve these necessary advancements over the next decade

Special Section:

Exploring planetary caves as windows into subsurface geology, habitability, and astrobiology

Key Points:

- Robotics and instrument advancements identified as linchpin focal areas for in situ study of planetary caves
- Research and technological development required for lunar and/or Martian cave exploration is achievable in next decade with proper investment
- First application of systematic and statistically rigorous social survey to identify science and engineering requirements in planetary science

Supporting Information:

Supporting Information may be found in the online version of this article.

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are attainable. Subsequently, we will be positioned to robotically examine lunar caves and search for evidence of life within Martian caves; in turn, this will set the stage for human exploration and potential habitation of both the lunar and Martian subsurface.

Plain Language Summary We have now acquired cave data across our solar system—including the identification of potential cave entrances on the Moon, Mars, and at least nine other planetary bodies. These discoveries gave rise to the study of planetary caves. To help advance this field, we conducted an expert-opinion based social survey to identify a strategy to explore caves beyond Earth. We focused primarily on astrobiology, the cave environment, geology, robotics, instrumentation, and human exploration. First, we assembled a list of 198 science and engineering questions. Then, through a series of social surveys, 114 scientists and engineers winnowed down the list to the top 53 highest priority questions. This exercise resulted in identifying emerging and crucial research areas that require robust development to ultimately support a robotic mission to a planetary cave—principally the Moon and/or Mars. With the necessary financial investment and institutional support, the research and technological development required to achieve these necessary advancements over the next decade are attainable. Subsequently, we will be positioned to robotically examine lunar caves and search for evidence of life within Martian caves; in turn, this will set the stage for human exploration and potential habitation of both the lunar and Martian subsurface.

1. Introduction

Roughly 50 years ago, two companion papers discussed the geologic rationale and provided mathematical modeling to support the likelihood of lava tubes on the Moon (Greeley, 1971; Oberbeck et al., 1969). Although Halliday (1966) speculated about their existence a few years earlier, these seminal papers reasoned the likelihood for caves in the Oceanus Procellarum region and mathematically estimated widths, roof thicknesses, and lengths of potential subsurface features. While these early works were built upon the analysis of low-resolution images (acquired for Apollo mission landing site selection), planetary missions over the past two decades have acquired imagery from increasingly higher resolution optical platforms and drastically improved the resolving capabilities of potential subsurface access points (SAPs) on other planetary bodies.

Today, possible SAPs and terrains likely to support subterranean features have been identified from Mercury to Pluto (Titus et al., 2021; Wynne et al., 2022). Over 1,000 potential cave openings have been identified on Mars (Cushing, 2017; Cushing et al., 2007) and over 200 potential cave-like features have been documented on the Moon (Haruyama et al., 2009; Wagner & Robinson, 2014, 2015, 2021). In the outer solar system, vents, pits, and fissures associated with water ice plumes have been discovered on Saturnian (C. J. Hansen et al., 2011; Porco et al., 2014), Jovian (Geissler & McMillan, 2008; Roth et al., 2014), and Neptunian (Duxbury & Brown, 1997) icy moons. For example, on Enceladus, within the four primary fractures of the south polar region, at least 100 active geysers have been identified (Porco et al., 2014). Incidentally, steep-sided depressions and equatorial pits have been observed on Titan (Wynne et al., 2022), which may have resulted from hydrocarbon fluids percolating through thick organic materials in a process similar to karstic dissolution (Malaska et al., 2020). Thus far, 3,545 SAPs have been identified on 11 bodies across our solar system (Wynne et al., 2022). Additionally, possible volcanic vents have been observed on Triton and Pluto, and numerous pit crater chains on icy and rocky bodies will require further examination (Wynne et al., 2022). Refer to Wynne et al. (2022) for a complete review of speleogenic processes and SAPs across the solar system.

Collectively, these features represent a new frontier in planetary exploration. Pits, vents, fissures, and caves provide access to near surface geology and liquid oceans without the need for drilling or digging (Stamenković et al., 2019). On Mars, these features may provide access to preserved volatiles including water ice (Schörghofer, 2021; Williams et al., 2010), brines (D. M. Burt & Knauth, 2003), and organic matter (Richardson et al., 2013). More broadly, planetary SAPs may ultimately provide data on volatile delivery and climatic oscillations. Cave climates typically reflect the average annual surface temperature at depth (Cropley, 1965; Pflitsch & Piasecki, 2003; Titus et al., 2010), suggesting that planetary subsurfaces likely represent warmer, more stable environments. Importantly, SAPs contain environments buffered from ionizing space radiation and other hostile surface conditions (De Angeles et al., 2002; Morthekai et al., 2007; Townsend & Fry, 2002). These factors combined make the planetary subsurface realm one of the most habitable locations to search for evidence of extinct or perhaps extant life (e.g., Boston et al., 2001; Carrier et al., 2020; Northup et al., 2011; Perkins, 2020;

Stamenković et al., 2019). For the Moon and Mars, SAPs arguably represent one of the best locations to establish astronaut shelters (Blamont, 2014; Titus, Phillips-Lander, et al., 2020; von Ehrenfried, 2019; Wynne et al., 2008).

Underscoring the growing importance of planetary caves, the 2023–2032 Decadal Survey included four contributed white papers discussing their significance (e.g., refer to NASEM [2022] for details). These papers likely gave rise to the steering committee emphasizing the following in the Decadal Survey: (a) the importance of maturing robotics and instrumentation to access planetary subsurfaces; (b) the need to identify environmental covariates governing subsurface habitability and diversity on Earth (so that these data can be potentially extrapolated to other bodies—in particular, Mars); and (c) the potential importance of the Martian subterranean realm in the search for life (NASEM, 2022).

Despite the tremendous potential that planetary subsurfaces represent, we are in the incipient phase of interpreting and examining the subsurface of planetary bodies in the solar system. To effectively explore a planetary cave, such a mission will ultimately require cross-planetary-body investigations spanning multiple disciplines including astrobiology, climatology, geology, robotics and instrumentation, human exploration, and operations. Given the inherent interdisciplinary nature of planetary cave science and exploration, we assembled a team of engineers, roboticists, astrobiologists, geologists, and physicists to conduct an expert-opinion-based and systematic social survey, often referred to as an "horizon scan." Our goal was to identify emerging and crucial research areas that require robust development to facilitate and support a successful robotic mission to a planetary cave—principally the Moon and/or Mars—that could ultimately lay the foundation for human cave exploration and habitation. Here we present our findings, which we believe will drive the next one to two decades of planetary cave research and technological development.

2. Horizon Scan Methodology

Over the past decade, horizon scans, which employ an expert-opinion-based paradigm (see Wintle et al., 2020), have been used to obtain insights and identify future directions into a panoply of medical, societal, and environmental research areas. These include identification of emerging technologies in cancer research (Gallego et al., 2012) and bioengineering (Kemp et al., 2020), storm- and waste-water management (Blumensaat et al., 2019), improvement of management policies for governmental agencies (Hines et al., 2018), and the identification of future directions in ecology (Mammola et al., 2020; Patiño et al., 2017; Sutherland et al., 2013), as well as annual assessments on global biological conservation issues, which have been conducted since 2011 (e.g., Sutherland et al., 2021; Sutherland, Bardsley, et al., 2011). To our knowledge, this is the first occasion where a horizon scan approach was applied to identify research priorities in planetary science or space exploration.

We employed the horizon scan methodology using an expert-opinion-based approach whereby we enlisted the input of a large interdisciplinary team of scientists and engineers to identify the fundamental questions in planetary cave exploration. While horizon scans are increasingly used to systematically examine available information to identify both emerging issues and priorities in various areas of research and societal growth (Brown, 2007; Könnölä et al., 2012; Sutherland, Bardsley, et al., 2011), we specifically used this approach to synthesize the scientific and engineering requirements to make planetary cave exploration a reality.

2.1. Compilation of Initial Survey Questions

For this study, we borrowed elements from Sutherland, Fleishman, et al. (2011), Patiño et al. (2017), and Mammola et al. (2020). Consisting of online surveys and an interdisciplinary group of scientists and engineers, we applied a systematic approach to forecast the most important research and technological questions in planetary cave exploration. In designing this horizon scan, we identified seven subject areas as crucial for advancing our ability to examine planetary subsurfaces including (a) astrobiology, (b) the cave environment, (c) geology, (d) instrumentation, (e) robotics, (f) human exploration, and (g) broad concepts. The last subject area was included to optimally capture the interdisciplinary nature of planetary cave science, while potentially identifying "bigger picture" concepts that may not fit into the other categories.

Each subject area consisted of one to two panel coordinators and from four to eight panel members (Table 1). Both panel coordinators and members were considered leading experts within each of the subject area groups. For example, the human exploration section was paneled by space suit engineers, habitation pod designers, and

Table 1
Summary of Panel Member Names, Total Number of Panel Members per Group, and Number of Questions per Subject Area

Subject area	Panelists	Members	Questions
Instrumentation	Uckert*, Malaska, Prettyman, Titus	4	25
Cave Environment	Titus*, Cushing, Prettyman, Williams, Wynne	5	16
Geology	Sauro*, De Waele*, Cushing, DeDecker, Frumkin, Kerber, Massironi, Onac	8	32
Robotics	Jones*, Agha-Mohammadi, Whittaker, Wong	4	22
Astrobiology	Demirel-Floyd*, Azua-Bustos, Boston, Fairén, Miller, Phillips-Lander, Sapers, Schulze-Makuch	8	24
Human Exploration	de León*, Chiao, Harris, Manyapu†, Parazynski†	5	27
Broad Concepts	Boston*, Alexander, Léveillé, Mylroie, Schulze-Makuch, Wynne	6	6
Other contributors	Kearney, Sonderegger, Wagner	--	--

Note. An * indicates panel coordinators. Four members served on more than one panel, while two panel members (†) participated in Survey 1 question development but were unavailable to partake in survey voting. The "Questions" column indicates the number of questions per group for Survey 1.

retired astronauts. Panel coordinators worked with the lead author (JJW) to identify and invite additional panel members. We also consulted broadly with colleagues to identify individuals who would contribute complementary expertise to each panel. Given the interdisciplinary nature of speleological research, planetary science, and space technology development, some panel members participated on more than one panel. Panel members were asked to submit 5–10 questions that they identified as fundamental within their subject area and thus likely to advance the field significantly. However, a few panel members submitted as many as 15 questions. This resulted in a total of 268 initial questions.

For each subject area, the lead author coordinated directly with panel leads to remove duplicate questions, revise questions for clarity (e.g., Mammola et al., 2020; Plavén-Sigray et al., 2017), and, in some cases, reassign questions to other subject areas. This was accomplished by working jointly with the panel coordinator(s) and panel member(s) who submitted the questions. To the extent possible, jargon was removed, and verbiage was standardized so that all questions had a similar degree of legibility. Once done, we had a total of 196 questions, which became the questions for Survey 1.

2.2. Down Selection of Fundamental Questions

All online surveys were developed using Google Forms. Across the three online surveys (Surveys 1 through 3), participants voted for each question as being either of "major" or "minor" importance (*sensu* Mammola et al., 2020). For these surveys, the order of survey questions was randomized for each respondent.

For Survey 1 (196 questions), 31 panelists (i.e., most of the coauthors of this paper) participated. All panel members voted on all questions irrespective of subject area. While Mammola et al. (2020) identified the top 20 questions per subject area based upon the percentage of votes for their first survey, we deemed that approach somewhat restrictive. Given that planetary cave exploration is an emerging facet of planetary research (Titus et al., 2021; Titus, Phillips-Lander, et al., 2020), we chose not to risk discarding important questions. Thus, we applied a more conservative approach whereby questions were retained for the next survey (Survey 2) if more than 50% of panelists considered a given question of "major importance." The outcome of this procedure resulted in 152 questions for the next survey (Survey 2).

For Survey 2, the broader speleological and planetary science community was invited to participate. We solicited participation using a combination of electronic listservs and individual panelists contacted their colleagues directly via email. Listservs included the SETI Institute's personnel list, and the National Cave and Karst Research Institute (NCKRI) monthly cave and karst news and announcements listserv. For the NCKRI mailing list alone, there were nearly 2,000 recipients including several addresses that represent national and regional lists—of these, between 50% and 60% were international recipients. Barring individuals who may forward a given monthly update, the estimated reach of this list alone was ~5,000 people (G. Veni; pers. (written) comm. 2021). We recognize that this likely resulted in some overlap, and that some email addresses were inactive. Overall, we estimated that Survey 2 reached at least 7,000 unique individuals. Of these, 82 individuals (who were not contributing authors on this work) completed Survey 2. The breakdown of Survey 2 respondents by profession includes the following: geologists (at 47.5%), astrobiologists/biologists (17%), physicists (5%), engineers (14.5%), two chemists, one climatologist, and 12.2% listing "other" as their profession. To gain further insights into the composition of Survey 2 by institution, we categorized respondents by the email addresses provided. This consisted of 18 individuals with U.S. academic addresses, 18 with non-U.S. academic addresses, 14 with non-academic professional addresses (e.g., NASA, ESA, and other governmental and non-governmental agencies), and 32 with personal email addresses (e.g., Gmail, Yahoo, and Hotmail accounts).

Upon completion of Survey 2, participants had the option of submitting one additional question (*sensu* Mammola et al., 2020). This provided us with the opportunity to ensure that we developed the most comprehensive process for identifying the fundamental questions in planetary cave exploration. Participants submitted a total of 24 additional questions/comments. Of these, three were general comments, two were general questions related to potential funding sources for a planetary cave mission, and four questions were either vaguely written or had been addressed theoretically through previous research. Once those nine questions/comments were removed, we applied the same revisionary approach as in Survey 1, whereby duplicate questions were removed (by crosschecking the submitted questions with Survey 1 and 2 questions, as well as between the submitted questions), jargon was removed, and wording standardized for clarity.

Once done, we had eight questions for Survey 3. For this survey, 31 panel members voted (same as for Survey 1). To identify the highest priority fundamental questions in planetary cave exploration, the results of Surveys 2 and 3 were combined. This resulted in a total of 160 questions. To determine the highest priority (i.e., fundamental) questions, percentages were calculated using the response data and then rank ordered. All questions from each survey are provided in Text S1–S3 of Supporting Information S1 (Wynne, 2022).

2.3. Caveats on Interpretation

Several considerations should be addressed when interpreting both the horizon scan approach and the results of this method. First and foremost, this work applied a methodology that may be most familiar to social and political scientists (i.e., a general social survey, GSS; refer to R. S. Burt, 1984). The backbone of this methodology involved: (a) developing questions across the spectrum of planetary cave science and engineering, (b) scrutinizing over each question through a series of surveys whereby participants either affirmed or negated a given question's importance via a binary vote, and (c) then rank-ordering the survey results to assemble the highest priority (or fundamental) questions. As we were merely presenting and subsequently interpreting the results of this systematic social survey, we do not have the latitude to interject ideas or other considerations beyond what was enumerated as the fundamental questions—doing so would violate the purpose of the horizon scan—which was to identify the highest priority science and engineering questions based upon the horizon scan procedures employed.

Concerning the interpretation of horizon scan results, most of these caveats have already been discussed. For details, refer to Sutherland, Fleishman, et al. (2011), Patiño et al. (2017), and Mammola et al. (2020). However, we identified three additional caveats that warrant further examination and discussion. First, there may be a potential for perception limitations and subjectivity of the panelists. For example, none of the panelists in the human exploration group had a strong working knowledge of speleology and/or planetary cave science. Conversely, more than half (55%) of all panelists had six or more years of scientific and/or recreational caving experience. Concerning bias, we examined the potential for bias by professional specialty. We suggest any potential shortcomings were, in part, addressed by the conservative down-selection method we applied to Survey 1. Additionally, including a relatively large number of panelists from a range of academic backgrounds and career stages (Figure 1) may have further mitigated bias (Sutherland, Fleishman, et al., 2011). Second, while Sutherland et al. (2013) suggested the use of subject areas (or themes) may facilitate lateral thinking, we do not believe this was the case for this exercise. Roughly 13% of all panelists served on more than one panel. Moreover, more than a quarter of panelists submitted questions that were ultimately subsumed into other subject area groups. While purely qualitative, we suggest this emphasizes both the interdisciplinary nature of the panel, as well as the panelists' ability to think broadly and dynamically about how best to advance the exploration of planetary caves. Finally, while many of the questions were presented to address planetary caves in general, lunar and Martian caves represent the most likely near-term targets for exploration; subsequently, many of the subject area summaries are focused on these bodies.

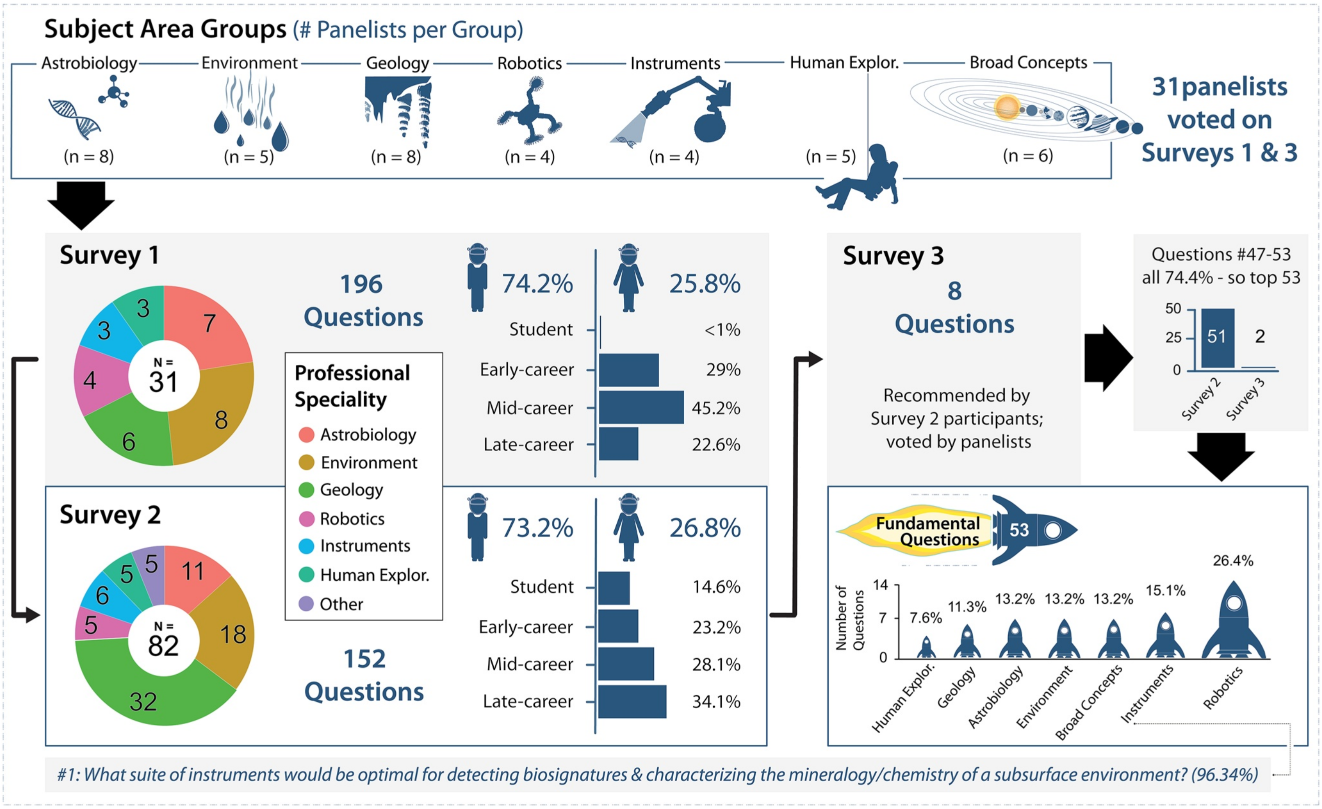

Figure 1. Summary by subject area groups, workflow, statistics of panelists (Surveys 1 and 3) and the broader community (Survey 2), and breakdown of the 53 fundamental questions in planetary cave science and engineering by subject area group.

2.4. Statistical Analysis

Given the professional specialties of participants across the two surveys were disproportionate in terms of the number of participants per professional specialty (Figure 1), we examined whether this contributed bias to the survey results. For example, ~48% of the Survey 2 participants identified "geology" as their professional specialty and we wanted to gain inference into whether survey results were skewed toward geology. Because Survey 3 participants were the same participants as Survey 1, we did not analyze the Survey 3 data set. We used nonmetric multidimensional scaling (NMDS) with 500 random starts (to obtain the lowest stress result). The higher the R^2 value, the better the "goodness of fit" of the data. NMDS also enabled us to examine how questions parsed by professional specialty in graphical space. We then used generalized linear mixed models (GLMM) to estimate relationships between survey responses and survey participants by professional specialty. To understand the practical significance of this factor, we used the GLMM R^2 (*sensu* Nakagawa & Schielzeth, 2013). All analyses were conducted using RStudio, version 3.4.0 (2017-04-21) with "vegan" and "glmmTMB" packages, respectively. GLMM R^2 calculation was completed using the "performance" package.

