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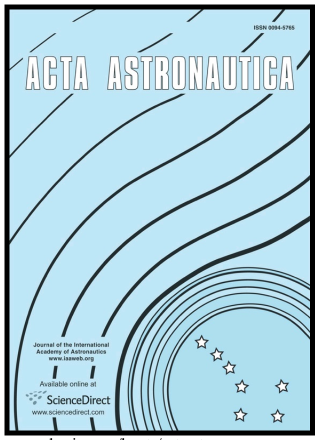

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**An ESA Roadmap for Geobiology in Space Exploration**

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**Abstract**

Geobiology, and in particular mineral-microbe interactions, has a significant role to play in current and future space exploration. This includes the search for biosignatures in extraterrestrial environments, and the human exploration of space. Microorganisms can be exploited to advance such exploration, such as through biomining, maintenance of life-support systems, and testing of life-detection instrumentation. In view of these potential applications, a European Space Agency (ESA) Topical Team "Geobiology in Space Exploration" was developed to explore these applications, and identify research avenues to be investigated to support this endeavour. Through community workshops, a roadmap was produced, with which to define future research directions via a set of 15 recommendations spanning three key areas: Science, Technology, and Community. These roadmap recommendations identify the need for research into: (1) New terrestrial space-analogue environments; (2) Community level microbial-mineral interactions; (3) Response of biofilms to the space environment; (4) Enzymatic and biochemical mineral interaction; (5) Technical refinement of instrumentation for space-based microbiology experiments, including precursor flight tests; (6) Integration of existing ground-based planetary simulation facilities; (7) Integration of fieldsite biogeography with laboratory- and field-based research; (8) Modification of existing planetary instruments for new geobiological investigations; (9) Development of *in situ* sample preparation techniques; (10) Miniaturisation of existing analytical methods, such as DNA sequencing technology; (11) New sensor technology to analyse chemical interaction in small volume samples; (12) Development of reusable Lunar and Near Earth Object experimental platforms; (13) Utility of Earth-based research to enable the realistic pursuit of extraterrestrial biosignatures; (14) Terrestrial benefits and technological spin-off from existing and future space-based geobiology investigations; and (15) New communication avenues between space agencies and terrestrial research organisations to enable this impact to be developed.

**1. Introduction**

Geobiology is the study of the interaction of organisms with geological substrates, through both active and passive processes, and in turn how the geological environment influences biology [1]. A core aspect of this is microbial-mineral interactions. This includes understanding how microbes acquire nutrients and energy supplies from geological substrates and how, in the process of carrying out these transformations, they physically and geochemically change the local environment. Many of these processes have applications in human and robotic space exploration, and on the surface of the Moon and Mars where the surface regolith contains minerals and elements useful for life support systems and In-Situ Resource Use (ISRU) [2, 3]. Some are near-term applications, such as the search for biosignatures [4], while some of have applications in long-term human exploration and settlement scenarios, such as the use of biomining to extract economically important elements or compounds from rocks. Regarding the latter, accessing and processing useful minerals often requires large amounts of energy and technical complexity. However, microorganisms, if supplied with appropriate nutrients (many of which can be sourced from rocks themselves), can be used to enhance this endeavour. Furthermore, understanding the interactions of microbes with minerals and the alteration signatures they leave behind form the basis of life detection elsewhere, such as on Mars [4].



Space applications of geobiology include:

1) *Extraction of nutrients.* Rocks contain many bioessential elements and nutrients [5] that can be used in life support systems to sustain microbial, fungal, and plant communities, and support human nutrition [6]. *In situ* access to these nutrients would remove the need to transport them to the Moon, Mars, or indeed elsewhere, thus reducing mass costs for human missions and improving the

redundancy of life-support systems by allowing the use of local crustal and atmospheric resources [3].

2) *Conditioning of soils for plant/microbial growth systems*. Further to the extraction of specific bio-essential elements and nutrients, microorganisms can be used to break down rocks into soils and 'condition' them, improving and extending their use in greenhouses and other life-support systems [7]. Microorganisms may also be used to fix atmospheric nitrogen, scavenge and concentrate trace elements, and cycle nutrients, thereby improving and maintaining the nutrient content of soils [3].

3) *Biomining*. On Earth, microorganisms are widely used to extract economically important metals from rocks [8-11]. Although a longer-term objective, microorganisms can be similarly used for ISRU (*e.g.,* [12-14] to extract and purify metals and other elements from extraterrestrial materials to support future mining and industrial activities with low energy needs. This application is relevant for both in situ access to metals and other elements, and to supplement diminishing Earth-based supplies.