3. Results and Discussion

We found little evidence to suggest that participants' professional specialties substantially influenced how they answered the survey questions. NMDS analysis reported low stress and a statistically non-significant effect on profession for both Survey 1 (stress = 0.114, $R^2 = 21.5\%$, $p = 0.252$) and Survey 2 (stress = 0.114, $R^2 = 6.4\%$, $p = 0.54$; Figures 2 and 3). There was no clustering by question group and respective professional specialty. This is further demonstrated when viewing sawtooth charts depicting how individual respondents answered questions per professional specialty (Figures 2c and 3c). Results from GLMM runs for Surveys 1 and 2 produced a statistically significant effect for the interaction terms only ($\chi^2 = 63.3.7$, df = 25, $p < 3.6 \times 10^{-5}$ and $\chi^2 = 124.7$, df = 36, $p < 1 \times 10^{-10}$, respectively). To further examine these differences, we then compared all paired comparisons of

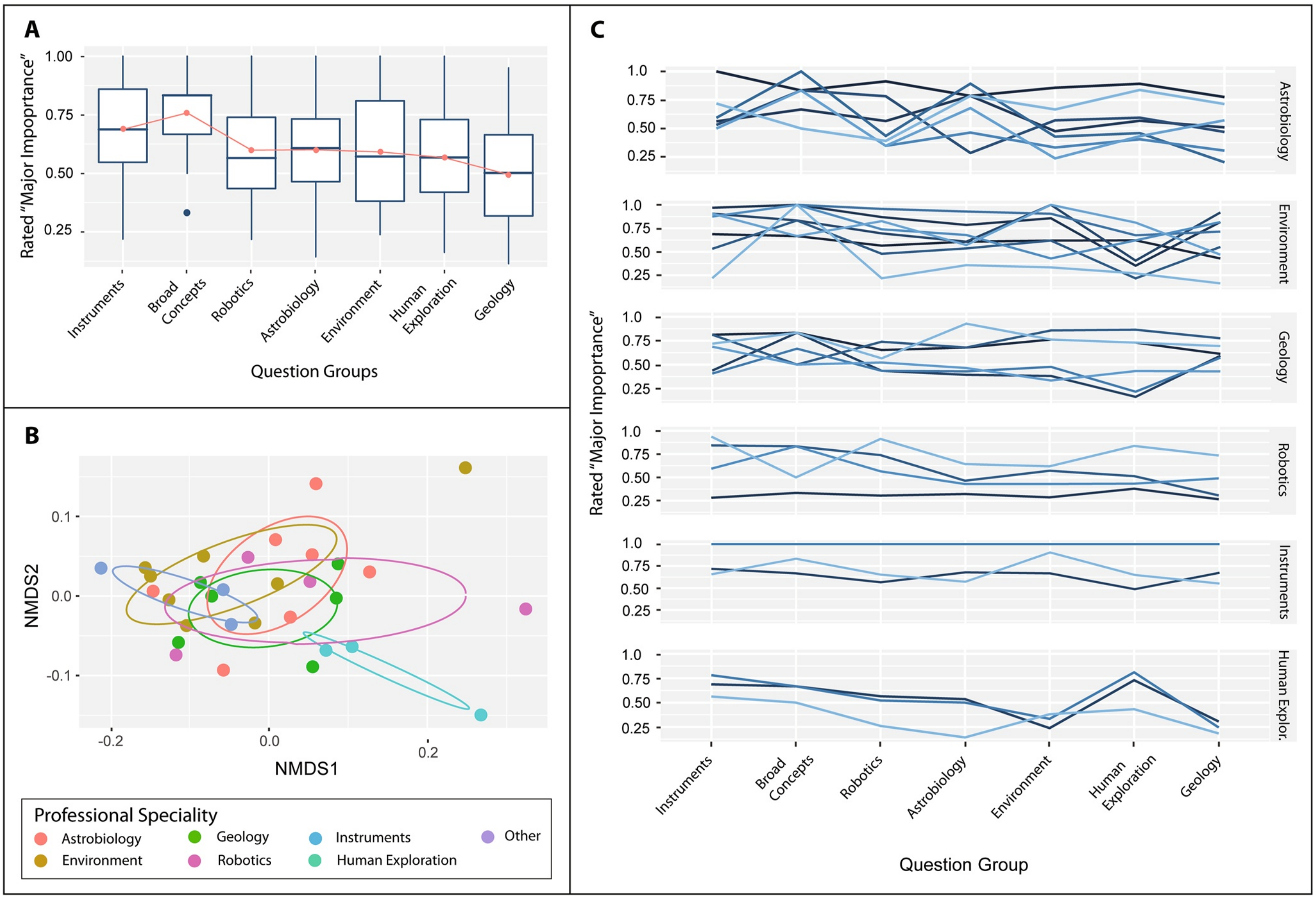

Figure 2. Evaluation of potential bias of survey participants by professional specialty for the 31 survey participants in Survey 1. (a) Whisker plots provide quartile breakdown; solid line within the box represents the median and dots are outliers. (b) NMDS illustrates the lack of clustering across the various professional specialties. Analysis ran with 500 random starts. (c) Summary of responses of participants (i.e., the authors) by professional specialty (individual blue lines of varying hues) identifying questions as “major importance” (y-axis) by question group (x-axis). Each line in this graph represents an individual survey participant. Each point along the line is the average of how many times the individual chose “major importance” for a given question group. For example, the datapoint for an individual in the robotics group who considered all broad concepts questions to be of “major importance” would appear as 1.0 (or 100%) on the graph.

survey participants by specialty for each question group; this resulted in some significant differences (Table 2). These results indicated that participants voted differently between specialties; thus, further suggesting that these individual differences contributed to the statistical significance given the interaction effect of professional specialty and question group. However, this had little practical effect as the R^2 value increased only from 22.2% to 26.1% and 33.0% to 34.0% for Surveys 1 and 2, respectively.

Upon completion of rank ordering the questions, we found that there was no clean break point at 50 questions. For questions ranked 48 through 53, the percentages were the same; these questions were all at 74.4% (or a split of 61 to 21). Thus, we could either have a top 47 or top 53 fundamental questions. We chose the latter option. The top 53 questions are provided, in rank order, as Table S1 and S2 in Supporting Information S2 (Wynne, 2022).

We now present the 53 top-priority questions in planetary cave science and engineering. In essence, these questions embody the data produced from the social surveys (and represent the combined results of Surveys 2 and 3). For each question, we provide the rank (#) among all total questions and the percentage of “major importance” votes received. The two questions submitted by Survey 2 participants are denoted by an asterisk (*). The purpose of the following seven sections (i.e., subject areas) represent data analysis and interpretations. Here, we discuss the state of knowledge pertaining to each question, as well as provide scientific and technical guidance for researchers addressing these issues in the future.

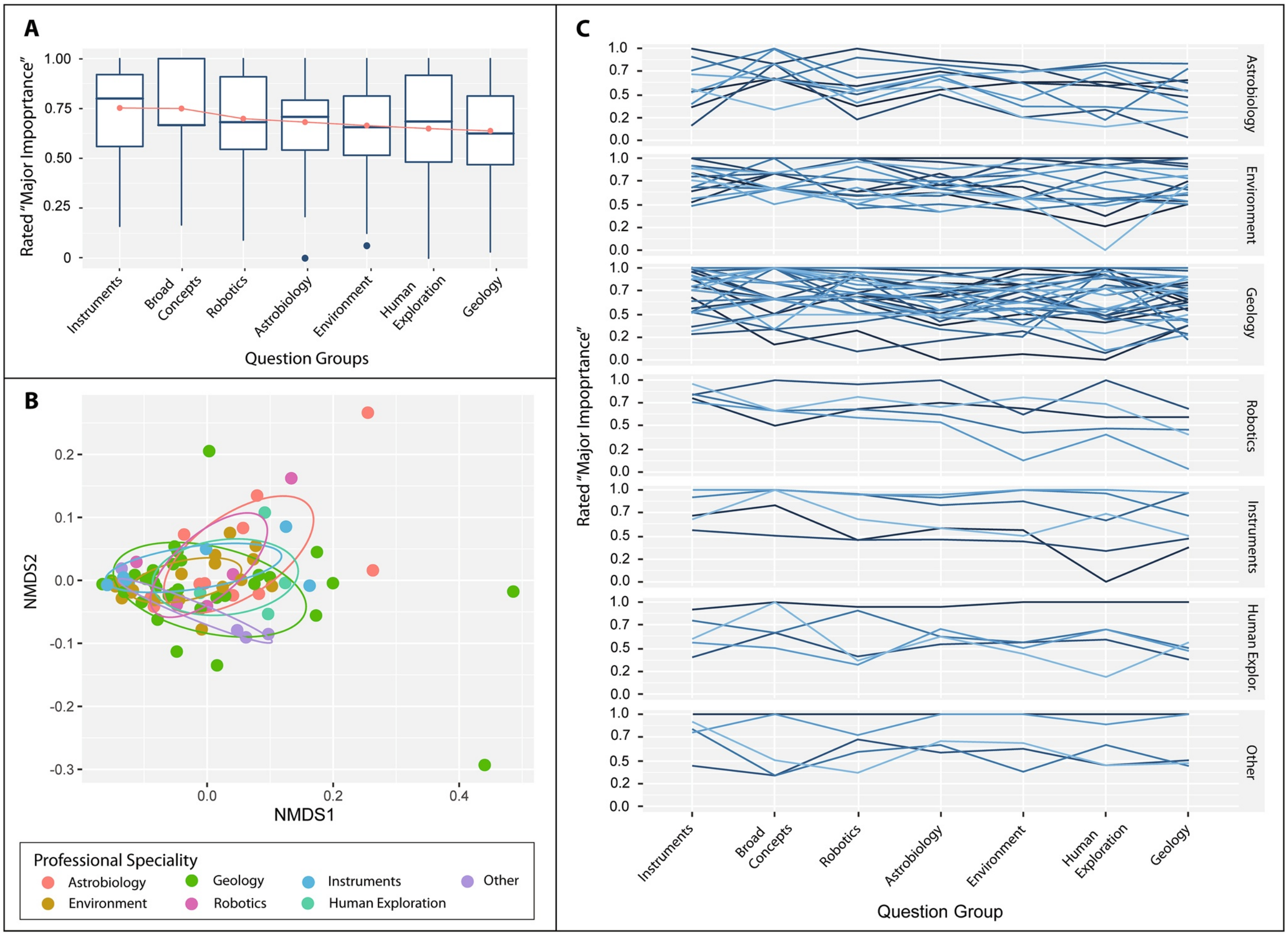

Figure 3. Evaluation of potential bias of survey participants by professional specialty for the 82 survey participants in Survey 2. (a) Whisker plots provide quartile breakdown; solid line within the box represents the median and dots are outliers. (b) NMDS illustrates the lack of clustering across the various professional specialties. Analysis ran with 500 random starts. (c) Summary of responses of participants by professional specialty (individual blue lines of varying hues) identifying questions as "major importance" (y-axis) by question group (x-axis). "Other" represents other profession. Each line in this graph represents an individual survey participant. Each point along the line is the average of how many times the individual chose "major importance" for a given question group. For example, the datapoint for an individual in the robotics group who considered all broad concepts questions to be of "major importance" would appear as 1.0 (or 100%) on the graph.

Table 2
Paired Comparisons of Professional Specialties by Question Groups for Surveys 1 and 2

Question group	Contrast of professional specialty	Odds ratio	SE	df	*t*-value	*p*-value
Survey 1						
Environment	Instruments/Astrobiology	11.69	8.703	6,033	3.304	0.012
Environment	Instruments/Human Explore	28.07	24.17	6,033	3.874	0.002
Environment	Robotics/Instruments	0.072	0.059	6,033	−3.245	0.015
Geology	Instruments/Human Explore	17.75	13.77	6,033	3.708	0.003
Survey 2						
Geology	Environment/Astrobiology	4.287	2.105	12,414	2.965	0.048

Note. Only comparisons with statistical significance ($p \leq 0.05$) are presented with odds ratios, standard errors (SE), degrees of freedom (df), t-distributed test statistic (t-value), and p-values provided.

3.1. Astrobiology

Q1: Do caves on Mars represent habitable systems for microbial life that once dwelled on the Martian surface? (#6; 85.4%)

Q2: What lines of evidence are required to conclusively prove life exists/existed in planetary caves? Specifically, how may we design missions to reduce the likelihood of false negatives? (#7; 84.2%)

Q3: Are speleothems in planetary caves potential archives for past microbial life? If so, how would we confidently identify these biosignatures? (#11; 82.9%)

Q4: How can we predict the astrobiological value of a planetary cave (i.e., a Martian cave) before exploring it? Specifically, are there indicators at/near cave entrances or surface expressions over the cave that could be indicative of microbial metabolic activity? (#16; 81.7%)

Q5: How do we define the preservation potential of biosignatures in Martian caves? Importantly, what are the most important factors/mechanisms that could facilitate preservation or decomposition of these biosignatures? (#17; 81.7%)

Q6: If microbial life were confirmed in planetary caves, what can we deduce concerning the origin of life? Importantly, could we acquire adequate samples to understand how these microbes evolved or diverged throughout time? (#20; 80.5%)

Q7: How do we expect water/moisture availability to affect biomineral formation or structure in Martian caves? (#37; 76.8%)

The importance of planetary caves in the search of life elsewhere in the solar system remains largely unstudied. Investigations will be required to determine whether caves may have been abodes for life on other planets, and if these features retain preserved biosignatures (or perhaps even support extant life). For the case of Mars, if microbial life arose and prospered on the surface, it may have later used caves as refugia (Q1) as the planet became increasingly drier and colder (Schulze-Makuch & Irwin, 2018). Caves on Earth, because they are protected from surface processes (such as extreme temperature fluctuations and UV radiation) and have stable physicochemical conditions, harbor a vast diversity of microorganisms able to interact with minerals and exploit different metabolic pathways (e.g., Boston et al., 2001; Miller et al., 2020). Thus, life, or the biosignatures left behind, may be protected within Martian caves—remaining more or less unchanged for millions of years (Léveillé & Datta, 2010). If this occurred, several lines of evidence will be required to conclusively demonstrate life exists or existed in Martian caves, or planetary caves more broadly (Q2). We will need to quantify the physicochemical parameters defining the cave environment and distinguish it from the regional conditions characterizing the adjacent surface environment. Furthermore, we will need to parameterize how these conditions affect both the ability of lifeforms to produce biosignatures and the preservation potential of these signatures. Devising a well-established biogenicity criteria tailored to the geochemical evolution of the cave environment will be of paramount importance (Azua-Bustos et al., 2020; Neveu et al., 2018; Röling et al., 2015; Rouillard et al., 2021; Westall et al., 2015).

On Earth, many microbial species actively grow on and within cave sediments and speleothem surfaces, forming colored microbial mats (Gonzalez-Pimentel et al., 2018; Hathaway et al., 2014) and promoting biomineralization processes (Ghezzi et al., 2021; Miller et al., 2014, 2016). These geomicrobiological interactions involve mineral dissolution, precipitation, and changes in the redox state (e.g., Fe^{2+} to Fe^{3+}), which can preserve traces of microbial features and are considered astrobiologically relevant biosignatures (Northup et al., 2011; Riquelme et al., 2015; Westall et al., 2015). Thus, mineral deposits such as speleothems could be important repositories for extant and past microbial life and represent a unique setting to search for putative biosignatures (Q3). For example, advanced microscopy techniques, DNA sequencing, and analytical biogeochemistry tools could provide the necessary information to assess microbe-mineral interactions recorded in Martian speleothems—from molecular to macroscopic scales (Castro-Wallace et al., 2017; Goordial et al., 2017; Miot et al., 2014; Onstott et al., 2018; Rouillard et al., 2021).

A priori methods to characterize microbial metabolic activity related to surface expressions and/or cave entrances have not been fully examined (Q4). However, determining the detectability of various gases and gas compounds produced by cave microorganisms may be a viable approach. For example, microalgae in Atacama Desert coastal caves produce oxygen as a photosynthetic byproduct (Azua-Bustos et al., 2009, 2010), while Webster et al. (2015)

and Webster (2019) have shown that chemical and isotopic constituents in cave air are distinguishable from the surrounding ambient air. While this approach seems promising, more research will be required to examine other gases (e.g., methane, hydrogen, and carbon monoxide; Lyu et al., 2018; Voordouw, 2002; Wang & Wan, 2009) produced by different microbial metabolisms.

Biomineralization involves the deposition, precipitation, or crystallization of minerals either inside or outside microbial cells, including within living organisms, dead biomass, and biological material—such as extracellular polymeric substances in biofilms. Thus, biominerals may compose a potential target for identifying microbial colonization in putatively habitable Martian caves. On Earth, their preservation potential depends on the physicochemical, environmental, geologic, and climatological conditions since their formation (Allwood et al., 2013; Banfield et al., 2001; Hays et al., 2017; Summons et al., 2011). However, the conundrum is that conditions facilitating preservation in one environment can be degrading in another; moreover, environmental factors supporting habitability typically degrade biosignatures (Hoehler & Westall, 2010; Summons et al., 2011). Importantly, nothing is known regarding the preservation potential of biosignatures in Martian caves (Hays et al., 2017) (Q5). Biomineralization, which occurs at the interface between the cell and its environment, is influenced by water availability (Q7), as well as the concentration of ions in solution, pH, redox state, and metabolic processes. Water availability in Martian caves is expected to vary by cave location, size, and morphology (refer to the Cave Environment section below). In terrestrial subsurfaces, at least an order of magnitude more cells are physically attached to a substrate than free-living cells in the aqueous phase (Bar-On et al., 2018). Using terrestrial cave microbes as an analog, cave microorganisms on Mars may employ a similar strategy and would most likely be rock associated provided water is available at the appropriate threshold to sustain life (Q7). For example, cryptoendolithic microorganisms living in the shallow subsurface of the McMurdo Dry Valleys of Antarctica were identified by the biomineralization of cells and cell casts following cell death, which suggested that fossilization processes could produce biosignatures in extremely water limited environments using organic matter as nucleation templates in the absence of active microbial metabolism (Wierzchos et al., 2005). Similar processes may be expected in Martian caves with transiently habitable conditions.

Terrestrial life requires liquid water, nutrients, and energy sources to sustain life functions. These requirements have varied spatially and temporally on Mars. If life exists or existed on Mars, this variation would have limited the origin and perhaps the continuous existence and evolution of life (Westall et al., 2013). For this reason, the likelihood of finding subsurface life on other planets (in particular, on Mars) will be dependent on defining the spatial and temporal variations of habitability—and how this variation pertains specifically to isolated environments such as caves (Q6). Additionally, well-established biogenicity criteria (elucidated in Q2 above) will be required.

While we first need to detect evidence of extraterrestrial life before we gain inference into how extraterrestrial microbes may have evolved and speciated over time, addressing both life detection and evolution will most likely require a similar approach. Developing a terrestrial data library of cave geologic, structural, and climatic information, as well as defining environmental zones (within a given cave(s) of interest) will be required to ultimately model habitability potential of caves beyond Earth. The highest likelihood of successfully identifying putative cave biosignatures will require knowledge of the optimal location(s) within a cave to sample, and the number of samples required for statistical significance. The ability to remotely define cave environmental zones (refer to Howarth [1980, 1982] for zonal definitions) should be developed for Martian caves. For example, on Mauna Loa, Big Island, Hawaii, active coralloids (or "cave popcorn," a speleothem that forms by the precipitation or evaporation of water) demarcate the cave transition zone, while the deep zone is defined as beyond the point where these speleothems are found (F. G. Howarth, pers. (written) comm. 2021). Additionally, deep zones of some Mauna Loa caves support perennial ice (Schörghofer et al., 2018). Thus, knowing where to sample within a given planetary cave will require a robust understanding of environmental zones within terrestrial analog caves, as well as how to accurately model and transfer those environmental conditions to another planetary body. Moreover, an appropriate instrument payload (i.e., temperature, relative humidity, and radiation sensors) with adequate time to collect environmental measurements represents a viable alternative to facilitate the characterization of distinct cave zones. For sampling intensity, accurately detecting past or extant extraterrestrial microbial life will require adequate statistical power to avoid contradictory results or false positives (Rouillard et al., 2021). For cave microbiological studies, limited samples are often collected to minimize impacts to the cave environment, which may fail to detect some microorganisms (Fletcher et al., 2011; Shao & Wang, 2009). In this context, it is important to identify the minimum number of samples required to optimize life detection. Future terrestrial cave studies that collect robust datasets to develop and test models to determine sample size requirements most accurately will be required.

3.2. The Cave Environment

Q8: What are the best terrestrial analogs for planetary caves? (#8; 84.2%)

Q9: How do geological events and extreme surface conditions affect planetary cave environments? (#12; 82.9%)

Q10: What is the typical extent of water ice formations within Martian caves? (#21; 80.5%)

Q11: As temperature and relative humidity are considered the primary and readily measurable meteorological variables driving microbial activity in caves, how do we acquire these data in a manner to identify the optimal locations to sample within a Martian cave from a rover platform? (#27; 79.3%)

Q12: For a given Martian cave, what is the diurnal and seasonal temperature and relative humidity variations of the cave interior? Importantly, what sections of a given cave are most variable and what sections are most stable? (#38; 76.8%)

Q13: How far does cosmic radiation attenuate beyond the cave entrance? In other words, how deep within the cave must either a rover or human traverse to reach an area insulated from surface radiation? (#42; 75.6%)

Q14: What are the prevalent gases within lunar and Martian caves? How might their presence affect the search for life (specifically, on Mars)? (#50; 74.4%)

Presently, Earth is the only planetary body where we can monitor the full range of processes that characterize the cave environment. The terrestrial subsurface encompasses a range of cave types, which are defined by formation processes and resulting structure (Boston, 2004; Titus et al., 2021; Titus, Phillips-Lander, et al., 2020; Wynne et al., 2022). Surface conditions also vary widely as caves are distributed globally, occurring in nearly every biome on land and underwater. Which of these locations supports the best caves for analog studies remains a key question (Q8)—as highlighted by the fact that it ranked 9th in our survey. Analogs provide a test bed for both technology demonstrations and validation of cave climate models (Léveillé & Datta, 2010). In addition to natural caves, human-made caves (such as tunnels and mines) would provide a more controlled environment. Importantly, model caves could be constructed inside temperature and pressure-controlled chambers (e.g., the Ames Planetary Aeolian Laboratory for simulating windborne processes), which could be used for both cave climate model validation, as well as to simulate predicted cave conditions on other planetary bodies.

The remaining prioritized questions for the cave environment were grouped into three categories: external drivers, cave geometry, and remote sensing of cave interiors. On Earth, cave climate is driven by a combination of surface climate including temperature (Cropley, 1965; Pflitsch & Piasecki, 2003), airflow, humidity, precipitation, cave geometry (Badino, 2010), and in some cases, subsurface conditions such as geothermal heat flux in volcanic regions. For other planetary bodies, cave climate (or the stability thereof) determines both habitability and the potential preservation of evidence of past habitability (Williams et al., 2010). In short, understanding the interactions of multiple abiotic processes influencing the cave environment is key to understanding potential habitability (Q9).

Characterizing radiation levels within planetary caves will be necessary for both habitability assessments and potential human exploration (e.g., Blank et al., 2018; Boston et al., 2001; Northup et al., 2011) (Q13). Measurements should include emissions from the decay of naturally occurring radioisotopes found in the subsurface, and the cascade of particles produced from the interaction of cosmic rays with the surface and/or atmosphere. The latter consists of electromagnetic radiation and energetic ions and neutral particles that can be deleterious to most terrestrial life (Atri & Melott, 2014). Galactic cosmic rays and their secondaries are highly penetrating and could reach cave interiors through thin ceilings (≤1–2 m; De Angeles et al., 2002; Morthekai et al., 2007; Townsend & Fry, 2002) and/or via cave entrances. The latter mechanism may be important for solar energetic particles, which are less penetrating but can result in harmful surface exposures (e.g., Hu et al., 2009). Surface radiation measurements should also be considered—as this would provide a boundary condition for particle transport models to predict cave radiation levels. Accurate simulations will also require knowledge of the physical and chemical properties of the surrounding rock (i.e., rock density and average atomic mass) and cave geometry. Direct internal cave measurements could be conducted with compact instrumentation (e.g., Hassler et al., 2014) and supplemented by modeling. Such instrumentation could have a dual use, including measurements of depth (e.g., Prettyman et al., 2020) and the elemental composition of the surrounding rock (refer to the Instrumentation section). The decay of naturally occurring radioisotopes may dominate the dose within deep caves, while the buildup of radon gas will be affected by cave climate and external forcing by fluctuations in surface conditions (e.g., temperature, relative humidity, and barometric pressure; Šebela & Turk, 2011).

Cave geometry also determines how surface conditions will influence the cave environment (de Freitas & Littlejohn, 1987; Tuttle & Stevenson, 1978; Williams & McKay, 2015; Williams et al., 2017). Acquiring a data set with adequate statistical power to model how temperature and humidity varies by structure will enable a robotic platform to both identify the most stable and buffered locations within a cave (Q11), which, in most cases, will represent the regions of optimal habitability and thus the best locations to sample for evidence of life (Q12). Moreover, Q10 highlights the importance of cave ice. Airflow, which is also influenced by cave geometry as well as surface temperature and barometric pressure shifts governs cave temperature and humidity regimes and water/water ice stability (Perşoiu & Onac, 2019; Williams & McKay, 2015; Williams et al., 2017).

Our last cave environment question (Q14) was focused on how to measure gases (e.g., radon, methane, CO_2, and water vapor) within lunar and Martian caves, and how these measurements may be used to search for evidence of life. As the gas composition within a cave could be modified by the presence of life (e.g., Mansor et al., 2018)—principally on Mars—this opens the possibility of using either spectroscopy via remote sensing or taking direct measurements at a cave entrance via a robotic platform. However, before researchers can move forward with these techniques, we need to address how the cave atmosphere could be modified by abiotic processes (e.g., methane; Klein et al., 2019). Importantly, could a life-modified atmosphere be detectable from inside the cave or possibly outside the cave if the cave is exhaling constituents produced by life?

The cave environment is the boundary condition for habitability but is determined by the complex interactions of several physical processes (e.g., conduction, convection, and advection), surface and subsurface conditions, and the cave geometry. Addressing these questions by investigating the appropriate terrestrial analogs will increase our understanding of these interactions, so that we may extend this to modeling cave environments on other planetary bodies.

3.3. Geology

Q15: Is there solid ice or carbon dioxide within caves on the Moon and Mars? (#18; 81.7%)
Q16: How do we accurately identify lunar and Martian pit craters that possess laterally trending passageway (i.e., a cave)? (#28; 79.3%)
Q17: Where are soluble formations (evaporites or carbonates) located on other planetary bodies? Once determined, do accessible dissolution caves exist within soluble formations (e.g., sulfates, carbonates, halides) on Mars and other planetary bodies? (#32; 78.1%)
Q18: Do dissolution caves formed by rising groundwater levels exist on Mars? If this is a possibility, where should we search for them? (#39; 76.8%)
Q19: How can we develop quantitative and highly accurate paleoclimate records from planetary cave deposits? (#43; 75.6%)
Q20: On which planets and satellites do caves actively form today? (#44; 75.6%)

Most of the remaining unanswered geologic questions related to planetary caves involve formation mechanisms, distribution and occurrence, morphologies, and the potential for internal deposits across different planetary and geologic settings. These questions should be framed within the scope of cave size and duration of existence, which can be highly variable (Mylroie, 2019). From our survey, 46 geology questions were identified; of these, six were considered fundamental.

The most important geology question (Q15, which garnered 82% of the votes from respondents) queried whether water ice deposits or solid carbon dioxide occur in caves on the Moon and Mars. Caves with (water) ice deposits are well known on Earth and may be present on Mars and the Moon under specific environmental conditions (Cooper, 1990; Perşoiu & Onac, 2019; Williams & McKay, 2015; Williams et al., 2010, 2017)—when sublimation and frosting dominates (Schörghofer, 2021). Sublimation could also generate cavities in water ice or solid carbon dioxide on the polar ice caps of Mars, as well as on icy bodies across the solar system (see Wynne et al., 2022). However, it remains unclear how these caves could form and what factors would contribute to their stability.

Numerous SAP candidates have been identified on the Moon and Mars (see Wynne et al., 2022). Many of these features have been detected in volcanic terrains, which suggests some may be associated with lava tubes (Kempe, 2012). For the Moon, at least eight have overhangs with lateral passage extending at least 20 m have been identified (Wagner & Robinson, 2021); some lunar features may support passageways several kilometers in length and volumes of hundreds of millions of cubic meters (Chappaz et al., 2017; Sauro et al., 2020; Q16). Many lunar pits occur within impact melt deposits, suggesting an origin related to the impact process or subsequent melt pond dynamics (Wagner & Robinson, 2014). However, another class of feature worth investigating is volcano-tectonic cavities (Ferrill et al., 2004; Wyrick et al., 2004), which appear to be more common than lava tubes (Wynne et al., 2022). Additionally, there are anomalous, isolated pits (e.g., Type 1 atypical pit craters; Cushing et al., 2015) whose formation mechanism(s) remain unclear. Since these include some of the deepest and most voluminous pits detected on Mars, the presence or absence of accessible lateral passageways remains an important constraint that has yet to be addressed. Question 16 could be addressed either via orbiter/flyby gravimetric surveys (e.g., Chappaz et al., 2017), or with rovers or landers equipped with ground penetrating radar sounders (Carrer et al., 2017; Kaku et al., 2017) or ground electric resistivity arrays (Torrese et al., 2021).

Other high priority questions involved the potential for speleogenic dissolution processes (Q17 and Q18) on Mars and other planetary bodies (Baioni & Wezel, 2010; Baioni et al., 2009; Malaska & Mitchell, 2017; Wynne et al., 2022; Zupan-Hajna et al., 2017). Dissolution caves are the most common on Earth (Palmer, 2007), developing where carbonate and evaporite lithologies predominate. Presently, the two planetary bodies for which dissolution has occurred or is likely to occur are Titan and Mars, respectively (Q17). On Titan, karst-like dissolution processes with liquid hydrocarbon dissolving thick organic deposits have been implicated in the formation of lake basins and "labyrinth terrains" (Cornet et al., 2015; Malaska et al., 2020). For Mars, recent studies suggest siliciclastic rocks can give rise to dissolution when specific environmental conditions exist (Wray & Sauro, 2017)—whether these lithologies could have interacted with ancient water sources on the Martian surface or shallow subsurface remains unknown. We do know that Mars contains extensive sulfate terrains and potential carbonate outcrops within ancient craters (Barbieri & Stivaletta, 2011; Palomba et al., 2009; Vaniman et al., 2004), while some geomorphic features on Mars resemble terrestrial diapiric dissolution features (Frumkin et al., 2021). Question 18 was also related to the potential presence of off-Earth hypogenic caves, formed by fluids rising along deep tectonic structures (Klimchouk, 2009, 2012). On Earth, this speleogenic mechanism is widespread and considered one of the primary cave-forming processes across a wide range of lithologies (Sauro et al., 2014).

Another important topic is how to identify, measure, and quantitatively examine paleoclimate records from planetary cave deposits (Q19). For Earth, paleoclimatic research involves examining the carbon and oxygen isotope composition of cave minerals and speleothems in both volcanic (Ulloa et al., 2013) and dissolution (both carbonate and evaporite) caves (De Waele et al., 2017; Fairchild & Baker, 2012). On the Moon, Mars, and other planetary bodies, the presence of secondary minerals is likely related to local geochemical processes, possibly due to the presence of volatiles, which has direct implications in the search of life on Mars. Importantly, could we apply the same terrestrial techniques to extract paleoclimatic and/or paleoenvironmental information from speleothems on another planetary body? Terrestrial caves are typically characterized by stable climatic conditions where evidence of past climates (mainly within sediments and chemical precipitates) can be preserved much better than on the surface. By comparing similar deposits on Earth (e.g., Fairchild & Baker, 2012), Martian cave deposits may represent key proxies for further characterizing the climatic history of Mars. However, until we can conduct a robotic mission to explore a Martian cave interior, this remains speculative.

Finally, there is a need to identify planetary bodies actively undergoing speleogenesis (Q20). This has preliminarily been addressed by Wynne et al. (2022), whereby a solar system wide inventory was conducted to identify past speleogenic processes and resultant products; they reported nine speleogenic processes on 15 planetary bodies and SAPs on 11 bodies. For example, Enceladus (Porco et al., 2014), Titan (Malaska et al., 2020; Wynne et al., 2022), and other icy bodies support active speleogenesis associated with tectonic activity and dissolution, while Mercury (Jozwiak et al., 2018), Venus (Davey et al., 2013), and Io (Wynne et al., 2022) likely support caves within tectonic and volcanic terrains (Wynne et al., 2022 and additional references therein). Additionally, fissures responding to seasonal processes may occur in subpolar regions of Mars, with potential subglacial networks of brine-filled cavities (e.g., Lauro et al., 2021). Characterizing areas of interest using repeat high resolution imagery will ultimately be required to ascertain whether a body of interest is undergoing speleogenesis—as the dynamics of subsurface processes over time will be crucial for understanding the potential role of planetary caves in the development and preservation of life on other planets.

3.4. Instrumentation

Q21: What suite of instruments would be optimal for detecting biosignatures and characterizing the mineralogy/chemistry of a subsurface environment? (#1; 96.3%)
Q22: What is the best instrument (or suite of instruments) required for the in situ study of microbe-mineral interactions? (#9; 84.2%)
Q23: Where are the primary science targets located (i.e., in the entrance zone, twilight zone, and/or deep zone) within a planetary cave? (#24; 80.5%)
Q24: What instrument resolution (spatial, spectral, and temporal) will be required to answer the key science questions in a cave environment? (#30; 79.3%)
Q25: For instruments deployed for long-term, stand-alone monitoring, how will instruments be powered and how will data be transmitted from cave to surface? (#31; 79.3%)
Q26: Can organic signatures be detected on walls from a distance (e.g., 2–3 m) using a stand-off UV Raman spectrometer? (#35; 78.1%)
Q27: What suite of navigational instruments and associated instrument resolutions would be optimal for both cave mobility and accessing potential sample locations within a cave? (#52; 74.4%)
Q28: What type of stand-off distance (close contact [<1 m], remote [10 m]) or in situ access (sample handling/ingestion or drilling) is required to address key scientific questions in a cave? (#53; 74.4%)

A future mission to a planetary cave will require a suite of instruments requiring innovations in mobility, navigation, and communications systems to collect the data to address key science questions. The most important question recognized in this survey (Q21; #1 as identified by ~96% of the respondents) emphasized the importance of identifying an optimal instrument suite to detect biosignatures and characterize the geochemistry of a planetary subsurface environment. The highest priority astrobiology, geology, and cave environment (refer to respective sections) science investigations will likely implement a combination of sampling, contact science, standoff, and remote sensing instrumentation. Instrument suite selection and their required performance characteristics (e.g., resolution, detection limits, and measurement cadence) (Q24) will be tailored to the science objectives of a specific mission, as well as other considerations including cost, operation requirements, instrument size, and power. In a subsurface environment, these restrictions may be more significant due to potentially complex mission architectures, limited communication, and accessibility challenges (refer to the Robotics section below). Considering the aforementioned constraints, proposed instrument suites should be capable of identifying habitable environments within caves—and to the extent possible—the physical and chemical signatures unique to life.

Due to the preservation potential of subsurface environments and the broad community support for astrobiological investigations, identifying instruments capable of studying microbe-mineral interactions will be a high priority (Q22). As a result, community engagement is needed to develop science objectives and instrument requirements considering the unique environment of planetary caves. This process would leverage considerable experience with studies of planetary surfaces via orbital and surface observations. For example, flight-qualified instruments for the assessment of habitability, life detection, and geologic characterization employed in recent Mars rover missions may be considered. These include: laser-induced breakdown spectroscopy (LIBS; e.g., Mars 2020 (M2020) SuperCam; Wiens et al., 2021); visible-near-infrared spectroscopy (e.g., the ExoMars MicrOmega; Bibring et al., 2017); Raman fluorescence spectrometers (e.g., the M2020 Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC); Bhartia et al., 2021); the ExoMars Raman Laser Spectrometer (Rull et al., 2017); X-ray fluorescence mapping spectrometers (e.g., the M2020 Planetary Instrument for X-ray Lithochemistry; Allwood et al., 2020); and X-ray diffraction (e.g., Mars Science Laboratory (MSL) Chemistry and Mineralogy (CheMin) instrument; Blake et al., 2012). A detailed chemical analysis could involve instrumentation similar to the MSL Sample Analysis at Mars (SAM) suite, which includes a gas chromatograph mass spectrometer and a tunable laser spectrometer (Mahaffy et al., 2012). Measurements of elemental composition, using nuclear spectroscopy (Prettyman et al., 2019; Trainer et al., 2018) or alpha-particle X-ray spectrometry demonstrated on Mars rovers (Gellert et al., 2006), could be useful in examining cave chemistry. Subsurface science objectives and operational constraints may require modifications to flight-qualified instruments or require a different set of instrumentation entirely to accommodate a planetary cave mission.

Access to high value science targets poses a challenge to any planetary science mission. However, in situ exploration of planetary caves may present a more substantial challenge than acquiring measurements on relatively flat surfaces. Data collection along cave walls or ceilings, where speleothems and other features are expected to occur (Northup et al., 2011) will require in situ access via hovering or climbing platforms (Uckert et al., 2020) or standoff instruments, which do not require placement within 1 m or contact with the surface (e.g., LIBS; Wiens et al., 2021). Standoff Raman spectroscopy may be implemented in these cases for organic or mineral characterization (Angel et al., 2012) (Q26). However, the acceptable measurement distance is dependent on sample properties and composition, ambient environmental conditions, and required detection limits. Additional sampling preparation and extraction may also be required, including drilling, rock abrasion, or instrument-specific preparation, as required for MSL CheMin and SAM (Q28). Characterization of cave geometry using lidar or three-dimensional imaging will be necessary to support bulk elemental analyses using nuclear spectroscopy data. The latter is likely to be included on any navigational platform and would also support characterization of cave geotechnical properties (refer to the Robotics section below).

In terrestrial caves, microbial distribution and biosignature preservation potential varies with distance to light sources (i.e., skylights and entrances; B. Jones, 2001). Science target locations within a subsurface environment may depend on the expected thermal gradient, airflow variability, and distribution of resources within a cave, which may drive instrument and robotic platform requirements (Q23). Investigations beyond a cave entrance may have limited communication relay rates, disrupting ground in-the-loop operations, and necessitating automated science decision-making (Q25).

The extreme terrain associated with ingress and accessing science targets within a cave necessitate robotic platforms inherently more complex than traditional wheeled surface rovers. These platforms may impose restrictions (mass, volume, and power) on instrument payloads due to additional resource consumption required for mobility, autonomy, and communication subsystems. Multiple mission architectures could be employed on such a mission, including a single robotic platform (e.g., LEMUR 3; Parness et al., 2017); multiple, more disposable (higher risk-posture) platforms each carrying a single science payload, such as hopping microbots (Kalita et al., 2017); deployable instruments for long-term monitoring and communication relay points; or tethered-rappelling rovers (Kerber et al., 2019; Nesnas et al., 2012). The ability to access a science target may depend on the selected mission architecture, further restricting a science payload. There are also opportunities for synergy whereby some of the instruments required for navigating the cave environment (navigational cameras) could be repurposed for science investigations (Q27). For example, visible spectrum or lidar imagery used for mapping and hazard avoidance could also be used to identify features of interest or determine geologic context. In addition, due to potentially limited communication relay rates, onboard processing or storage and automated science decision-making, may be required.

3.5. Robotics

Q29: What capabilities and sensors will best position robots to obtain the data required to evaluate a planetary cave for scientific inquiry, human exploration, in situ resource utilization, and other uses? (#3; 91.5%)

Q30: What strategies enable communication between subsurface robotic cave explorers and the planetary surface so that humans (whether astronauts or ground controllers) can direct robot operations and examine the science data? (#4; 89%)

Q31: What are the first scientific instruments that a rover should carry beyond those traditionally used for navigation? What sensors would provide the greatest impact to science inquiry, while not limiting the payload for mobility? (#5; 87.8%)

Q32: What tasks can robots conduct on the surface to identify planetary caves and/or map cave entrances? (#13; 82.9%)

Q33: As the technical readiness levels for most of the technology required for a cave explorer rover are quite low (i.e., TRL <4), how do we develop a competitive planetary caves mission within the cost cap of NASA science missions? (#14; 82.9%)

Q34: How can robots effectively and efficiently perceive geometric and non-geometric hazards that must be traversed or avoided to enter and explore caves? (#15; 82.9%)

Q35: What mobility solutions enable traversal of planetary surface regolith as well as vertical, steep, and/or blocky cave entrances and interiors? (#19; 81.7%)

Q36: What level of variations in terrain shape and type of planetary caves can state-of-the-art mobility systems handle? What developments will be required to optimize traversability of cave interiors? (#22; 80.5%)

Q37: What are the range of obstructions a rover should be expected to encounter within a lunar or Martian cave? (#23; 80.5%)

Q38: Beyond carrying instruments into caves, what capabilities of robotic cave explorers (e.g., precise localization of instrument readings or multimodal context) provide the greatest benefit for cave science? (#29; 79.3%)

Q39: Since cave robots have high power requirements for mobility, perception, and substantial processing for autonomous operation in the dark, what power source must these robots carry and/or how will it be supplied? (#33; 78.1%)

Q40: What near-term actions, such as technology development on Earth, technology demonstration missions, and precursor missions position us best for robotic planetary cave exploration? (#34; 78.1%)

Q41: What autonomy strategies and algorithms will be most effective for planetary cave exploration? (#45; 75.6%)

Q42: How can planetary protection be ensured for cave robots that may require complex mobility systems beyond anything we've used with surface rovers? In other words, how do we reduce the risks of contamination and false positives in the search for evidence of subterranean life? (#51; 74.4%)

Robots are likely to be the first explorers of planetary caves (Huber et al., 2014; Husain et al., 2013; Titus et al., 2021; Titus, Phillips-Lander, et al., 2020; Titus, Wynne, et al., 2020). To effectively explore these targets, future robotic systems will require the functionality to: (a) properly sense their environment; (b) support and deliver scientific payloads to sites of interest; (c) plan actions and movements; and (d) negotiate a complex landscape to execute these actions. These functionalities will be challenged by the unique features within cave interiors including low light to aphotic conditions, indirect line-of-sight communication requirements, subsurface power considerations, and rough, uneven, three-dimensional terrain that precludes satellite pre-mapping.