4) *Control of atmospheric fines (dust)*. Dust is a ubiquitous problem for humans and instrumentation in extraterrestrial planetary environments, particularly on the surface of the Moon and Mars where a well-developed and global regolith comprises exceptionally fine silicate (Moon) and iron oxide (Mars) dust. Such dust poses direct health hazards to humans present within these environments, as well as physically disrupting the mechanical operations of instrumentation, and compromising seals within space suits and habitation units. Microorganisms can be used in enclosed spaces to bind fine dust and limit its movement [15], thereby providing an effective mechanism for locally controlling dust particulates.

5) *Testing of Life Detection Instruments.* Environments in which microbes interact with minerals are the likely places to host life on rocky planets such as Mars [16]. Microbe-mineral interactions and their by-products must be distinguished from abiotic processes if they are to be used successfully as a life detection approach [4, 17]. Terrestrial microbe-mineral interactions can therefore be used to

improve life detection methods by providing examples of detectable biosignatures with which to develop and test future instrumentation designed for life detection missions [18].

6) *Planetary Protection*. The spread of organisms through crustal environments is important for assessing the potential release of biological contaminants in extraterrestrial environments, particularly in those extraterrestrial localities that are known to have localised and at least temporary availability of liquid water, or Mars Special Regions [19]. As such, Planetary Protection has a major influence on mission evolution, landing site selection, and achievable scientific and technical objectives, and must be carefully understood to strike an adequate balance between scientific advancement and responsible exploration. Microbe-mineral interactions and geobiology research on Earth have implications for on-going planetary protection, and can further advance and guide future developments and mission requirements [4].

In view of these applications, a European Space Agency (ESA) topical team "Geobiology in Space Exploration" (GESE) was developed to identify necessary research directions. The two primary purposes of GESE were to: (1) explore and review the full range of potential uses of geobiology, particularly microbe-mineral interactions, in the robotic and human exploration of space, and (2) consolidate a team to propose new geomicrobiology ESA flight experiments on board the International Space Station (ISS) and on future planetary missions and to carry these experiments to completion [13]. To facilitate these two objectives, two GESE international workshops were held, the first in Marrakech, Morocco in February 2011 and the second in Sardinia, Italy, in May 2015. During these workshops, breakout sessions were held to discuss the application of geobiology to space exploration, and to identify new applications, research areas, and technology that could be developed. These discussions were structured around advancements within three categories: Science, Technology, and Community. These categories form the structure of this roadmap. The result of these discussions is a set of 15 recommendations for the broader space science and exploration community that can be followed in developing geobiology further and enhancing its capacity to improve the successful robotic and human exploration of space.

## 2. Science Recommendations

A total of 5 Science recommendations were devised by the community, encompassing new microbiology and space-analogue investigations.

### *2.1 What organisms or communities should be examined to advance geobiology in space exploration?*

Due to the plethora of microbial communities that involve mineral-microbe interaction [4], it is necessary to define those existing, and new, microorganisms that are relevant for future experimental investigation.

#### *2.1.1 Existing organisms for geobiology experiments*

Many organisms have been studied so far in geobiology. Cyanobacteria have received particular attention [20, 21]. However, there are many environments in which microbe-mineral interactions are still not well known, particularly in 'extreme' environments [22], including: a) polar and low-temperature environments, b) anaerobic environments, c) high radiation environments, and d) subsurface and cave environments. These environments have direct relevance to extraterrestrial surfaces and astrobiology [23]. Furthermore, microbes should be sought and studied that can transform geological substrates into soils, to facilitate extraterrestrial soil formation, and also those that can be used for biomining [10]. Regarding the latter, significant progress has been made in terrestrial environmental microbial consortia would be very useful for these processes and should be sought in the environments described above. In addition, synthetic biology also offer another way of engineering these organisms for specific purposes [14, 24], particularly where functions have major interactions with the local mineral environment (*e.g.* the production of extracellular polysaccharide).

**Recommendation 1**: New terrestrial environments relevant to space need to be identified and their microbe-mineral interactions characterized. Polar, anaerobic, and high radiation environments are particularly important, although environments not traditionally considered extreme should not be neglected as they may yield organisms adapted to extreme microniches. Likewise, the plethora of accessible subsurface cave environments provides a largely untapped global resource of important planetary-analogue environments and microbial communities [25-27].

*2.1.2 Single taxa vs. communities*

In the context of the search for life there is a need to look for the full suite of biosignatures created by whole communities, including non-cellular biosignatures such as those produced by viruses [28]. These will complement existing and ongoing studies that focus on specific organisms. There is a further need for all aspects of mineral-microbe interaction to utilise studies on heterogeneous communities as well as individual species, as many microorganisms have interdependencies or cross-communication (*e.g.* quorum sensing), which in turn will affect their geobiological response. This is true not just for biosignatures, but also for developing microbial communities for applied purposes, such as biomining and bioremediation [24]. A more integrated approach looking at the whole suite of mineral-microbe interactions and associated biosignatures within a given environment needs to be developed. Furthermore, there is a need for more abiotic control experiments to try and understand the formation and preservation of biosignatures, and their distinction from abiotic counterparts.

**Recommendation 2:** Research is needed to understand how mineral-microbe interactions and the associated suite of biosignatures produced by microbial communities are influenced by different environmental conditions relevant to extraterrestrial planetary environments. A crucially undeveloped area is the study of reaction rates of microbe-mineral interactions within whole communities, and their responses to extraterrestrial extremes.

*2.1.3 Suitability of 'model' organisms*

The effects of space conditions on biofilm formation, microbial physiology, and the morphology and chemistry of resulting biosignatures has important implications in space exploration, and further studies on space environment stresses on these processes would be valuable [29, 30], such as the effects of UV radiation, ionizing radiation, microgravity, and the effects of these stressors at different parts of the growth cycle (*e.g.* such as the research conducted into bacterial spores, [31-33]), both in isolation and in combination. Our understanding of how long microbes can survive or grow under these stresses is currently limited. Previous work has largely focused on short-term experiments. Long-term space experiments will be useful for understanding the long-term viability and practicality of utilising microorganisms in space exploration [30]. Much remains to be learnt about the influence of space environments on other vital aspects of microbial physiology, such as mobile genetic elements like plasmids, and the virulence of viruses and phages. The lack of experimentation to date is largely due to the inherent complexity of space-based studies, however further studies should be more comprehensively undertaken, particularly using heterogeneous microbial communities (see Recommendation 2) [24].

**Recommendation 3:** Space experiments should be conducted on biofilms to understand better how communities respond to the space environment. Microbial interactions between organisms and with other elements such as phages need to be better characterized in space.

### *2.2 What experimental avenues should be explored?*

As space exploration advances, it is necessary to prioritise both near-term and long-term geobiology space experiments that make use of existing ground-based and space-based opportunities. These build on existing space-based experiments, the many of which have focused on microbial response to space radiation and vacuum conditions [*e.g*. 29, 34].

#### *2.2.1 Near-term future geobiology space experiments*

Several potential developments in the near-term are identified. Due to planetary protection restrictions that limit the types of microbial material that can be delivered to the space environment [19], experiments in the near-term should explore a compromise between abiotic chemical methods of modifying rocks for practical uses, and the use of active microorganisms. One example is investigating enzyme-based methods of planetary regolith alteration or elemental extraction to provide a way to circumvent concerns about biological contamination within the space environment, building on the similar use of enzymes on Earth [35]. In addition, fundamental to any use of microbes or enzymes in extraterrestrial environments is the radiation environment. Although models exist of the radiation effect on individuals cells [36], more complex models of radiation effects inside closed, but space-based environments such as biomining reactors, would be useful. For example, the extent to which microbes 'self-shield' from radiation effects in liquid conditions, as well as through biomineralisation (*e.g.* microbial encrustation) [37] will provide a crucial insight into the possibilities of biomining in space. These models can then be used to optimise mixing regimes and apparatus design criteria for life support systems and biomining apparatus to minimise radiation effects. This would also be useful for the design of near-term preliminary experiments. Finally, near-term future research opportunities would benefit from the coordinated experimentation, where individual experiments have a defined experimental sequence, such as initial demonstration of processes, followed by proof-of-concept studies, and finally experiments to demonstrate the ability to upscale experiments to an 'industrial', real-application level.

**Recommendation 4:** Enzymes and biochemical interaction with minerals should be explored, including the effects of radiation (*e.g.* [4], and an established protocol of successive experimentation developed to provide a normalised research approach to enable direct transfer of results and outcomes across the international community.

*2.2.2. Long-term future geobiology space experiments*

Future experiments revolve around extending experimentation within the space environment from the ISS to Lunar and NEO experimental platforms. These include experiments that place well-defined mineral substrates in contact with microbes on the lunar surface to study long-term radiation effects on already well-understood systems. Preliminary experiments should be deployed on NEOs to investigate bio-cementation (*e.g.* for space-based construction purposes) and biomining to extract resources such as oxygen and metals. Such experiments will allow us to develop Earth-orbit and lunar/NEO experiments to investigate the links between biohazards and radiation effects on microbial communities. In a similar vein, investigating the effects of space conditions on biosignatures would provide important insight into life-detection strategies on planets such as Mars, and further afield. In particular, if extraterrestrial microorganisms or biosignatures are found, there will be a need to determine if those microorganisms are terrestrial forward contaminants. Long term exposure to extraterrestrial conditions may have transformed the morphological and chemical properties of contaminant biosignatures so that it is not easily recognizable as an Earth-based microorganism.

**Recommendation 5:** Carry out further laboratory investigations using existing planetary analogue substrates in preparation for future microbiology experiments on the Moon and on Near-Earth Objects. Furthermore, precursor flights, such as those provided through the ESA ELIPS (European Life and Physical Sciences) programme, will greatly enhance the ability to conduct increasingly complex space-based experiments.