The third most fundamental question, acquiring support of 91.5% of respondents, was related to robotic capabilities and payloads (Q29). Ultimately, these parameters will be determined by mission objectives (i.e., life detection, evaluation for human exploration, and in situ resource utilization (ISRU)). Reconnaissance with highly specialized instrumentation could potentially address the most pressing investigations early on, but broad, multipurpose sensing will provide the best information for site selection and mission planning. However, as sensor instruments will serve as the robot's "eyes and ears," the instrumentation suite will directly dictate how data are collected and the mission is executed (Nesnas et al., 2019; Rossi et al., 2021).

Constrained by limited payloads, cave robotic designs will represent a barter between every gram of mobility and navigational sensing technologies and scientific instrumentation (Goel et al., 2021; Yoshida et al., 2013) (Q31). Limited payload capacity driven by navigational and mobility systems better suited to challenging cave interiors will preclude the more comprehensive science laboratories common to previous Mars surface rover missions (Uckert et al., 2020). While payloads will be determined by mission objectives, highly accurate three-dimensional maps of caves will represent the geospatial backbone of any planetary cave mission (Q38)—as navigation and mobility will be reliant on how well the rover can "sense" its surroundings. For example, an astrobiology-focused mission may feature a combined mobility-navigation-life detection payload that leverages dual-purpose mapping.

Advancing onboard survey instrumentation to obtain high-resolution three-dimensional cave geometries to both establish safe traverse routes and avoid hazards will be required (Q34). For surface rovers in relatively benign environments, stereo vision sensors have proven highly effective and efficient. However, many unique hazards, including complex interior geometry, dust, and darkness, will challenge sensor arrays in Martian caves and will likely require the development of new sensors (Wong et al., 2011). For example, micro-depth sensors have been used to map and navigate around obstacles (Santamaria-Navarro et al., 2019), and lidar has been used for navigation of multi-limbed climbing robots (Uckert et al., 2020). Additionally, a multi-instrument navigation payload including lidar, visible, and thermal sensors is being advanced for terrestrial cave rotorcraft drones (Dharmadhikari et al., 2021). Importantly, if these technologies represent the most viable approach for navigating and mapping caves, this approach will need to be matured.

Navigational capabilities will also vary according to the mobility platform used. A wide range of mobility platforms have been developed to negotiate cave interiors (Q35) including tethered single axle rovers (Kerber et al., 2019; Nesnas et al., 2019), legged platforms (Bouman et al., 2020), multi-limbed climbing robots (Parness et al., 2017; Uckert et al., 2020), micro-robot swarms (Funabiki et al., 2020; Lowe et al., 2018; Otsu et al., 2020), and rotorcraft (Aoki et al., 2018; Goel et al., 2021; Radotich et al., 2021). Each platform provides a unique combination of benefits, capabilities, and constraints. Alternatively, rather than choosing a singular platform, developing architectures involving multiple robotic platforms to either accomplish single mission objectives more thoroughly (i.e., mapping; Husain et al., 2013) or multiple mission objectives concurrently (Agha-Mohammadi et al., 2018, 2021) could be considered—as such an approach would also increase the breadth of science payloads entering a Martian cave.

Despite our rather thorough inventories of SAPs on the Moon and Mars (Titus, Wynne, Malaska, et al., 2021; Wynne et al., 2022), our knowledge of these features is founded primarily upon the remotely sensed examination on surface expressions—save for limited gravimetric analysis of lunar SAPs (refer to Chappaz et al., 2017). The next step will be to characterize and prioritize these features for both additional imagery acquisition (e.g., Kearney et al., 2021; Wagner & Robinson, 2021) and develop and/or expound upon gravimetric analysis (where appropriate) in support of ultimate robotic precursor missions (Q32). Provided the surface terrain surrounding a cave entrance is stable, traditional rovers may be used for entrance inspection (Titus et al., 2021; Titus, Wynne, et al., 2020). More committed, tethered single-axle rovers (e.g., Nesnas et al., 2019) may be lowered into cave entrances to both examine and map the entrance and the surrounding interior. Also, on worlds with atmospheres such as Mars, rotorcraft drones (e.g., Aoki et al., 2018; Radotich et al., 2021) could be used for inspecting cave entrances, and potentially examining and mapping the deeper reaches of a high priority cave. In all cases, these platforms would offer the first inspection of subsurface geologic stratigraphy and could potentially collect and examine rock samples.

Ingress, achieving mission objectives, and egress of a lunar or Martian cave will require navigating a complex three-dimensional landscape. Obtaining a detailed three-dimensional model of the target cave's interior prior to entry to identify obstacles and establish traverse routes will further improve mission success (Fan et al., 2021; Thakker et al., 2021) (Q36). Remotely sensed gravimetric data (*sensu* Chappaz et al., 2017) may be used for developing a coarse first-order rendition of a cave interior, while multiple robotic platforms could be used for mapping cave entrances and potentially characterizing shallow cave interiors (e.g., dual- and single-axle rovers and rotorcraft). The same navigational challenges that occur in terrestrial caves are expected to occur within SAPs on the Moon and Mars including uneven terrain, boulder-strewn breakdown fields, steep slopes, pits, cracks, and narrow passages (Q37). Additionally, for both Martian (e.g., Cushing, 2012) and lunar features, large accumulations of dust (likely meters thick), especially within entrances, will also have to be overcome.

While several of the aforementioned platforms are capable of negotiating cave interiors, most still require human assistance or direct navigation. Overall, successful exploration in a three-dimensional landscape will require the tight integration and co-design of mobility systems, traversability assessment instruments, and innovative automation/AI algorithms (Agha-Mohammadi et al., 2018, 2021; Ahmed et al., 2019; Sauder et al., 2017). Robots will need to traverse terrain that is at best partially characterized or at worst completely unknown using onboard autonomy (Otsu et al., 2020) and perception capabilities (Ebadi et al., 2020; Santamaria-Navarro et al., 2019), as well as respond to off-nominal and unexpected events during operations (Agha-Mohammadi et al., 2018; Kim et al., 2021) (Q41).

Further challenging robotic exploration will be the availability of a communications link between mission control and the robot, and the powering of systems while underground. Wireless communication is impaired by the lack of line of sight both in communication with the surface and within the cave; these impairments can result in signal fading, multipath effects, and diminished signal strength at the boundaries (Walsh et al., 2019). Various solutions have been proposed to address some of these challenges including bundling power delivery within a tether connected to a surface lander or rover (Kerber et al., 2019; Nesnas et al., 2019), data muling where the mobile robotic systems repeatedly come near the cave entrance to establish line of sight communication

(Agha-Mohammadi et al., 2021), and a set of repeaters deployed along a line of sight to construct a wireless mesh network (Q30). A repeater network could be established from the cave to the surface and may be either static or locally mobile (Ginting et al., 2020, 2021; Vaquero et al., 2020). These solutions may be used singularly or in combination based on data bandwidth requirements, maximum tolerable latency, mission duration, endurance and power requirements, mass and size limitations, and environmental considerations.

Given the demanding requirements of maintaining high mobility and the processing requirements for autonomous operations, subsurface robotics can be powered via lithium-ion batteries, limited on-demand hydrogen fuel cells, and/or laser-driven power beaming from surface to cave interior (Himangshu & Thangavelautham, 2020) (Q39). Over time, lithium-ion batteries will fail, while hydrogen fuel cell life is dependent on the amount (i.e., mass) of LiH and $LiClO_4$ transported into the cave (for hydrolysis) and the hydrolysis instrumentation. Power beaming is also both technologically and mass intensive. The number of relay stations or microbots will be dependent on the required minimum distance between stations due to line-of-sight constraints and the depth traversed within the cave; these relays would be equipped with both photovoltaic panels for receiving power and a laser for transmitting power. Energy would be beamed from the surface to the last relay point within the cave. Determining the best power source is both platform and mission dependent. Furthermore, a combination of power sources could provide both redundancy and enable deeper subsurface ingress. However, the power source and associated mass requirements would become part of the trade-space when weighing mission objectives against power needs.

All the technologies discussed thus far require significant investment and maturation before robotic cave exploration beyond Earth can become a reality. A lunar precursor mission with a traditional rover might even be achieved within 5 years under the lower-cost Payloads and Research Investigations on the Surface of the Moon (PRISM) framework, if precision landing is employed (Whittaker et al., 2020, 2021). For Mars, based on a mission concept study, Phillips-Lander et al. (2020) found that a near-term cave life detection mission would exceed the NASA New Frontiers cost cap and would require funding at the level of a Flagship Mission. However, with sagacious site selection, advances in terrestrial robotics and autonomous sampling in conjunction with leveraging Mars2020 precision-landing heritage and Mars Sample Return technologies, a Martian cave mission could fit within the New Frontiers cost cap this decade (Phillips-Lander et al., 2020) (Q33). However, to have the greatest latitude in mission objectives and scope, the aforementioned robotic platforms should be advanced in tandem (Titus et al., 2021) (Q40), while AI/autonomous navigation and decision-making programming, and cave-robotics instrument payloads progress toward flight-qualified/proven status (TRL 8–9).

Most space-faring nations have scientific representation on the Committee on Space Research (COSPAR), the international organization responsible for Planetary Protection Policy (NASA, 2021). Their decisions include drafting guidelines for both current robotic and future human exploration planetary missions (Q42). Additionally, COSPAR is charged with designating “Special Regions” (i.e., protected areas) on Mars and other planetary bodies. These areas represent regions where terrestrial microorganisms are likely to survive and replicate and have a high likelihood for supporting extant indigenous life (NASEM, 2015; Rummel et al., 2014). During the 2014 NASA Mars Exploration Program Analysis Group meeting, Martian caves were classified as “Uncertain Regions.” As such, these features will be treated as Special Regions until data can be acquired to formally classify them as either “Special” or “Non-Special” Regions (Rummel et al., 2014). Under both designations, robotic operations and associated hardware that may encounter these regions must undergo stringent cleaning procedures prior to launch to avoid forward contamination as per planetary protection categorization IVc (Rummel et al., 2014).

In addition to forward contamination, robots need to avoid damaging life that might be present in the cave or leaving non-biologic contamination that might cause problems for follow-on missions. For example, a drop over an unexpected precipice or a rotorcraft crash could result in scattered robot debris and contamination associated with fluid from instruments, hydraulics, and thermal control heat pipes and batteries. These failures may have particularly damaging consequences in an enclosed cave chamber (Goh, 2021). While developing innovative robots to meet cave mobility challenges, careful attention must be paid to materials selection and design to minimize environmental impacts related to mission-ending crashes.

Technical hurdles for a robotic cave exploration mission are indeed significant. However, robots represent the best chance for humans to examine a lunar and/or Martian cave within the next one to two decades (Titus et al., 2021; Titus, Wynne, et al., 2020; Wynne et al., 2022). To make robotic exploration of a planetary cave possible, critical investment will be required to: (a) miniaturize and ruggedize robotic sensory systems suitable for low-light to completely dark environments; (b) further develop autonomy for monitoring overall robot health and functionality, and traverse route planning; (c) mature mobility systems; (d) develop communications systems; (e) create efficient power systems for subsurface use; (f) minimize potential for contamination; and (g) miniaturize science payloads.

3.6. Human Exploration

Q43: Do Martian caves (or a subset of them) support water ice, which is reasonably accessible and can be extricated efficiently for life support? (#25; 80.5%)
Q44: How will Martian dust within caves adversely affect robotics, instrumentation, and the outer layers of habitation pods and spacesuits? Importantly, how will astronaut crews living/working in a Martian cave manage dust (i.e., to reduce both damage to equipment and inhalation threat)? (#46; 75.6%)
Q45: What modifications are required to existing extravehicular activity (EVA) tools, and/or what tools need to be developed, to work and live safely in lunar and Martian caves? (#48; 74.4%)
Q46: For lava tubes used as human habitats, what internal structural modifications will be required to maintain the structural integrity of the pressurized habitat? (#49; 74.4%)

Human exploration, ISRU, and potential human habitation represent the culmination of planetary cave exploration activities (Titus et al., 2021; Titus, Wynne, et al., 2020; Wynne et al., 2022). For long-duration human planetary exploration missions (specifically to the Moon and Mars), access to, and the habitation of SAPs will be of paramount importance (e.g., Davila et al., 2015; Titus, Phillips-Lander, et al., 2020; Titus, Wynne, et al., 2020). In most cases, the cave system will need to be fully examined (refer to the Robotics section) prior to human entry—for any use. First, the system will need to be thoroughly modeled via remote sensing assets and evaluated to determine if the necessary resources are likely to exist. Thereafter, the cave will require a robotic survey to confirm the presence of adequate water ice deposits (see Cave Environment section), life (see Astrobiology section), and/or geologic stability (see Geology section), and protection from the surface environment (see Cave Environment section). If life is detected, planetary protection protocols will be required (see Broad Concepts section).

The most important question for human exploration (as identified by ~81% of the respondents) was whether Martian caves support water ice, and how this resource may be accessed and used for life support (Q43). To do this, we must first apply mathematical models to identify caves with the greatest likelihood of supporting necessary quantities of water ice (see Cave Environment section). Thereafter, either robotic or human examination will be required to confirm the presence of water ice. If confirmed, the ice will need to be analyzed to determine whether it contains evidence of life (refer to Astrobiology section); if extant lifeforms are identified, planetary protection protocols would be invoked (see Broad Concepts section). If extraction can move forward, water ice could be robotically mined and then heated to a liquid state. For human consumption, the liquid water (likely a liquid brine), will require an intermediary desalinization step (refer to Jackson et al., 2014). Additionally, if there is potential for life, water should be sufficiently filtered as unknown life (life as we don't know it or can't detect it) may still exist and represents a potential threat to human health. For other purposes, liquid H_2O can be split into its atomic components (oxygen and hydrogen). Oxygen would then be used for life support, while hydrogen can be stored and used for fuel cells (Belz, 2016). Both oxygen and hydrogen could be used for rocket fuel for the return trip to Earth (Titus, Phillips-Lander, et al., 2020), while hydrogen fuel cells could power various life support systems including recycling management (e.g., carbon dioxide removal and waste combustion; Belz, 2016) and other power requirements. Incidentally, given the majority of Mars' atmosphere is carbon dioxide, oxygen recovery via CO_2 electrolysis (Burke & Jiao, 2016; Hecht et al., 2021) would likely represent the primary component of a life support system with oxygen from water electrolysis serving as a byproduct from energy production.

For human habitation of a lunar or Martian cave to occur, a robotic assessment would first be required. This assessment would involve an examination of the cave internal structure (i.e., volume, depth, and roof height), structural stability (i.e., low likelihood of roof fall/collapse), and an assessment to determine whether the cave is sufficiently buffered from the surface (see Cave Environment section). Once determined, a cave may then be considered for the insertion of a habitation module (or series of modules) (Q46). While some inflatable and hybrid inflatable-rigid habitation prototypes have been tested and proof-of-concept models developed (Daga et al., 2010; Krishnan, 2021; Litteken, 2019), these systems were not designed for caves. Modifications would be required to ensure these modules are sufficiently ruggedized for underground use. Another possibility would be to develop habitation modules using in situ resources (Naser & Chen, 2021); however, ISRU and their potential is in a nascent developmental stage (Starr & Muscatello, 2020), and a cave-centric focus has not been explored. Regardless of the platform selected for human habitation, the structure should have a ruggedized roof and/or be placed beneath a free-standing rigid roof structure to protect the habitation module, and the structure should be situated clear of cave walls. These considerations would reduce the likelihood of damage to the structure from roof fall and/or partial collapse.

Other considerations are how dust within caves would affect instrumentation, habitation modules, and spacesuit exterior layers, as well as the dust mitigation strategies required for astronaut crews living/working in a Martian cave (Q44). Typically, if a terrestrial cave occurs in a dust ridden environment, the cave will also be dust ridden. Because both lunar and Martian surfaces are dusty environments, we anticipate their caves will be equally dusty.

The impacts of lunar and Martian dust have challenged surface operations for decades. During the Apollo missions, the deleterious effects of lunar dust on spacesuits, buggies and other critical hardware are well established (e.g., Gaier, 2007; Wagner, 2006). On Mars, the hand lens imager onboard Curiosity rover required the development of both dust mitigation strategies and estimating dust contamination from imaged samples (Yingst et al., 2020). Additionally, solar panels on Martian rovers were periodically covered in dust and damaged by dust abrasion (McMillon-Brown et al., 2019); these impacts can compromise power acquisition and mission objectives. Similarly, life support systems and equipment will be challenged by dust because dust mobilization and adhesion (particularly the finest dust fraction (<45 μm)) reduce equipment performance and may cause health complications.

In addition to developing methods to estimate dust contamination, some mitigating factors include electrostatic precipitators (Calle et al., 2011; Manyapu & Peltz, 2018; Margiotta et al., 2010) and scroll media filters (Linne et al., 2017); these systems can be built into life support and other instrumentation to reduce dust contamination. Regarding habitation modules and spacesuits, both will require ruggedization against highly pervasive and damaging dust. To reduce dust within human habitats, dust mitigating technologies (such as electrostatic precipitators, electrostatic air filters, vacuum suction removal, and gas showers within airlocks) could be used to remove damaging dust particles; however, to our knowledge, these technologies have not been tested for this purpose.

Developing a tool kit for humans to work and live safely underground off Earth has not been examined (Q45). However, we offer the following considerations. First and foremost, a ruggedized EVA spacesuit permitting high dexterity will be required. Current spacesuit technology (e.g., EVA spacesuits used on the International Space Station) restricts mobility and would be at a high risk of suit breach if used for underground operations. One design that shows promise for underground use is BioSuit technology (Bethke et al., 2004)—a svelte and flexible alternative to current spacesuits. However, these suits and their associated donning and doffing technologies are at the proof-of-concept stage. To become "SpeleoSuits," BioSuits must be immensely ruggedized to become puncture and abrasion resistant and should include reinforced/ballistic material applied to knee, elbow, and hand regions. For tool development, a first step would be to evaluate flight proven (TRL 9) EVA (Fullerton, 1993) and Apollo lunar sampling tools (Allton, 1989). Additionally, NASA is designing EVA tools (based on Apollo-era heritage designs) for the Artemis program with greater emphasis on sustained operations and long-duration exploration on the Moon (Coan, 2020). Some of this equipment may be either suitable or retrofitted for use on a planetary cave mission. In terms of technical caving equipment (i.e., rappelling and ascending devices, harnesses, protection devices, anchor systems, etc.), presently there have been no technical climbing/caving equipment developed for underground extraterrestrial human operations, nor have there been any studies to examine or test how terrestrial equipment may be modified for extraterrestrial use.

3.7. Broad Concepts

*Q47: In case life is discovered, what planetary protection protocols are most applicable to ensure that we will not negatively impact these lifeforms? (#2; 93.6%)

Q48: To optimize planetary cave candidate selection, what remote sensing instruments will be required (or need to be developed) to determine cave structure and depth with a suitable degree of accuracy? (#10; 84.2%)

Q49: For candidate selection for both the search for life and human habitation, how do we systematically evaluate planetary caves for both applications? (#26; 80.5%)

*Q50: How does cave exploration integrate with other scientific/exploration mission goals on Mars? In what mission framework could a cave exploration mission be conducted? (#36; 77.4%)

Q51: What is the range of types of subterranean features that occur on planetary bodies within our solar system? (#40; 76.8%)

Q52: Can we develop a data-derived method to predict the likelihood of different types of caves using the fundamental properties of a planetary body (e.g., presence of volatiles, viscosity of lava when flowing, presence or absence of internal tectonism of some variety, etc.)? (#41; 76.8%)

Q53: What are the primary factors contributing to the apparently high microbial biodiversity observed in the Earth's subsurface? (#47; 75.6%)

Fundamental questions in the broad concepts subject area ranged from planetary protection to leveraging our knowledge of terrestrial microbial diversity to gain inference into the possibilities to extraterrestrial subsurface life—well-encapsulating big picture ideas and concepts. Importantly, the only two questions identified by our Survey 2 participants were within this subject area group (denoted with an *).

Our number two fundamental question dealt with protecting extraterrestrial life (should it exist) from lifeforms introduced from Earth (Q47). A general overview of planetary protection procedures as it relates to robotic operations is provided above in question 42. Our inability to adequately "clean" spacecraft prior to planetary missions has been well-established (refer to Nicholson et al. [2009] and Fairén et al. [2017]). Thus, some have reasoned that given our stringent protocols for cleaning spacecraft prior to missions, we have already sent the most resilient terrestrial microbes to other planetary bodies (Fairén et al., 2017; Nicholson et al., 2009). Similarly, "superbugs" have been documented in hospitals subjected to intensive decontamination procedures (Dancer, 2009; Humphries & McDonnell, 2015; Muscarella, 2014). Overall, the impacts of introducing terrestrial microbes to Mars or other planetary bodies is expected to be tantamount to nonnative species introductions on Earth (e.g., Simberloff & Rejmánek, 2011); release from terrestrial competition and predation compounded with potentially being supercharged by rigorous cleaning procedures, these terrestrial microbes may thus be particularly pernicious and resilient should they become established on other planetary bodies. Concomitantly, others (e.g., Glavin et al., 2004; McKay, 2009; Siefert et al., 2012) have suggested planetary protection concerns become moot once humans arrive on another planetary body—as forward contamination will be unavoidable. Regardless of this undesirable outcome, given the availability of next generation genetic/genomic techniques, we should be able to discern terrestrial from Martian microbes (Fairén et al., 2017); if life beyond Earth has a different biochemistry, it will be much easier to determine that forward contamination did not occur.

Concerning habitats of possible cave-dwelling extraterrestrial microbes, the range of formation processes and the diversity of planetary bodies in our solar system gives rise to a plethora of planetary cave types (Titus, Phillips-Lander, et al., 2020; Wynne et al., 2022) (Q51). Speleogenic processes include thermal erosion/deposition (lava tube formation), dissolution (karst), sublimation, phase change to create void space, erosional removal (suffusion), and block break down (Boston, 2020; Titus, Phillips-Lander, et al., 2020; Wynne et al., 2022). Key properties influencing solar system-wide cave formation include temperature, pressure, gravity field, and if there is a liquid cycle, the properties of that liquid (e.g., water vs. supercritical CO_2 vs. methane; Malaska & Hodyss, 2014; Malaska et al., 2011). Host rock (or ice) properties will also influence cave formation processes; these include the strength (of various moduli) and deformation characteristics of substrate materials at local environmental conditions. While we have made considerable strides toward identifying and categorizing the assorted cave-formation processes and their associated properties (Titus, Wynne, et al., 2020), our knowledge of planetary caves in the solar system remains incomplete. For example, formation processes for SAPs on Venus are unknown (Wynne et al., 2022). Three upcoming missions, NASA's VERITAS and DAVINCI+ and ESA's EnVision may serve to partially address this knowledge gap and may potentially reveal novel Venusian cave formation processes. VERITAS will acquire a global three-dimensional surface map at 15–30 m resolution using a synthetic aperture radar instrument (InSAR; Freeman et al., 2016), while DAVINCI+ will include a descending probe designed to examine the uncharacterized lower atmosphere and collect imagery to produce high-resolution (from altitudes of 5 km to near the surface) digital elevation models of the highly geologically deformed Tesserae formations (Garvin et al., 2020; V. L. Hansen & Willis, 1998). EnVision will acquire near-global coverage data to characterize geologic types and weathering, identify regions of active volcanic activity, and collect high-resolution atmospheric measurements (Helbert et al., 2019).

While many speleogenic processes on Earth are well understood (Dreybrodt et al., 2004), extrapolating this information to planetary caves will require theoretical modeling and laboratory experiments to understand the key intrinsic properties (Cornet et al., 2015; Malaska & Hodyss, 2014; Raulin, 1987) (Q52). To illustrate, the putative karstic processes on Saturn's moon Titan involve liquid methane and ethane as the working fluid dissolving organic bedrock and/or other organic minerals (Malaska et al., 2011; Maynard-Casely et al., 2018). While, at some level, this process is comparable to terrestrial karst formation, some of the specific details are quite different (Cornet et al., 2017). For example, the complex aqueous equilibrium of carbon dioxide partial pressure affecting carbonate dissolution is nonexistent on Titan. On Mars, karstic processes likely occur in deposited salts such as kieserite ($MgSO_4 \cdot H_2O$) that would exist in different dehydration states on Earth or would be so soluble that they would quickly dissolve (Baioni & Sgavetti, 2013). Locally dry conditions on Mars presumably allow this material, and these karstic remnants, to exist. In this Martian example, the relative time scale of fluid availability and cycling allows caves to exist, where on wetter worlds a similar cave would quickly be dissolved away. Thus, the kinetics of the cave formation process relative to other processes (e.g., collapse, dissolution, etc.) may also be an important factor. Thus, we have, and should, continue to use our knowledge of planetary body specific geology to influence where we search for SAPs (see Wynne et al., 2022).

Question 49 intimates how best to develop systematic procedures for parsing cave types into candidates for robotic exploration, possible human habitation, or perhaps both. This procedure will be driven by the space-bound assets available to conduct the evaluation. Overall, the roadmap proposed by Titus, Wynne, Malaska, et al. (2021) outlines two critical steps identified as prerequisites for planetary cave exploration—identification and characterization. To this end, high-resolution imagery of possible SAPs and their surrounding topography must be acquired and examined, then near-surface to ground assets will be required to further scrutinize and evaluate cave candidate sites for both robotic and human exploration. However, in the near term, robotic exploration will factor more prominently than human use. On Mars, selection criteria for robotics will be chiefly centered around life detection and should include identifying features with the highest probability for supporting water ice (e.g., Schörghofer, 2021; Williams et al., 2010) and being accessible, as well as the additional selection criteria elucidated by other workers (refer to Wynne et al. [2014], Kearney et al. [2021], and Titus, Wynne, Malaska, et al. [2021]).

To examine the "characterization" stage more fully, the realities of limited resources and constrained budgets will necessitate the selection of multipurpose interdisciplinary missions whenever possible (Q48). From orbit, remote sensing instrumentation including electrical resistivity (Selim et al., 2014) and gravimetry (Chappaz et al., 2017) may be used to "map" known subsurface voids and possibly detect new ones. Near-surface and surface assets should include both drones and traditional rovers. Drones can perform a broad range of non-cave specific science activities, while also being employed to identify and characterize features of interest using standard science and navigation payloads (e.g., cameras; Titus, Wynne, et al., 2020; Titus, Wynne, Malaska et al., 2021). Traditional surface rovers could be assigned the cave-related tasks of further examining a feature of interest. For example, if the rover payload included ground-penetrating radar, the subsurface void space for features of interest could be characterized (e.g., Esmaeili et al., 2020; Hamran et al., 2020).

Progressing toward the "exploration" stage, several approaches can be taken to optimize payload/instrumentation for cave specific missions. For example, a surface communications relay station should also include meteorological and/or seismic instrumentation. The robotic platform entering the cave should be equipped with environmental, geologic, and astrobiology instrumentation. Additional information on this topic is provided in the Instrumentation and Robotics sections above.

Even in locations without caves, data from cave robotic instrumentation would provide new geologic insights into the near surface (Q50). For example, the Dynamic Albedo of Neutrons (DAN) onboard the Mars Science Laboratory actively and passively probes the near surface by monitoring neutron and gamma ray flux (e.g., Kerner et al., 2020). DAN is specifically looking for evidence of water bound to minerals near the surface. Similarly, depending upon the robotic platform and payload, surface-related science data could be collected during a cave mission—including validation of remote sensing interpretations, as well as providing additional insights into near-surface geology. Thus, such a mission would maximally benefit the science community.

Regarding life potential, recent terrestrial studies revealed that subsurface geological settings provide the most diverse ecosystems—often dominated by chemolithotrophs and novel microbial lifeforms with significant implications for the origin and evolution of life on Earth (Escudero et al., 2020; Magnabosco et al., 2018; Miller et al., 2020; Selensky et al., 2021). These microorganisms play vital roles in almost all biological processes, such as global biogeochemical cycling, biomineralization, and pedogenesis (Gaboyer et al., 2017; Miller et al., 2018; Tornos et al., 2014). However, and despite the advent of new high-throughput genetic sequencing technologies, several fundamental aspects of their distribution and ecology remain unknown. While it has been reasonably established that mineralogical composition contributes significantly to subsurface microbial diversity and biomass (Casar et al., 2020; Escudero et al., 2020; A. A. Jones & Bennett, 2017; Rempfert et al., 2017), researchers have yet to quantify the environmental variables contributing to high microbial biodiversity in subterranean ecosystems (Q53). To achieve this, an integrative, multidisciplinary approach involving metagenomics, microscopy, mineralogy, and geochemistry (Cockell et al., 2019; Miot et al., 2014), as well as ecological and climatological modeling across a variety of cave lithologies, geometries and disparate study areas represents a viable research frame to significantly advance our knowledge. Through such an approach, we should be able to robustly parameterize the drivers of subsurface microbial diversity and ultimately pioneer a viable methodology to identify the best caves to study, as well as optimally select within-cave locations to sample.

4. Conclusions

To our knowledge, this is the first time a horizon scan approach has been applied to synthesize research needs in planetary science. We believe this work has shown the viability and importance of expert-opinion-based social surveys in the planetary sciences. As such, we hope this inspires future efforts to examine other subdisciplines in planetary science and space exploration using similar techniques.

Evaluations concerning whether horizon scans achieve their stated goals have been rarely, if ever, undertaken (Wintle et al., 2020). We recommend revisiting this topic periodically to synthesize the progress made, as well as to potentially recalibrate the research efforts to ensure planetary cave exploration technologies are adequately progressing. However, we identified fundamental research questions rather than more broadly scoped themes. Ensuing evaluative exercises will require a theme-based approach (e.g., Brown, 2007; Hughes et al., 2020; Könnölä et al., 2012; Sutherland, Bardsley, et al., 2011). By using the same subject area groups applied here, future efforts should examine the progress within each subject area through evaluating advances made, identifying remaining knowledge gaps, and pinpointing the specific steps required to address scientific and/or technological needs. We recommend scheduling "progress" workshops during the International Planetary Caves Conference, which has convened biennially to triennially since 2011.

At 14 questions, the robotics group had twice as many questions as the other categories. This suggested that perhaps the broader community recognized advancing robotic technologies represented the linchpin of a planetary cave mission. Importantly, several recently funded in situ cave investigations designed to further develop robotic subsystems and advance operational readiness are underway. These include rock-climbing robotics (Uckert et al., 2020), microbots (Dubowsky et al., 2006; Kalita et al., 2017), tethered rovers (Kerber et al., 2019), and autonomous quadruped rover technologies (Bouman et al., 2020). As we have evinced, relevancy of a specific subsystem will be driven by the mission; thus, for a planetary cave mission to have the greatest latitude, all the aforementioned platforms should be improved concomitantly. To accomplish this, significant investment will be required to support these innovations maturing to a flight-qualified level (Titus, Wynne, et al., 2020; Titus, Wynne, Malaska, et al., 2021; Wynne et al., 2022).

Mammola et al. (2020) suggested that voting exercises focused on selecting questions (as we have done here) often skew toward general rather than specific themes. These authors reported this to be the case and we found a similar trend in our study. For example, our top 10 questions were broadly focused. While one explanation may be that given the interdisciplinary composition of survey participants in Survey 2, general or broad-focused questions may have a broader appeal by an interdisciplinary group and thus be identified as important. However, as we qualitatively noted a disproportionate focus on robotics questions, this may be indicative of another trend. As engineers comprised only ∼15% of Survey 2 respondents, it is possible that participants recognized the substantial lacunae associated with underdeveloped robotic platforms and cast their votes accordingly. In either case, we felt that we should provide all questions across all three surveys, so that future workers will be able to further examine and scrutinize over our findings (refer to Supporting Information S1; Wynne, 2022).

Perhaps one of the most important aspects of this work was harnessing the vast interdisciplinary knowledge of 25 scientists (across multiple disciplines), nine engineers, and two retired astronauts. We assembled a diverse interdisciplinary group to identify a strategy to advance scientific knowledge and technology to ultimately explore caves on other planetary bodies. Furthermore, we brought six disparate yet interrelated subjects under one roof. Such interdisciplinary efforts are essential to catalyze innovations (Moirano et al., 2020) and improve cross-disciplinary efficiency (e.g., Kreuz et al., 2020; Pfohl et al., 2017). Subsequently, we believe horizon scanning efforts, such as the one presented here, will greatly benefit planetary science research—as most subdisciplines are equally reliant on interdisciplinary synergistic collaborations and activities.

We would also like to emphasize that Decadal Survey and National Academy of Science Space Studies Board (NASSSB) white papers are essentially horizon scans. These efforts aggregate expert opinions on a given planetary topic and/or body into a document that guides future research. However, these guiding documents are typically drafted by a cadre of lead authors with contributing authors providing input thereafter (as was the case with Titus, Wynne, et al., 2020). As horizon scans can be designed to engage a broad swath of the community at the formative stage, we submit such an approach (as the one employed here) can be more encompassing and therefore more representative of the broader scientific community. Importantly, our horizon scan approach was both systematic and statistically rigorous and may be considered a template for similar planetary science exercises. Thus, we recommend that future Decadal Survey and NASSSB working groups apply an approach that embodies many of the elements presented in this study.

With the passing of the 50th anniversary of the two seminal mathematical modeling efforts on the potential for lunar lava tubes (Greeley, 1971; Oberbeck et al., 1969), we felt this was the perfect opportunity to take stock of the significant advances in planetary cave exploration. Our collective knowledge has progressed from musing to confirming the presence of SAPs beyond Earth—not only on the Moon, but on at least 10 other planetary bodies (Wynne et al., 2022). To date, detection capabilities have been developed and refined (e.g., Chappaz et al., 2017; Cushing, 2017; Pisani & De Waele, 2021; Wynne et al., 2008, 2021), and astrobiological sampling techniques and associated instrumentation suites have been advanced by several key research projects (e.g., Agha-Mohammadi et al., 2021; Blank, 2020; Uckert et al., 2020). Moreover, a bevy of robotic platforms are slowly moving toward flight-qualified status (see Robotics section above), while astronauts are now being trained to conduct subsurface missions (Sauro et al., 2021). These accomplishments were unfathomable 50 years ago. Incidentally, most of these achievements have transpired over the past 10 years.

We anticipate the next 10 years will be as riveting as the past decade. As robotic platforms and instrumentation suites mature, humans move ever closer to embarking upon a robotic planetary cave mission—most likely to the Moon first, then to Mars. These advances will further bolster the importance of planetary subsurfaces for human use, which will inevitably result in humans exploring and perhaps establishing astronaut bases underground. When this comes to pass, humans will return to sojourning in caves. While humanity abandoned this practice millennia ago, humans dwelling beyond Earth are likely to seek shelter underground once again for safety and protection.

Disclaimers

The survey results reported herein was organized and implemented by JJW, Northern Arizona University, and were not conducted on behalf of the U.S. Geological Survey. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

This is a review paper driven by a series of expert opinion based general social surveys. The questions used for three individual online surveys, all survey results, the combined results of Survey 1 and 2, and the top 53 fundamental questions are available via the Harvard Dataverse (https://doi.org/10.7910/DVN/HJA6QI).

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References

Agha-Mohammadi, A., Agarwal, S., Kim, S., Chakravorty, S., & Amato, N. (2018). SLAP: Simultaneous localization and planning for physical mobile robots via enabling dynamic replanning in belief space. *IEEE Transactions on Robotics*, *34*(5), 1195–1214. https://doi.org/10.1109/tro.2018.2838556

Agha-Mohammadi, A., Otsu, K., Morrell, B., Fan, D. D., Thakker, R., Santamaria-Navarro, A., et al. (2021). NeBula: Quest for robotic autonomy in challenging environments; TEAM CoSTAR at the DARPA subterranean challenge. *Journal of Field Robotics*. Accepted. https://arxiv.org/abs/2103.11470

Ahmed, M., Hossain, K., & Miles, J. (2019). *Analysis, design, and construction of autonomous robots* (p. 68). NASA Goddard Space Flight Center. Retrieved from https://njsgc.rutgers.edu/sites/default/files/nasa-giss-research-paper-2Nesnas 019.pdf

Allton, J. H. (1989). *Catalog of Apollo lunar surface geological sampling tools and containers*. JSC-23454, LESC-2276 (p. 101). NASA Johnson Space Center. Retrieved from https://repository.hou.usra.edu/handle/20.500.11753/678

Allwood, A. C., Beaty, D., Bass, D., Conley, C., Kminek, G., Race, M., et al. (2013). Conference summary: Life detection in extraterrestrial samples. *Astrobiology*, *13*(2), 203–216. https://doi.org/10.1089/ast.2012.0931

Allwood, A. C., Wade, L. A., Foote, M. C., Elam, W. T., Hurowitz, J. A., Battel, S., et al. (2020). PIXL: Planetary instrument for X-ray lithochemistry. *Space Science Reviews*, *216*, 1–132.

Angel, S. M., Gomer, N. R., Sharma, S. K., & McKay, C. (2012). Remote Raman spectroscopy for planetary exploration: A review. *Applied Spectroscopy*, *66*(2), 137–150. https://doi.org/10.1366/11-06535

Aoki, R., Oyama, A., Fujita, K., Nagai, H., Kanazaki, M., Kanou, K., et al. (2018). *Conceptual helicopter design for exploration of pit craters and caves on Mars* (p. 5362). AIAA Space and Astronautics Forum and Exposition.

Atri, D., & Melott, A. L. (2014). Cosmic rays and terrestrial life: A brief review. *Astroparticle Physics*, *53*, 186–190. https://doi.org/10.1016/j.astropartphys.2013.03.001

Azua-Bustos, A., Fairén, A. G., Silva, C. G., Carrizo, D., Fernández-Martínez, M. Á., Arenas-Fajardo, C., et al. (2020). Inhabited subsurface wet smectites in the hyperarid core of the Atacama Desert as an analog for the search for life on Mars. *Scientific Reports*, *10*(1), 19183. https://doi.org/10.1038/s41598-020-76302-z

Azua-Bustos, A., González-Silva, C., Mancilla, R. A., Salas, L., Palma, R. E., Wynne, J. J., et al. (2009). Ancient photosynthetic eukaryote biofilms in an Atacama Desert coastal cave. *Microbial Ecology*, *58*(3), 485–496. https://doi.org/10.1007/s00248-009-9500-5

Azua-Bustos, A., González-Silva, C., Salas, L., & Vicuña, R. (2010). A novel subaerial *Dunaliella* sp. Growing on cave spiderwebs in the Atacama Desert. *Extremophiles*, *14*(5), 443–452. https://doi.org/10.1007/s00792-010-0322-7

Badino, G. (2010). Underground meteorology-"What's the weather underground?". *Acta Carsologica*, *39*(3), 427–448. https://doi.org/10.3986/ac.v39i3.74

Baioni, D., & Sgavetti, M. (2013). Karst terrains as possible lithologic and stratigraphic markers in northern Sinus Meridiani, Mars. *Planetary and Space Science*, *75*, 173–181. https://doi.org/10.1016/j.pss.2012.08.011

Baioni, D., & Wezel, F. C. (2010). Morphology and origin of an evaporitic dome in the eastern Tithonium Chasma, Mars. *Planetary and Space Science*, *58*(5), 847–857. https://doi.org/10.1016/j.pss.2010.01.009

Baioni, D., Zupan-Hajna, N., & Wezel, F. C. (2009). Karst landforms in a Martian evaporitic dome. *Acta Carsologica*, *38*(1), 9–18. https://doi.org/10.3986/ac.v38i1.132

Banfield, J. F., Moreau, J. W., Chan, C. S., Welch, S. A., & Little, B. (2001). Mineralogical biosignatures and the search for life on Mars. *Astrobiology*, *1*(4), 447–465. https://doi.org/10.1089/153110701753593856

Barbieri, R., & Stivaletta, N. (2011). Continental evaporites and the search for evidence of life on Mars. *Geological Journal*, *46*(6), 513–524. https://doi.org/10.1002/gj.1326

Bar-On, Y. M., Phillips, R., & Milo, R. (2018). The biomass distribution on Earth. *Proceedings of the National Academy of Sciences*, *115*(25), 6506–6511. https://doi.org/10.1073/pnas.1711842115

Belz, S. (2016). A synergetic use of hydrogen and fuel cells in human spaceflight power systems. *Acta Astronautica*, *121*, 323–331. https://doi.org/10.1016/j.actaastro.2015.05.031

Bethke, K., Carr, C. E., Pitts, B. M., & Newman, D. J. (2004). Bio-suit development: Viable options for mechanical counter pressure. *SAE Transactions*, *113*, 426–437. https://doi.org/10.4271/2004-01-2294

Bhartia, R., Beegle, L. W., DeFlores, L., Abbey, W., Hollis, J. R., Uckert, K., et al. (2021). Perseverance's scanning habitable environments with Raman and luminescence for organics and chemicals (SHERLOC) investigation. *Space Science Reviews*, *217*, 1–115.

Bibring, J.-P., Hamm, V., Pilorget, C., Vago, J. L., & the MicrOmega Team. (2017). The micrOmega investigation onboard ExoMars. *Astrobiology*, *17*(6–7), 621–626. https://doi.org/10.1089/ast.2016.1642

Blake, D., Vaniman, D., Achilles, C., Anderson, R., Bish, D., Bristow, T., et al. (2012). Characterization and calibration of the CheMin mineralogical instrument on Mars Science Laboratory. *Space Science Reviews*, *170*(1), 341–399. https://doi.org/10.1007/978-1-4614-6339-9_12

Blamont, J. (2014). A roadmap to cave dwelling on the Moon and Mars. *Advances in Space Research*, *54*(10), 2140–2149. https://doi.org/10.1016/j.asr.2014.08.019

Blank, J. G. (2020). Robotic mapping and exploration of a terrestrial lava tube: A structured planetary cave mission simulation with a remote astrobiology science team. In *Paper presented at 3rd International Planetary Caves Conference*. LPI Contributions No. 1047.

Blank, J. G., Roush, T. L., Stoker, C. L., Colaprete, A., Datta, S., Wong, U., et al. (2018). Planetary caves as astrobiology targets. *A white paper submitted to the Space Studies Board of the National Academy of Sciences* (Vol. 5).

Blumensaat, F., Leitão, J. P., Ort, C., Rieckermann, J., Scheidegger, A., Vanrolleghem, P. A., & Villez, K. (2019). How urban storm-and wastewater management prepares for emerging opportunities and threats: Digital transformation, ubiquitous sensing, new data sources, and beyond-a horizon scan. *Environmental Science & Technology*, *53*(15), 8488–8498. https://doi.org/10.1021/acs.est.8b06481

Boston, P. J. (2004). Extraterrestrial caves. In J. Gunn (Ed.), *Encyclopedia of caves and karst science* (pp. 355–358). Fitzroy Dearborn.

Boston, P. J. (2020). Cavities and caves throughout the solar system: Prospects revisited for occurrence and astrobiological significance. In *Paper presented at 3rd International Planetary Caves Conference*. LPI Contributions No. 1076.

Boston, P. J., Spilde, M. N., Northup, D. E., Melim, L. A., Soroka, D. S., Kleina, L. G., et al. (2001). Cave biosignature suites: Microbes, minerals, and Mars. *Astrobiology*, *1*, 25–55. https://doi.org/10.1089/153110701750137413

Bouman, A., Ginting, M. F., Alatur, N., Palieri, M., Fan, D. D., Touma, T., et al. (2020). Autonomous spot: Long-range autonomous exploration of extreme environments with legged locomotion. *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2518–2525. https://doi.org/10.1109/iros45743.2020.9341361

Brown, D. (2007). Horizon scanning and the business environment—The implications for risk management. *BT Technology Journal*, *25*(1), 208–214. https://doi.org/10.1007/s10550-007-0022-8

Burke, K. A., & Jiao, F. (2016). *Game changing development program-next generation life support project: Oxygen recovery from carbon dioxide using ion exchange membrane electrolysis technology*. NASA/TM—2016-219436, NASA STI Program (p. 55). NASA Langley Research Center Hampton. Retrieved from https://ntrs.nasa.gov/api/citations/20160014804/downloads/20160014804.pdf

Burt, D. M., & Knauth, L. P. (2003). Electrically conducting, Ca-rich brines, rather than water, expected in the Martian subsurface. *Journal of Geophysical Research*, *108*, E4. https://doi.org/10.1029/2002je001862

Burt, R. S. (1984). Network items and the general social survey. *Social Networks*, *6*(4), 293–339. https://doi.org/10.1016/0378-8733(84)90007-8

Calle, C. I., Buhler, C. R., Johansen, M. R., Hogue, M. D., & Snyder, S. J. (2011). Active dust control and mitigation technology for lunar and Martian exploration. *Acta Astronautica*, *69*(11–12), 1082–1088. https://doi.org/10.1016/j.actaastro.2011.06.010

Carrer, L., Gerekos, C., & Bruzzone, L. (2017). Detection of lunar lava tubes with orbiting radar sounder systems. *European Planetary Science Congress*, *11*, EPSC2017–290.

Carrier, B. L., Beaty, D. W., Meyer, M. A., Blank, J. G., Chou, L., DasSarma, S., et al. (2020). Mars extant life: What's next? *Astrobiology*, *20*(6), 785–814. https://doi.org/10.1089/ast.2020.2237

Casar, C. P., Kruger, B. R., Flynn, T. M., Masterson, A. L., Momper, L. M., & Osburn, M. R. (2020). Mineral-hosted biofilm communities in the continental deep subsurface, Deep Mine Microbial Observatory, SD, USA. *Geobiology*, *18*(4), 508–522. https://doi.org/10.1111/gbi.12391

Castro-Wallace, S. L., Chiu, C. Y., John, K. K., Stahl, S. E., Rubins, K. H., McIntyre, A. B., et al. (2017). Nanopore DNA sequencing and genome assembly on the International Space Station. *Scientific Reports*, *7*(1), 18022. https://doi.org/10.1038/s41598-017-18364-0

Chappaz, L., Sood, R., Melosh, H. J., Howell, K. C., Blair, D. M., Milbury, C., & Zuber, M. T. (2017). Evidence of large empty lava tubes on the Moon using GRAIL gravity. *Geophysical Research Letters*, *44*(1), 105–112. https://doi.org/10.1002/2016gl071588

Coan, D. (2020). *Exploration EVA system concept of operations*. EVA-EXP-0042, Revision B (p. 175). NASA Headquarters. Retrieved from https://www.nasa.gov/sites/default/files/atoms/files/eva-exp-0042_xeva_system_con_ops_rev_b_final_dtd_10192020_ref_doc.pdf

Cockell, C. S., Holt, J., Campbell, J., Groseman, H., Josset, J. L., Bontognali, T. R., et al. (2019). Subsurface scientific exploration of extraterrestrial environments (MINAR 5): Analogue science, technology and education in the Boulby Mine, UK. *International Journal of Astrobiology*, *18*(2), 157–182. https://doi.org/10.1017/s1473550418000186

Cooper, B. L. (1990). Sources and subsurface reservoirs of lunar volatiles. *Lunar and Planetary Science Conference Proceedings*, *20*, 259–269.

Cornet, T., Cordier, D., Bahers, T. L., Bourgeois, O., Fleurant, C., Mouélic, S. L., & Altobelli, N. (2015). Dissolution on Titan and on Earth: Toward the age of Titan's karstic landscapes. *Journal of Geophysical Research: Planets*, *120*(6), 1044–1074. https://doi.org/10.1002/2014je004738

Cornet, T., Fleurant, C., Seignovert, B., Cordier, D., Bourgeois, O., Le Mouélic, S., et al. (2017). Landscape formation through dissolution on Titan: A 3D landscape evolution model. In *Paper presented at 48th Lunar and Planetary Science Conference*. LPI Contributions No. 1835.

Cropley, J. B. (1965). Influence of surface conditions on temperatures in large cave systems. *National Speleological Society Bulletin*, *27*, 1–9.

Cushing, G. E. (2012). Candidate cave entrances on Mars. *Journal of Cave and Karst Studies*, *74*(1), 33–47. https://doi.org/10.4311/2010ex0167r

Cushing, G. E. (2017). *Mars global cave candidate catalog archive bundle*. U.S. Geological Survey. Retrieved from astrogeology.usgs.gov/search/map/Mars/MarsCaveCatalog/mars_cave_catalog.zip

Cushing, G. E., Okubo, C. H., & Titus, T. N. (2015). Atypical pit craters on Mars: New insights from THEMIS, CTX, and HiRISE observations. *Journal of Geophysical Research: Planets*, *120*(6), 1023–1043. https://doi.org/10.1002/2014je004735

Cushing, G. E., Titus, T. N., Wynne, J. J., & Christensen, P. (2007). THEMIS observes possible cave skylights on Mars. *Geophysical Research Letters*, *34*(17), L17201. https://doi.org/10.1029/2007gl030709

Daga, A., Schneider Puente, I., Uzman, Z., de Leon, P., & Harris, G. (2010). Habitat architecture concept definition for "integrated strategies for the human exploration of the Moon and Mars" (a NASA-funded study): Interim status report. In *Paper presented at 40th International Conference on Environmental Systems AIAA* (pp. 2010–6072).

Dancer, S. J. (2009). The role of environmental cleaning in the control of hospital-acquired infection. *Journal of Hospital Infection*, *73*(4), 378–385. https://doi.org/10.1016/j.jhin.2009.03.030

Davey, S. C., Ernst, R. E., Samson, C., & Grosfils, E. B. (2013). Hierarchical clustering of pit crater chains on Venus. *Canadian Journal of Earth Sciences*, *50*(1), 109–126. https://doi.org/10.1139/cjes-2012-0054

Davila, A. F., Fairén, A. G., Rodríguez, A. P., Schulze-Makuch, D., Rask, J., & Zavaleta, J. (2015). The Hebrus Valles exploration zone: Access to the Martian surface and subsurface. In *First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars*. LPI Contributions No. 1012.

De Angeles, G., Wilson, J. W., Clowdsley, M. S., Nealy, J. E., Humes, D. H., & Clem, J. M. (2002). Lunar lava tube radiation safety analysis. *Journal of Radiation Research*, *43*, S41–S45. https://doi.org/10.1269/jrr.43.s41

de Freitas, C. R., & Littlejohn, R. N. (1987). Cave climate: Assessment of heat and moisture exchange. *Journal of Climatology*, *7*(6), 553–569. https://doi.org/10.1002/joc.3370070604

De Waele, J., Carbone, C., Sanna, L., Vattano, M., Galli, E., Sauro, F., & Forti, P. (2017). Secondary minerals from salt caves in the Atacama Desert (Chile): A hyperarid and hypersaline environment with potential analogies to the Martian subsurface. *International Journal of Speleology*, *46*(1), 51–66. https://doi.org/10.5038/1827-806x.46.1.2094

Dharmadhikari, M., Nguyen, H., Mascarich, F., Khedekar, N., & Alexis, K. (2021). *Autonomous cave exploration using aerial robots. International Conference on Unmanned Aircraft Systems (ICUAS)* (pp. 942–949). IEEE.

Dreybrodt, W., Gabrovšek, F., & Romanov, D. (2004). *Processes of speleogenesis: A modeling approach*. ZRC Publishing.

Dubowsky, S., Iagnemma, K., & Boston, P. J. (2006). *Microbots for large-scale planetary surface and subsurface exploration*. NIAC Phase II, Year 1 Report (p. 6). Massachusetts Institute of Technology.

Duxbury, N. S., & Brown, R. H. (1997). The role of an internal heat source for the eruptive plumes on Triton. *Icarus*, *125*(1), 83–93. https://doi.org/10.1006/icar.1996.5554

Ebadi, K., Chang, Y., Palieri, M., Stephens, A., Hatteland, A., Heiden, E., et al. (2020). LAMP: Large-scale autonomous mapping and positioning for exploration of perceptually-degraded subterranean environments. *IEEE International Conference on Robotics and Automation*, 80–86. https://doi.org/10.1109/icra40945.2020.9197082

Escudero, C., Del Campo, A., Ares, J. R., Sánchez, C., Martínez, J. M., Gómez, F., & Amils, R. (2020). Visualizing microorganism-mineral interaction in the Iberian Pyrite Belt subsurface: The acidovorax case. *Frontiers in Microbiology*, *11*, 2833. https://doi.org/10.3389/fmicb.2020.572104

Esmaeili, S., Kruse, S., Jazayeri, S., Whelley, P., Bell, E., Richardson, J., et al. (2020). Resolution of lava tubes with ground penetrating radar: The TubeX project. *Journal of Geophysical Research: Planets*, *125*(5), e2019JE006138. https://doi.org/10.1029/2019je006138

Fairchild, I. J., & Baker, A. (2012). *Speleothem science: From process to past environments*. Wiley-Blackwell.

Fairén, A. G., Parro, V., Schulze-Makuch, D., & Whyte, L. (2017). Searching for life on Mars before it is too late. *Astrobiology*, *17*(10), 962–970. https://doi.org/10.1089/ast.2017.1703

Fan, D. D., Otsu, K., Kubo, Y., Dixit, A., Burdick, J., & Agha-Mohammadi, A. (2021). STEP: Stochastic traversability evaluation and planning for safe off-road navigation. *Robotics: Science and Systems*. Retrieved from https://arxiv.org/pdf/2103.02828

Ferrill, D. A., Wyrick, D. Y., Morris, A. P., Sims, D. W., & Franklin, N. M. (2004). Dilational fault slip and pit chain formation on Mars. *Geological Society of America Today*, *14*(10), 4–12. https://doi.org/10.1130/1052-5173(2004)014<4:dfsapc>2.0.co;2

Fletcher, L. E., Conley, C. A., Valdivia-Silva, J. E., Perez-Montaño, S., Condori-Apaza, R., Kovacs, G. T., et al. (2011). Determination of low bacterial concentrations in hyperarid Atacama soils: Comparison of biochemical and microscopy methods with real-time quantitative PCR. *Canadian Journal of Microbiology*, *57*(11), 953–963. https://doi.org/10.1139/w11-091

Freeman, A., Smrekar, S. E., Hensley, S., Wallace, M., Sotin, C., Darrach, M., et al. (2016). VERITAS: A discovery-class Venus surface geology and geophysics mission (pp. 1–11). *IEEE*.

Frumkin, A., Pe'eri, S., & Zak, I. (2021). Development of banded terrain in an active salt diapir: Potential analog to Mars. *Geomorphology*, *389*, 107824. https://doi.org/10.1016/j.geomorph.2021.107824

Fullerton, R. K. (1993). *EVA tools and equipment reference book*. JSC-20466, Rev. B, NASA-TM-109350 (p. 750). NASA Johnson Space Center. Retrieved from https://ntrs.nasa.gov/citations/19940017339

Funabiki, N., Morrell, B., Nash, J., & Agha-Mohammadi, A. (2020). Range-aided pose-graph-based SLAM: Applications of deployable ranging beacons for unknown environment exploration. *IEEE Robotics and Automation Letters*, *6*(1), 48–55. https://doi.org/10.1109/lra.2020.3026659

Gaboyer, F., Le Milbeau, C., Bohmeier, M., Schwendner, P., Vannier, P., Beblo-Vranesevic, K., et al. (2017). Mineralization and preservation of an extremotolerant bacterium isolated from an early Mars analog environment. *Scientific Reports*, *7*(1), 8775. https://doi.org/10.1038/s41598-017-08929-4

Gaier, J. R. (2007). *The effects of lunar dust on EVA systems during the Apollo missions*. NASA/TM-2005-213610 (p. 73). NASA Glenn Research Center.

Gallego, G., Bridges, J. F., Flynn, T., Blauvelt, B. M., & Niessen, L. W. (2012). Using best-worst scaling in horizon scanning for hepatocellular carcinoma technologies. *International Journal of Technology Assessment in Health Care*, *28*(3), 339–346. https://doi.org/10.1017/s026646231200027x

Garvin, J. B., Arney, G., Getty, S., Johnson, N., Kiefer, W., Lorenz, R., et al. (2020). DAVINCI+: Deep Atmosphere of Venus Investigation of Noble gases, Chemistry, and Imaging Plus. In *Paper presented at 51st Lunar and Planetary Science Conference*. LPI Contributions No. 2599.

Geissler, P. E., & McMillan, M. T. (2008). Galileo observations of volcanic plumes on Io. *Icarus*, *197*(2), 505–518. https://doi.org/10.1016/j.icarus.2008.05.005

Gellert, R., Rieder, R., Brückner, J., Clark, B. C., Dreibus, G., Klingelhöfer, G., et al. (2006). Alpha Particle X-ray Spectrometer (APXS): Results from Gusev crater and calibration report. *Journal of Geophysical Research*, *111*, E2. https://doi.org/10.1029/2005je002555

Ghezzi, D., Sauro, F., Columbu, A., Carbone, C., Hong, P. Y., Vergara, F., et al. (2021). Transition from unclassified Ktedonobacterales to Actinobacteria during amorphous silica precipitation in a quartzite cave environment. *Scientific Reports*, *11*(1), 3921. https://doi.org/10.1038/s41598-021-83416-5

Ginting, M. F., Otsu, K., Edlund, J. A., Gao, J., & Agha-Mohammadi, A. (2021). CHORD: Distributed data-sharing via hybrid ROS 1 and 2 for multi-robot exploration of large-scale complex environments. *IEEE Robotics and Automation Letters*, *6*(3), 5064–5071. https://doi.org/10.1109/lra.2021.3061393

Ginting, M. F., Touma, T., Edlund, J., & Agha-Mohammadi, A. (2020). *Deployable mesh network for enabling reliable communication from within subsurface voids to the planetary surface*. American Geophysical Union. P055-0001.

Glavin, D. P., Dworkin, J. P., Lupisella, M., Kminek, G., & Rummel, J. D. (2004). Biological contamination studies of lunar landing sites: Implications for future planetary protection and life detection on the Moon and Mars. *International Journal of Astrobiology*, *3*, 265–271. https://doi.org/10.1017/s1473550404001958

Goel, K., Tabib, W., & Michael, N. (2021). Rapid and high-fidelity subsurface exploration with multiple aerial robots. In B. Siciliano, C. Laschi, & O. Khatib (Eds.), *Experimental Robotics*. *Springer Proceedings in Advanced Robotics* (Vol. 19). Springer. https://doi.org/10.1007/978-3-030-71151-1_39

Goh, J. (2021). A literature review of medical support in cave rescue and confined space medicine–implications in urban underground space development. *IOP Conference Series: Earth and Environmental Science*, *703*(1), 012042. https://doi.org/10.1088/1755-1315/703/1/012042

Gonzalez-Pimentel, J. L., Miller, A. Z., Jurado, V., Laiz, L., Pereira, M. F., & Saiz-Jimenez, C. (2018). Yellow coloured mats from lava tubes of La Palma (Canary Islands, Spain) are dominated by metabolically active Actinobacteria. *Scientific Reports*, *8*, 1–11. https://doi.org/10.1038/s41598-018-20393-2

Goordial, J., Altshuler, I., Hindson, K., Chan-Yam, K., Marcolefas, E., & Whyte, L. G. (2017). In situ field sequencing and life detection in remote (79°26′N) Canadian high arctic permafrost ice wedge microbial communities. *Frontiers in Microbiology*, *8*, 2594. https://doi.org/10.3389/fmicb.2017.02594

Greeley, R. (1971). Lava tubes and channels in the lunar Marius Hills. *The Moon*, *3*, 289–314. https://doi.org/10.1007/bf00561842

Halliday, W. R. (1966). Terrestrial pseudokarst and the lunar topography. *National Speleological Society Bulletin*, *28*, 167–170.

Hamran, S. E., Paige, D. A., Amundsen, H. E., Berger, T., Brovoll, S., Carter, L., et al. (2020). Radar imager for Mars' subsurface experiment—RIMFAX. *Space Science Reviews*, *216*(8), 1–39. https://doi.org/10.1007/s11214-020-00740-4

Hansen, C. J., Shemansky, D. E., Esposito, L. W., Stewart, A. I. F., Lewis, B. R., Colwell, J. E., et al. (2011). The composition and structure of the Enceladus plume. *Geophysical Research Letters*, *38*(11), L11202. https://doi.org/10.1029/2011gl047415

Hansen, V. L., & Willis, J. J. (1998). Ribbon terrain formation, southwestern Fortuna Tessera, Venus: Implications for lithosphere evolution. *Icarus*, *132*(2), 321–343. https://doi.org/10.1006/icar.1998.5897

Haruyama, J., Hioki, K., Shirao, M., Morota, T., Hiesinger, H., van der Bogert, C. H., et al. (2009). Possible lunar lava tube skylight observed by SELENE cameras. *Geophysical Research Letters*, *36*(21), L21206. https://doi.org/10.1029/2009gl040635

Hassler, D. M., Zeitlin, C., Wimmer-Schweingruber, R. F., Ehresmann, B., Rafkin, S., Eigenbrode, J. L., et al. (2014). Mars' surface radiation environment measured with the Mars Science Laboratory's Curiosity rover. *Science*, *343*, 1244797. https://doi.org/10.1126/science.1244797

Hathaway, J. J. M., Garcia, M. G., Balasch, M. M., Spilde, M. N., Stone, F. D., Dapkevicius, M. D. L. N., et al. (2014). Comparison of bacterial diversity in Azorean and Hawai'ian lava cave microbial mats. *Geomicrobiology Journal*, *31*(3), 205–220. https://doi.org/10.1080/01490451.2013.777491

Hays, L. E., Graham, H. V., Des Marais, D. J., Hausrath, E. M., Horgan, B., McCollom, T. M., et al. (2017). Biosignature preservation and detection in Mars analog environments. *Astrobiology*, *17*(4), 363–400. https://doi.org/10.1089/ast.2016.1627

Hecht, M., Hoffman, J., Rapp, D., McClean, J., SooHoo, J., Schaefer, R., et al. (2021). Mars oxygen ISRU experiment (MOXIE). *Space Science Reviews*, *217*, 1–76. https://doi.org/10.1007/s11214-020-00782-8

Helbert, J., Vandaele, A. C., Marcq, E., Robert, S., Ryan, C., Guignan, G., et al. (2019). The VenSpec suite on the ESA EnVision mission to Venus. *SPIE Infrared Remote Sensing and Instrumentation XXVII* (Vol. 11128, p. 1112804). International Society for Optics and Photonics. https://doi.org/10.1117/12.2529248

Himangshu, K., & Thangavelautham, J. (2020). Long term exploration of planetary pits, caves, and lava tubes. In *International Symposium on Artificial Intelligence, Robotics and Automation in Space*. LPI Contributions No. 5062.

Hines, A., Bengston, D. N., Dockry, M. J., & Cowart, A. (2018). Setting up a horizon scanning system: A US federal agency example. *World Futures Review*, *10*(2), 136–151. https://doi.org/10.1177/1946756717749613

Hoehler, T. M., & Westall, F. (2010). Mars exploration program analysis group goal one: Determine if life ever arose on Mars. *Astrobiology*, *10*(9), 859–867. https://doi.org/10.1089/ast.2010.0527

Howarth, F. G. (1980). The zoogeography of specialized cave animals: A bioclimatic model. *Evolution*, *34*(2), 394–406. https://doi.org/10.2307/2407402

Howarth, F. G. (1982). Bioclimatic and geological factors governing the evolution and distribution of Hawaiian cave insects. *Entomologia Generalis*, *8*(1), 17–26. https://doi.org/10.1127/entom.gen/8/1982/17

Hu, S., Kim, M. H. Y., McClellan, G. E., & Cucinotta, F. A. (2009). Modeling the acute health effects of astronauts from exposure to large solar particle events. *Health Physics*, *96*(4), 465–476. https://doi.org/10.1097/01.hp.0000339020.92837.61

Huber, S. A., Hendrickson, D. B., Jones, H. L., Thornton, J. P., Whittaker, W. L., & Wong, U. Y. (2014). Astrobotic technology: Planetary pits and caves for science and exploration. *Annual Meeting of the Lunar Exploration Analysis Group* (Vol. 1820, p. 3065).

Hughes, A. C., Lechner, A. M., Chitov, A., Horstmann, A., Hinsley, A., Tritto, A., et al. (2020). Horizon scan of the belt and road initiative. *Trends in Ecology & Evolution*, *35*(7), 583–593. https://doi.org/10.1016/j.tree.2020.02.005

Humphries, R. M., & McDonnell, G. (2015). Superbugs on duodenoscopes: The challenge of cleaning and disinfection of reusable devices. *Journal of Clinical Microbiology*, *53*(10), 3118–3125. https://doi.org/10.1128/jcm.01394-15

Husain, A., Jones, H., Kannan, B., Wong, U., Pimentel, T., Tang, S., et al. (2013). Mapping planetary caves with an autonomous, heterogeneous robot team. *IEEE Aerospace Conference* (pp. 1–13). https://doi.org/10.1109/aero.2013.6497363

Jackson, W. A., Barta, D. J., Anderson, M. S., Lange, K. E., Hanford, A. J., Shull, S. A., et al. (2014). Water recovery from brines to further close the water recovery loop in human spaceflight. In *International Conference on Environmental Systems, ICES-2014–186*.

Jones, A. A., & Bennett, P. C. (2017). Mineral ecology: Surface specific colonization and geochemical drivers of biofilm accumulation, composition, and phylogeny. *Frontiers in Microbiology*, *8*, 491. https://doi.org/10.3389/fmicb.2017.00491

Jones, B. (2001). Microbial activity in caves−A geological perspective. *Geomicrobiology Journal*, *18*(3), 345–357. https://doi.org/10.1080/01490450152467831

Jozwiak, L. M., Head, J. W., & Wilson, L. (2018). Explosive volcanism on Mercury: Analysis of vent and deposit morphology and modes of eruption. *Icarus*, *302*, 191–212. https://doi.org/10.1016/j.icarus.2017.11.011

Kaku, T., Haruyama, J., Miyake, W., Kumamoto, A., Ishiyama, K., Nishibori, T., et al. (2017). Detection of intact lava tubes at Marius Hills on the Moon by SELENE (Kaguya) Lunar Radar Sounder. *Geophysical Research Letters*, *44*(20), 10155–10161. https://doi.org/10.1002/2017gl074998

Kalita, H., Nallapu, R. T., Warren, A., & Thangavelautham, J. (2017). Guidance, navigation and control of multirobot systems in cooperative cliff climbing. *Advances in the Astronautical Sciences Guidance, Navigation and Control*, *159*, 1–14.

Kearney, M. L., Wynne, J. J., Cushing, G. E., Bardabelias, N. M., & Barlow, N. G. (2021). Robotic exploration potential of Martian caves. In *Paper presented at 52nd Lunar and Planetary Science Conference*. LPI Contributions No. 2078.

Kemp, L., Adam, L., Boehm, C. R., Breitling, R., Casagrande, R., Dando, M., et al. (2020). Point of view: Bioengineering horizon scan 2020. *Elife*, *9*, e54489. https://doi.org/10.7554/elife.54489

Kempe, S. (2012). Volcanic rock caves. In W. B. White & D. C. Culver (Eds.), *Encyclopedia of Caves* (2nd ed., pp. 865–873). Elsevier.

Kerber, L., Denevi, B. W., Nesnas, I., Keszthelyi, L., Head, J. W., Pieters, C., et al. (2019). Moon diver: A discovery mission concept for understanding secondary crust formation through the exploration of a lunar mare pit cross-section. In *Lunar and Planetary Science Conference, Abstract #1163, LPI Contribution No. 2132*. Retrieved from https://www.hou.usra.edu/meetings/lpsc2019/pdf/1163.pdf

Kerner, H. R., Hardgrove, C. J., Czarnecki, S., Gabriel, T. S., Mitrofanov, I. G., Litvak, M. L., et al. (2020). Analysis of active neutron measurements from the Mars Science Laboratory Dynamic Albedo of Neutrons Instrument: Intrinsic variability, outliers, and implications for future investigations. *Journal of Geophysical Research: Planets*, *125*(5), e2019JE006264. https://doi.org/10.1029/2019je006264

Kim, S. K., Bouman, A., Salhotra, G., Fan, D. D., Otsu, K., Burdick, J., et al. (2021). PLGRIM: Hierarchical value learning for large-scale exploration in unknown environments. *Proceedings of the International Conference on Automated Planning and Scheduling* (Vol. 31). Retrieved from https://arxiv.org/pdf/2102.05633.pdf

Klein, F., Grozeva, N. G., & Seewald, J. S. (2019). Abiotic methane synthesis and serpentinization in olivine-hosted fluid inclusions. *Proceedings of the National Academy of Sciences*, *116*(36), 17666–17672. https://doi.org/10.1073/pnas.1907871116

Klimchouk, A. (2009). Morphogenesis of hypogenic caves. *Geomorphology*, *106*(1–2), 100–117. https://doi.org/10.1016/j.geomorph.2008.09.013

Klimchouk, A. (2012). Speleogenesis, hypogenic. In W. B. White & D. C. Culver (Eds.), *Encyclopedia of caves* (2nd ed., pp. 748–765). Academic Press.

Könnölä, T., Salo, A., Cagnin, C., Carabias, V., & Vilkkumaa, E. (2012). Facing the future: Scanning, synthesizing and sense-making in horizon scanning. *Science and Public Policy*, *39*(2), 222–231. https://doi.org/10.1093/scipol/scs021

Kreuz, F., Juraschek, M., Bucherer, M., Söfker-Rieniets, A., Spengler, A., Clausen, U., et al. (2020). Urban factories—Interdisciplinary perspectives on resource efficiency. In R. Elbert, C. Friedrich, M. Boltze, & H. C. Pfohl (Eds.), *Urban freight transportation systems* (pp. 41–52). Elsevier.

Krishnan, S. (2021). A polyhedral approach for design of inflatable lunar habitats. In *Paper presented at 17th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments* (pp. 1004–1011).

Lauro, S. E., Pettinelli, E., Caprarelli, G., Guallini, L., Rossi, A. P., Mattei, E., et al. (2021). Multiple subglacial water bodies below the south pole of Mars unveiled by new MARSIS data. *Nature Astronomy*, *5*(1), 63–70. https://doi.org/10.1038/s41550-020-1200-6

Léveillé, R. J., & Datta, S. (2010). Lava tubes and basaltic caves as astrobiological targets on Earth and Mars: A review. *Planetary and Space Science*, *58*(4), 592–598. https://doi.org/10.1016/j.pss.2009.06.004

Linne, D. L., Sanders, G. B., Starr, S. O., Eisenman, D. J., Suzuki, N. H., Anderson, M. S., et al. (2017). Overview of NASA technology development for in-situ resource utilization (ISRU). In*Paper presented at 68th International Astronautical Congress, Adelaide, Australia, 25–29 September 2017*. IAC-17-D3.3.1. Retrieved from https://ntrs.nasa.gov/api/citations/20180000407/downloads/20180000407.pdf

Litteken, D. A. (2019). Inflatable technology: Using flexible materials to make large structures *Electroactive polymer actuators and devices (EAPAD) XXI* (Vol. 10966, p. 1096603). SPIE.

Lowe, C. M., Sarnell, J. A., Stuehrmann, L. G., Schwartzman, M. C., & Robbins, T. J. (2018). *A Heterogeneous swarm solution for disaster reconnaissance: A feasibility study*. Worcester Polytechnic Institute. Retrieved from https://core.ac.uk/download/pdf/212986929.pdf

Lyu, Z., Shao, N., Akinyemi, T., & Whitman, W. B. (2018). Methanogenesis. *Current Biology*, *28*(13), R727–R732. https://doi.org/10.1016/j.cub.2018.05.021

Magnabosco, C., Lin, L. H., Dong, H., Bomberg, M., Ghiorse, W., Stan-Lotter, H., et al. (2018). The biomass and biodiversity of the continental subsurface. *Nature Geoscience*, *11*(10), 707–717. https://doi.org/10.1038/s41561-018-0221-6

Mahaffy, P. R., Webster, C. R., Cabane, M., Conrad, P. G., Coll, P., Atreya, S. K., et al. (2012). The sample analysis at Mars investigation and instrument suite. *Space Science Reviews*, *170*, 401–478. https://doi.org/10.1007/s11214-012-9879-z

Malaska, M., Radebaugh, J., Mitchell, K., Lopes, R., Wall, S., & Lorenz, R. (2011). Surface dissolution model for Titan karst. In *Paper presented at 1st International Planetary Cave Workshop*. LPI Contributions No. 8018.

Malaska, M. J., & Hodyss, R. (2014). Dissolution of benzene, naphthalene, and biphenyl in a simulated Titan lake. *Icarus*, *242*, 74–81. https://doi.org/10.1016/j.icarus.2014.07.022

Malaska, M. J., & Mitchell, K. (2017). Predicting cave formations in Saturn's moon Titan. *GSA Annual Meeting*. Retrieved from https://trs.jpl.nasa.gov/bitstream/handle/2014/48703/CL%2317-5343.pdf?sequence=1

Malaska, M. J., Radebaugh, J., Lopes, R. M., Mitchell, K. L., Verlander, T., Schoenfeld, A. M., et al. (2020). Labyrinth terrain on Titan. *Icarus*, *344*, 113764. https://doi.org/10.1016/j.icarus.2020.113764

Mammola, S., Amorim, I. R., Bichuette, M. E., Borges, P. A. V., Cheeptham, N., Cooper, S. J. B., et al. (2020). Fundamental research questions in subterranean biology. *Biological Reviews*, *95*(6), 1855–1872. https://doi.org/10.1111/brv.12642

Mansor, M., Harouaka, K., Gonzales, M. S., Macalady, J. L., & Fantle, M. S. (2018). Transport-induced spatial patterns of sulfur isotopes (δ^{34}S) as biosignatures. *Astrobiology*, *18*(1), 59–72. https://doi.org/10.1089/ast.2017.1650

Manyapu, K. K., & Peltz, L. (2018). *Mitigation system utilizing conductive fibers*. U.S. Patent No. 10,016,766. U.S. Patent and Trademark Office. Dust.

Margiotta, D. V., Peters, W. C., Straka, S. A., Rodríguez, M., McKittrick, K. R., & Jones, C. B. (2010). The Lotus coating for space exploration: A dust mitigation tool. In *Optical System Contamination: Effects, Measurements, and Control* (Vol. 7794, p. 77940I). International Society for Optics and Photonics.https://doi.org/10.1117/12.864480

Maynard-Casely, H., Cable, M., Vu, T., Malaska, M., Choukroun, M., & Hodyss, R. (2018). Prospects for mineralogy on Titan. *American Mineralogist*, *103*(3), 343–349. https://doi.org/10.2138/am-2018-6259

McKay, C. P. (2009). Planetary ecosynthesis on Mars: Restoration ecology and environmental ethics. In C. M. Bertka (Ed.), *Exploring the origin, extent, and future of life: Philosophical, ethical, and theological perspectives* (Vol. 4, pp. 245–260). Cambridge University Press.

McMillon-Brown, L., Peshek, T. J., Pal, A., & McNatt, J. (2019). Dust abrasion damage on Martian solar arrays: Experimental investigation and opportunity rover performance analysis. In *IEEE 46th Photovoltaic Specialists Conference* (pp. 2838–2844). IEEE.

Miller, A. Z., García-Sánchez, A. M., Coutinho, M. L., Costa Pereira, M. F., Gázquez, F., Calaforra, J. M., et al. (2020). Colored microbial coatings in show caves from the Galapagos Islands (Ecuador): First microbiological approach. *Coatings*, *10*(11), 1134. https://doi.org/10.3390/coatings10111134

Miller, A. Z., Garcia-Sanchez, A. M., Martin-Sanchez, P. M., Costa Pereira, M. F., Spangenberg, J. E., Jurado, V., et al. (2018). Origin of abundant moonmilk deposits in a subsurface granitic environment. *Sedimentology*, *65*(5), 1482–1503. https://doi.org/10.1111/sed.12431

Miller, A. Z., José, M., Jiménez-Morillo, N. T., Pereira, M. F., González-Pérez, J. A., Calaforra, J. M., & Saiz-Jimenez, C. (2016). Analytical pyrolysis and stable isotope analyses reveal past environmental changes in coralloid speleothems from Easter Island (Chile). *Journal of Chromatography A*, *1461*, 144–152. https://doi.org/10.1016/j.chroma.2016.07.038

Miller, A. Z., Pereira, M. F., Calaforra, J. M., Forti, P., Dionísio, A., & Saiz-Jimenez, C. (2014). Siliceous speleothems and associated microbe-mineral interactions from Ana Heva Lava Tube in Easter Island (Chile). *Geomicrobiology Journal*, *31*(3), 236–245. https://doi.org/10.1080/01490451.2013.827762

Miot, J., Benzerara, K., & Kappler, A. (2014). Investigating microbe-mineral interactions: Recent advances in X-ray and electron microscopy and redox-sensitive methods. *Annual Review of Earth and Planetary Sciences*, *42*(1), 271–289. https://doi.org/10.1146/annurev-earth-050212-124110

Moirano, R., Sánchez, M. A., & Štěpánek, L. (2020). Creative interdisciplinary collaboration: A systematic literature review. *Thinking Skills and Creativity*, *35*, 100626. https://doi.org/10.1016/j.tsc.2019.100626

Morthekai, P., Jain, M., Dartnell, L., Murray, A. S., Bøtter-Jensen, L., & Desorgher, L. (2007). Modelling of the dose-rate variations with depth in the Martian regolith using GEANT4. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *580*(1), 667–670. https://doi.org/10.1016/j.nima.2007.05.118

Muscarella, L. F. (2014). Risk of transmission of carbapenem-resistant Enterobacteriaceae and related "superbugs" during gastrointestinal endoscopy. *World Journal of Gastrointestinal Endoscopy*, *6*(10), 457–474. https://doi.org/10.4253/wjge.v6.i10.457

Mylroie, J. E. (2019). Caves in space. *Journal of Cave and Karst Studies*, *81*(1), 25–32. https://doi.org/10.4311/2018es0102

Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R^2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution*, *4*(2), 133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x

NASA. (2021). *Planetary protection*. NASA. Retrieved from https://sma.nasa.gov/sma-disciplines/planetary-protection/#planetaryProtection_conferenceDocuments

Naser, M. Z., & Chen, Q. (2021). Extraterrestrial construction in lunar and Martian environments. In *Paper presented at 17th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments* (pp. 1200–1207).

National Academies of Sciences, Engineering, and Medicine [NASEM]. (2015). *Review of the MEPAG report on Mars special regions*. The National Academies Press. https://doi.org/10.17226/21816

National Academies of Sciences, Engineering, and Medicine [NASEM]. (2022). *Origins, worlds, and life: A decadal strategy for planetary science and astrobiology 2023–2032*. The National Academies Press. https://doi.org/10.17226/26522

Nesnas, I. A., Kerber, L., Parness, A., Kornfeld, R., Sellar, G., McGarey, P., et al. (2019). Moon diver: A discovery mission concept for understanding the history of secondary crusts through the exploration of a lunar mare pit. In *IEEE Aerospace Conference* (pp. 1–23). IEEE. https://doi.org/10.1109/aero.2019.8741788

Nesnas, I. A., Matthews, J. B., Abad-Manterola, P., Burdick, J. W., Edlund, J. A., Morrison, J. C., et al. (2012). Axel and DuAxel rovers for the sustainable exploration of extreme terrains. *Journal of Field Robotics*, *29*(4), 663–685. https://doi.org/10.1002/rob.21407

Neveu, M., Hays, L. E., Voytek, M. A., New, M. H., & Schulte, M. D. (2018). The ladder of life detection. *Astrobiology*, *18*(11), 1375–1402. https://doi.org/10.1089/ast.2017.1773

Nicholson, W. L., Schuerger, A. C., & Race, M. S. (2009). Migrating microbes and planetary protection. *Trends in Microbiology*, *17*(9), 389–392. https://doi.org/10.1016/j.tim.2009.07.001

Northup, D. E., Melim, L. A., Spilde, M. N., Hathaway, J. J. M., Garcia, M. G., Moya, M., et al. (2011). Lava cave microbial communities within mats and secondary mineral deposits: Implications for life detection on other planets. *Astrobiology*, *11*(7), 601–618. https://doi.org/10.1089/ast.2010.0562

Oberbeck, V. R., Quaide, W. L., & Greeley, R. (1969). On the origin of lunar sinuous rilles. *Modern Geology*, *1*, 75–80.

Onstott, T. C., Ehlmann, B. L., Sapers, H., Coleman, M., Ivarsson, M., Marlow, J. J., et al. (2018). Paleo-rock-hosted life on Earth and the search on Mars: A review and strategy for exploration. *Astrobiology*, *19*(10), 1230–1262. https://doi.org/10.1089/ast.2018.1960

Otsu, K., Tepsuporn, S., Thakker, R., Vaquero, T. S., Edlund, J. A., Walsh, W., et al. (2020). Supervised autonomy for communication-degraded subterranean exploration by a robot team. In *2020 IEEE Aerospace Conference* (pp. 1–9).

Palmer, A. N. (2007). *Cave geology*. Cave Books.

Palomba, E., Zinzi, A., Cloutis, E. A., d'Amore, M., Grassi, D., & Maturilli, A. (2009). Evidence for Mg-rich carbonates on Mars from a 3.9 μm absorption feature. *Icarus*, *203*(1), 58–65. https://doi.org/10.1016/j.icarus.2009.04.013

Parness, A., Abcouwer, N., Fuller, C., Wiltsie, N., Nash, J., & Kennedy, B. (2017). Lemur 3: A limbed climbing robot for extreme terrain mobility in space. In *IEEE International Conference on Robotics and Automation (ICRA)* (pp. 5467–5473).

Patiño, J., Whittaker, R. J., Borges, P. A., Fernández-Palacios, J. M., Ah-Peng, C., Araújo, M. B., et al. (2017). A roadmap for island biology: 50 fundamental questions after 50 years of The Theory of Island Biogeography. *Journal of Biogeography*, *44*(5), 963–983. https://doi.org/10.1111/jbi.12986

Perkins, S. (2020). Core concept: Lava tubes may be havens for ancient alien life and future human explorers. *Proceedings of the National Academy of Sciences*, *117*(30), 17461–17464. https://doi.org/10.1073/pnas.2012176117

Perșoiu, A., & Onac, B. P. (2019). Ice in caves. In W. B. White, D. C. Culver, & T. Pipan (Eds.), *Encyclopedia of caves* (3rd ed., pp. 553–558). Academic Press.

Pflitsch, A., & Piasecki, J. (2003). Detection of an airflow system in Niedzwiedzia (Bear) Cave, Kletno, Poland. *Journal of Cave and Karst Studies*, *63*, 160–173.

Pfohl, H.-C., Berbner, U., & Zuber, C. (2017). Interdisciplinary decisions in production, logistics, and traffic and transport: Measures for overcoming barriers in interdisciplinary decision-making. In E. Abele, M. Boltze, & H.-C. Pfohl (Eds.), *Dynamic and seamless integration of production, logistics and traffic* (pp. 13–30). Springer International Publishing.

Phillips-Lander, C. M., Agha-Mohamadi, A., Wynne, J. J., Titus, T. N., Chanover, N., Demirel-Floyd, C., et al. (2020). Mars Astrobiological Cave and Internal habitability Explorer (MACIE): A new frontiers mission concept. *Bulletin of the American Astronomical Society*, *53*, 4.

Pisani, L., & De Waele, J. (2021). Candidate cave entrances in a planetary analogue evaporite karst (Cordillera de la Sal, Chile): A remote sensing approach and ground-truth reconnaissance. *Geomorphology*, *389*, 107851. https://doi.org/10.1016/j.geomorph.2021.107851

Plavén-Sigray, P., Matheson, G. J., Schiffler, B. C., & Thompson, W. H. (2017). The readability of scientific texts is decreasing over time. *Elife*, *6*, e27725. https://doi.org/10.7554/elife.27725

Porco, C., DiNino, D., & Nimmo, F. (2014). How the geysers, tidal stresses, and thermal emission across the south polar terrain of Enceladus are related. *The Astronomical Journal*, *148*(3), 45. https://doi.org/10.1088/0004-6256/148/3/45

Prettyman, T. H., Englert, P. A. J., Yamashita, N., & Landis, M. E. (2019). Neutron, gamma-ray, and X-ray spectroscopy of planetary bodies. In J. L. Bishop, J. F. Bell, & J. E. Moersch (Eds.), *Remote Compositional Analysis* (pp. 588–603). Cambridge University Press.

Prettyman, T. H., Titus, T. N., Cushing, G. E., Okubo, C. H., Sankey, J. B., Williams, K. E., et al. (2020). Muon overburden gauge for planetary analog studies of cave ice stability. In *Paper presented at 3rd International Planetary Caves Conference*. LPI Contributions No. 2197.

Radotich, M., Withrow-Maser, S., deSouza, Z., Gelhar, S., & Gallagher, H. (2021). *A study of past, present, and future Mars rotorcraft* (p. 17). NASA Ames Research Center. Retrieved from https://rotorcraft.arc.nasa.gov/Publications/files/Radotich_aVTOL_Tech_Meeting_Final_Revised_012521.pdf

Raulin, F. (1987). Organic chemistry in the oceans of Titan. *Advances in Spaces Research*, *7*(5), 71–81. https://doi.org/10.1016/0273-1177(87)90358-9

Rempfert, K. R., Miller, H. M., Bompard, N., Nothaft, D., Matter, J. M., Kelemen, P., et al. (2017). Geological and geochemical controls on subsurface microbial life in the Samail Ophiolite, Oman. *Frontiers in Microbiology*, *8*, 56. https://doi.org/10.3389/fmicb.2017.00056

Richardson, C. D., Hinman, N. W., & Scott, J. R. (2013). Evidence for biological activity in mineralization of secondary sulphate deposits in a basaltic environment: Implications for the search for life in the Martian subsurface. *International Journal of Astrobiology*, *12*(4), 357–368. https://doi.org/10.1017/s1473550413000256

Riquelme, C., Marshall Hathaway, J. J., Enes Dapkevicius, M. D. L., Miller, A. Z., Kooser, A., Northup, D. E., et al. (2015). Actinobacterial diversity in volcanic caves and associated geomicrobiological interactions. *Frontiers in Microbiology*, *6*, 1342. https://doi.org/10.3389/fmicb.2015.01342

Röling, W. F., Aerts, J. W., Patty, C. H., Ten Kate, I. L., Ehrenfreund, P., & Direito, S. O. (2015). The significance of microbe-mineral-biomarker interactions in the detection of life on Mars and beyond. *Astrobiology*, *15*(6), 492–507. https://doi.org/10.1089/ast.2014.1276

Rossi, A. P., Maurelli, F., Unnithan, V., Dreger, H., Mathewos, K., Pradhan, N., et al. (2021). *DAEDALUS-Descent And Exploration in Deep Autonomy of Lava Underground Structures: Open Space Innovation Platform (OSIP) lunar caves-system study. Würzburger Forschungsberichte in Robotik und Telematik*. University of Würzburger. Retrieved from https://opus.bibliothek.uni-wuerzburg.de/opus4-wuerzburg/frontdoor/deliver/index/docId/22791/file/Rossi_et_al_DAEDALUS.pdf

Roth, L., Saur, J., Retherford, K. D., Strobel, D. F., Feldman, P. D., McGrath, M. A., & Nimmo, F. (2014). Transient water vapor at Europa's south pole. *Science*, *343*(6167), 171–174. https://doi.org/10.1126/science.1247051

Rouillard, J., van Zuilen, M., Pisapia, C., & Garcia-Ruiz, J. M. (2021). An alternative approach for assessing biogenicity. *Astrobiology*, *21*(2), 151–164. https://doi.org/10.1089/ast.2020.2282

Rull, F., Maurice, S., Hutchinson, I., Moral, A., Perez, C., Diaz, C., et al. (2017). The Raman laser spectrometer for the ExoMars rover mission to Mars. *Astrobiology*, *17*(6–7), 627–654. https://doi.org/10.1089/ast.2016.1567

Rummel, J. D., Beaty, D. W., Jones, M. A., Bakermans, C., Barlow, N. G., Boston, P. J., et al. (2014). A new analysis of Mars "special regions": Findings of the second MEPAG special regions science analysis group (SR-SAG2). *Astrobiology*, *11*, 888–868. https://doi.org/10.1089/ast.2014.1227

Santamaria-Navarro, A., Thakker, R., Fan, D. D., Morrell, B., & Agha-Mohammadi, A. (2019). Towards resilient autonomous navigation of drones. In *International Symposium on Robotics Research* (pp. 922–937). Springer.

Sauder, J., Hilgemann, E., Johnson, M., Parness, A., Hall, J., Kawata, J., et al. (2017). *Automation rover for extreme environments*. NASA Innovative Advanced Concepts (NIAC) Phase I, Final Report. NASA Jet Propulsion Laboratory, California Institute of Technology. Retrieved from https://www.nasa.gov/sites/default/files/atoms/files/niac_2016_phasei_saunder_aree_tagged.pdf

Sauro, F., De Waele, J., Onac, B. P., Galli, E., Dublyansky, Y., Baldoni, E., & Sanna, L. (2014). Hypogenic speleogenesis in quartzite: The case of Corona 'e Sa Craba Cave (SW Sardinia, Italy). *Geomorphology*, *211*, 77–88. https://doi.org/10.1016/j.geomorph.2013.12.031

Sauro, F., De Waele, J., Payler, S. J., Vattano, M., Sauro, F. M., Turchi, L., & Bessone, L. (2021). Speleology as an analogue to space exploration: The ESA CAVES training programme. *Acta Astronautica*, *184*, 150–166. https://doi.org/10.1016/j.actaastro.2021.04.003

Sauro, F., Pozzobon, R., Massironi, M., De Berardinis, P., Santagata, T., & De Waele, J. (2020). Lava tubes on Earth, Moon and Mars: A review on their size and morphology revealed by comparative planetology. *Earth-Science Reviews*, *209*, 103288. https://doi.org/10.1016/j.earscirev.2020.103288

Schörghofer, N. (2021). Ice caves on Mars: Hoarfrost and microclimates. *Icarus*, *357*, 114271. https://doi.org/10.1016/j.icarus.2020.114271

Schörghofer, N., Businger, S., & Leopold, M. (2018). The coldest places in Hawaii: The ice-preserving microclimates of high-altitude craters and caves on tropical island volcanoes. *Bulletin of the American Meteorological Society*, *99*(11), 2313–2324. https://doi.org/10.1175/bams-d-17-0238.1

Schulze-Makuch, D., & Irwin, L. N. (2018). *Life in the universe: Expectations and constraints* (3rd ed.). Springer.

Šebela, S., & Turk, J. (2011). Local characteristics of Postojna Cave climate, air temperature, and pressure monitoring. *Theoretical and Applied Climatology*, *105*(3–4), 371–386. https://doi.org/10.1007/s00704-011-0397-9

Selensky, M. J., Masterson, A. L., Blank, J. G., Lee, S. C., & Osburn, M. R. (2021). Stable carbon isotope depletions in lipid biomarkers suggest subsurface carbon fixation in lava caves. *Journal of Geophysical Research: Biogeosciences*, *126*(7), e2021JG006430. https://doi.org/10.1029/2021jg006430

Selim, E. I., Basheer, A. A., Elqady, G., & Hafez, M. A. (2014). Shallow seismic refraction, two-dimensional electrical resistivity imaging, and ground penetrating radar for imaging the ancient monuments at the western shore of Old Luxor city, Egypt. *Archaeological Discovery*, *2*(02), 31–43. https://doi.org/10.4236/ad.2014.22005

Shao, Q., & Wang, Y. G. (2009). Statistical power calculation and sample size determination for environmental studies with data below detection limits. *Water Resources Research*, *45*, 9. https://doi.org/10.1029/2008wr007563

Siefert, J. L., Souza, V., Eguiarte, L., & Olmedo-Alvarez, G. (2012). Microbial stowaways: Inimitable survivors or hopeless pioneers? *Astrobiology*, *12*(7), 710–715. https://doi.org/10.1089/ast.2012.0833

Simberloff, D., & Rejmánek, M. (2011). *Encyclopedia of biological invasions* (Vol. 3). University of California Press.

Stamenković, V., Beegle, L. W., Zacny, K., Arumugam, D. D., Baglioni, P., Barba, N., et al. (2019). The next frontier for planetary and human exploration. *Nature Astronomy*, *3*(2), 116–120. https://doi.org/10.1038/s41550-018-0676-9

Starr, S. O., & Muscatello, A. C. (2020). Mars in situ resource utilization: A review. *Planetary and Space Science*, *182*, 104824. https://doi.org/10.1016/j.pss.2019.104824

Summons, R. E., Amend, J. P., Bish, D., Buick, R., Cody, G. D., Des Marais, D. J., et al. (2011). Preservation of Martian organic and environmental records: Final report of the Mars biosignature working group. *Astrobiology*, *11*(2), 157–181. https://doi.org/10.1089/ast.2010.0506

Sutherland, W. J., Atkinson, P. W., Butchart, S. H., Capaja, M., Dicks, L. V., Fleishman, E., et al. (2021). A horizon scan of global biological conservation issues for 2022. *Trends in Ecology & Evolution*, *37*(1), 95–104. https://doi.org/10.1016/j.tree.2021.10.014

Sutherland, W. J., Bardsley, S., Bennun, L., Clout, M., Côté, I. M., Depledge, M. H., et al. (2011). A horizon scan of global conservation issues for 2011. *Trends in Ecology & Evolution*, *26*(1), 10–16. https://doi.org/10.1016/j.tree.2010.11.002

Sutherland, W. J., Fleishman, E., Mascia, M. B., Pretty, J., & Rudd, M. A. (2011). Methods for collaboratively identifying research priorities and emerging issues in science and policy. *Methods in Ecology and Evolution*, *2*(3), 238–247. https://doi.org/10.1111/j.2041-210x.2010.00083.x

Sutherland, W. J., Freckleton, R. P., Godfray, H. C. J., Beissinger, S. R., Benton, T., Cameron, D. D., et al. (2013). Identification of 100 fundamental ecological questions. *Journal of Ecology*, *101*(1), 58–67. https://doi.org/10.1111/1365-2745.12025

Thakker, R., Alatur, N., Fan, D., Tordesillas, J., Paton, M., Otsu, K., et al. (2021). Autonomous off-road navigation over extreme terrains with perceptually-challenging conditions. In *Experimental Robotics: 17th International Symposium* (pp. 161–171).

Titus, T. N., Phillips-Lander, C. M., Boston, P. J., Wynne, J. J., & Kerber, L. (2020). Planetary cave exploration progresses. *Eos Transactions American Geophysical Union*, *101*. https://doi.org/10.1029/2020eo152045

Titus, T. N., Wynne, J. J., Boston, P. J., de Leon, P., Demirel-Floyd, C., Jones, H., et al. (2020). Science and technology requirements to explore caves in our Solar System. *Bulletin of the American Astronomical Society*, *53*(4), 167. https://doi.org/10.3847/25c2cfeb.a68ba8cb

Titus, T. N., Wynne, J. J., Malaska, M. J., Agha-Mohammadi, A., Buhler, P. B., Alexander, E. C., et al. (2021). A roadmap for planetary cave science and exploration. *Nature Astronomy*, *5*(6), 524–525. https://doi.org/10.1038/s41550-021-01385-1

Titus, T. N., Wynne, J. J., Ruby, D., & Cabrol, N. A. (2010). The Atacama Desert cave Shredder: A case for conduction thermodynamics. In *41st Lunar and Planetary Science Conference*, LPI Contributions No. 1096.

Tornos, F., Velasco, F., Menor-Salván, C., Delgado, A., Slack, J. F., & Escobar, J. M. (2014). Formation of recent Pb-Ag-Au mineralization by potential sub-surface microbial activity. *Nature Communications*, *5*(1), 4600. https://doi.org/10.1038/ncomms5600

Torrese, P., Pozzobon, R., Rossi, A. P., Unnithan, V., Sauro, F., Borrmann, D., et al. (2021). Detection, imaging and analysis of lava tubes for planetary analogue studies using electric methods (ERT). *Icarus*, *357*, 114244. https://doi.org/10.1016/j.icarus.2020.114244

Townsend, L. W., & Fry, R. J. M. (2002). Radiation protection guidance for activities in low-Earth orbit. *Advances in Space Research*, *30*(4), 957–963. https://doi.org/10.1016/s0273-1177(02)00160-6

Trainer, M. G., Brinckerhoff, W. B., Freissinet, C., Lawrence, D. J., Peplowski, P. N., Parsons, A. M., et al. (2018). Dragonfly: Investigating the surface composition of Titan. In *Paper presented at 49th Lunar and Planetary Science Conference*. LPI Contributions No. 2586.

Tuttle, M. D., & Stevenson, D. E. (1978). Variation in the cave environment and its biological implications. In R. Zuber, J. Chester, S. Gilbert, & D. Rhodes (Eds.), *1977 National Cave Management Symposium Proceedings* (pp. 108–121). Adobe Press.

Uckert, K., Parness, A., Chanover, N., Eshelman, E. J., Abcouwer, N., Nash, J., et al. (2020). Investigating habitability with an integrated rock-climbing robot and astrobiology instrument suite. *Astrobiology*, *20*(12), 1427–1449. https://doi.org/10.1089/ast.2019.2177

Ulloa, A., Campos-Fernández, C. S., & Rojas, L. (2013). Minerals Cave, Irazú volcano, Costa Rica: Description, mineralogy and origin. *Revista Geologica de America Central*, *48*, 169–187.

Vaniman, D. T., Bish, D. L., Chipera, S. J., Fialips, C. I., Carey, J. W., & Feldman, W. C. (2004). Magnesium sulphate salts and the history of water on Mars. *Nature*, *431*(7009), 663–665. https://doi.org/10.1038/nature02973

Vaquero, T., Saboia da Silva, M., Otsu, K., Kaufmann, M., Edlund, J., & Agha-Mohammadi, A. (2020). Traversability-aware signal coverage planning for communication node deployment in planetary cave exploration. In *International Symposium on Artificial Intelligence, Robotics and Automation in Space*. LPI Contributions No. 5023.

von Ehrenfried, M. (2019). *From Cave Man to Cave Martian: Living in Caves on the Earth, Moon and Mars*. Springer.

Voordouw, G. (2002). Carbon monoxide cycling by *Desulfovibrio vulgaris* Hildenborough. *Journal of Bacteriology*, *184*(21), 5903–5911. https://doi.org/10.1128/jb.184.21.5903-5911.2002

Wagner, R. V., & Robinson, M. S. (2014). Distribution, formation mechanisms, and significance of lunar pits. *Icarus*, *237*, 52–60. https://doi.org/10.1016/j.icarus.2014.04.002

Wagner, R. V., & Robinson, M. S. (2015). Update: The search for lunar pits. In *Paper presented at 2nd International Planetary Caves Conference*. LPI Contributions 9021.

Wagner, R. V., & Robinson, M. S. (2021). Occurrence and origin of lunar pits: Observations from a new catalog. In *Paper presented at 52nd Lunar and Planetary Science Conference*. LPI Contributions No. 2530.

Wagner, S. A. (2006). *The Apollo experience lessons learned for constellation lunar dust management*. TP-2006-213726 (p. 73). NASA Johnson Space Center.

Walsh, S. M., Strano, M. S., & Stanton, S. C. (2019). Approaching robotics and autonomous systems as an integrated materials, energy, and control problem. In S. M. Walsh & M. S. Strano (Eds.), *Robotic systems and autonomous platforms: Advances in materials and manufacturing* (pp. 19–46). Elsevier.

Wang, J., & Wan, W. (2009). Factors influencing fermentative hydrogen production: A review. *International Journal of Hydrogen Energy*, *34*(2), 799–811. https://doi.org/10.1016/j.ijhydene.2008.11.015

Webster, K. D. (2019). Developing cave air as a biosignature. *Mars extant life: What's next? Conference*. LPI Contributions No. 5048.

Webster, K. D., Drobniak, A., Sauer, P. E., Mastalerz, M., & Schimmelmann, A. (2015). Cave air as a biosignature. In *Paper presented at 2nd International Planetary Caves Conference*. LPI Contributions No. 9009.

Westall, F., Foucher, F., Bost, N., Bertrand, M., Loizeau, D., Vago, J. L., et al. (2015). Biosignatures on Mars: What, where, and how? Implications for the search for Martian life. *Astrobiology*, *15*(11), 998–1029. https://doi.org/10.1089/ast.2015.1374

Westall, F., Loizeau, D., Foucher, F., Bost, N., Betrand, M., Vago, J., & Kminek, G. (2013). Habitability on Mars from a microbial point of view. *Astrobiology*, *13*(9), 887–897. https://doi.org/10.1089/ast.2013.1000

Whittaker, W. L., Jones, H. L., Ford, J. S., Sharif, K., & Wong, U. Y. (2021). Skylight: A mission concept for in-situ investigation of the morphology, geology and mineralogy of lunar pits. In *Lunar and Planetary Science Conference*. LPI Contributions No. 2644.

Whittaker, W. L., Jones, H. L., Wong, U. Y., Ford, J. S., Whittaker, W. C., Khera, N., et al. (2020). Micro-rover exploration of lunar pits deployable by commercial lander. In *Paper presented at 3rd International Planetary Caves Conference*. LPI Contributions No. 1074.

Wiens, R. C., Maurice, S., Robinson, S. H., Nelson, A. E., Cais, P., Bernardi, P., et al. (2021). The SuperCam instrument suite on the NASA Mars 2020 rover: Body unit and combined system tests. *Space Science Reviews*, *217*, 1–87.

Wierzchos, J., Sancho, L. G., & Ascaso, C. (2005). Biomineralization of endolithic microbes in rocks from the McMurdo Dry Valleys of Antarctica: Implications for microbial fossil formation and their detection. *Environmental Microbiology*, *7*(4), 566–575. https://doi.org/10.1111/j.1462-2920.2005.00725.x

Williams, K. E., & McKay, C. (2015). Comparing flow-through and static ice cave models for Shoshone Ice Cave. *International Journal of Speleology*, *44*(2), 115–123. https://doi.org/10.5038/1827-806x.44.2.2

Williams, K. E., McKay, C. P., Toon, O., & Head, J. W. (2010). Do ice caves exist on Mars? *Icarus*, *209*(2), 358–368. https://doi.org/10.1016/j.icarus.2010.03.039

Williams, K. E., Titus, T. N., Okubo, C. H., & Cushing, G. E. (2017). Martian cave air-movement via Helmholtz resonance. *International Journal of Speleology*, *46*(3), 439–444. https://doi.org/10.5038/1827-806x.46.3.2130

Wintle, B. C., Kennicutt, M. C., II, & Sutherland, W. J. (2020). Scanning horizons in research, policy and practice. In W. J. Sutherland, P. N. M. Brotherton, Z. G. Davies, N. Ockenden, N. Pettorelli, & J. A. Vickery (Eds.), *Making a difference in conservation: Linking science and policy* (pp. 30–47). Cambridge University Press.

Wong, U., Morris, A., Lea, C., Lee, J., Whittaker, C., Garney, B., & Whittaker, R. (2011). Comparative evaluation of range sensing technologies for underground void modeling. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 3816–3823. https://doi.org/10.1109/iros.2011.6094938

Wray, R. A., & Sauro, F. (2017). An updated global review of solutional weathering processes and forms in quartz sandstones and quartzites. *Earth-Science Reviews*, *171*, 520–557. https://doi.org/10.1016/j.earscirev.2017.06.008

Wynne, J. J. (2022). *Supplemental information for: Fundamental science and engineering questions in planetary cave exploration*. Harvard Dataverse. https://doi.org/10.7910/DVN/HJA6QI

Wynne, J. J., Ashley, J. W., Boston, P. J., Cushing, G. E., & Parness, A. (2014). Target selection and evaluation criteria for caves on the Moon and Mars. In *2014 NASA/JPL Planetary Cave Workshop* (p. 2).

Wynne, J. J., Jenness, J., Sonderegger, D. L., Titus, T. N., Jhabvala, M. D., & Cabrol, N. A. (2021). Advancing cave detection using terrain analysis techniques and thermal imagery. *Remote Sensing*, *13*(18), 3578. https://doi.org/10.3390/rs13183578

Wynne, J. J., Mylroie, J. E., Titus, T. N., Malaska, M. J., Buczkowski, D. L., Buhler, P. B., et al. (2022). Planetary caves: A solar system view of processes and products. *Journal of Geophysical Research: Planets*. https://doi.org/10.1029/2022JE007303

Wynne, J. J., Titus, T. N., & Chong Diaz, G. (2008). On developing thermal cave detection techniques for Earth, the Moon and Mars. *Earth and Planetary Science Letters*, *272*(1–2), 240–250. https://doi.org/10.1016/j.epsl.2008.04.037

Wyrick, D., Ferrill, D. A., Morris, A. P., Colton, S. L., & Sims, D. W. (2004). Distribution, morphology, and origins of Martian pit crater chains. *Journal of Geophysical Research*, *109*, E6. https://doi.org/10.1029/2004je002240

Yingst, R. A., Bray, S., Herkenhoff, K., Lemmon, M., Minitti, M. E., Schmidt, M. E., et al. (2020). Dust cover on Curiosity's Mars Hand Lens Imager (MAHLI) calibration target: Implications for deposition and removal mechanisms. *Icarus*, *351*, 113872. https://doi.org/10.1016/j.icarus.2020.113872

Yoshida, K., Britton, N., & Walker, J. (2013). Development and field testing of moonraker: A four-wheel rover in minimal design. In *Proceedings of the 12th International Symposium on Artificial Intelligence, Robotics and Automation in Space*. Retrieved from http://robotics.estec.esa.int/i-SAIRAS/isairas2014/Data/Session%202a/ISAIRAS_FinalPaper_0114.pdf

Zupan-Hajna, N., Baioni, D., & Tramontana, M. (2017). Karst landforms within Noctis Labyrinthus, Mars. *Acta Carsologica*, *46*, 73–82.