## 3. Technology Recommendations

Space-based geobiology research is inherently dependent upon co-developing experimental technology. As such, a total of 6 Technology recommendations were devised by the community. These focused on expanding ground-based experiments to include field-based geobiology and sample curation, and developing science-driven instrumentation to address the need for miniaturisation and multi-parameter sensors.

### *3.1 What ground-based experiments should be done to better understand microbes in mineral substrates?*

Space-based experimentation is inherently limited, both financially and logistically. Therefore, well-integrated ground-based experiments can significantly aid those valuable experiments conducted on 'high risk' platforms. While previous space-based experiments have been controlled by the ground-based counterparts, the need to expand ground-based experiments into the realm of technology development and planetary analogue field testing was identified.

#### *3.1.1 Planetary simulation facilities*

A diversity of existing facilities that can be used to investigate the interaction of microbes with minerals under simulated extraterrestrial conditions are available worldwide to provide ground-controls to space experiments. These planetary simulation facilities that allow for the study of mineral-microbe interactions under simulated extraterrestrial extremes such as simulated Martian surface, subsurface, and radiation environments. Experimental chambers focused on the Martian atmosphere have been developed, such as *The Mars Atmosphere Simulation Chamber*, developed to test rover-housed Raman spectrometer instrumentation under Mars atmospheric conditions [38], and the *Mars environmental wind tunnel* to simulate atmospheric transport on Mars [39]. In addition to these, a number of complementary chambers exist that broadly simulate the Martian surface. These include the '*MARTE*' Mars environmental simulation vacuum chamber designed to test instrumentation used in space missions, such as the environmental sensors from the Rover Environment Monitoring Station onboard the MSL Curiosity rover [40]; the *Mars Environmental Simulation Chamber*, developed for running long-term experiments at Mars surface conditions [41]; the *Mars Simulation Facility* at the German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt, DLR) [42], and the *Planetary Atmosphere and Surfaces Chamber* [43]. For investigations of extraterrestrial surface fluids, experimental chambers such as the *Michigan Mars Environmental Chamber*, developed to investigate Martian brines [44], and the *Planetary Environmental Liquid Simulator*, designed to investigate the geochemistry and microbiology of aqueous environments on Mars and icy moons [45], have been constructed in the past few years. Likewise, several Mars regolith simulators have been established [46], often for inclusion within planetary simulation chambers such as those highlighted above.



**Recommendation 6:** There are a large number of international ground-based planetary simulation facilities, many of them with overlapping capabilities. A valuable task will be to integrate all these data and make them available to the geobiology community. For this, missing capabilities can be recognized and co-ordination of the availability of existing apparatus can be better achieved. Integration of existing facilities with relevant terrestrial biogeochemical experiments should also be pursued.

*3.1.2 Laboratory curation and analysis of field samples*

There is a need for further research that links studies in the laboratory and in space with natural field conditions (such as in planetary analogue environments). Comparative studies of samples examined in the field using field portable analytical techniques and sophisticated laboratory-based equipment are useful to cross-validate analytical methods on challenging substrates and in non-ideal analytical conditions. This has proven incredibly valuable for instrument development for Mars and Moon exploration [47-49]. With specific reference to geomicrobiology, comparison of similar geological samples of different ages but within the same field environment would also be a useful way to investigate the temporal influence on mineral-microbe interactions. For example, the volcanic outflows from the Mojave Desert, lava flows in Iceland, and the deserts of Morocco incorporate geobiological environments formed at different, datable, time-points. Coordinated analysis of samples from different temporal locations would be a valuable future field campaign. Finally, techniques need to be developed to curate geobiological field samples from environments such as polar sites, from the deep subsurface, or from anoxic environments in a way that allows the study of microbe –mineral interactions in the original environment through maximizing sample integrity. These can then feed into new and future curation efforts and sample receiving facilities for a Mars Sample Return mission, building on existing sample return missions such as Stardust [50].



*3.1.3 Enhancing ground-based experiments*

Several areas were identified that could be improved to further benefit research for geobiology in space exploration, particularly where robotic instrumentation is deployed on planetary surfaces, for example for life detection. Ground-based experiments can be improved through incorporating blind testing within the field environment, with separated teams working together on a single field site to provide independently-verified results. Likewise, strategic understanding of how to coordinate many teams that are working independently with different types of instruments will enable multiple datasets to be effectively correlated. Examples of Mars analogue sites are discussed in [51]. Previous successful examples include the ESA Sample Field Acquisition Experiment with a Rover campaign [52]. To this end, the development of an on-line software tool that would be able to analyze multiple datasets from different organizations and field sites would be especially worthwhile, with the aim to integrate lab-based and field analysis with comparison of samples.

**Recommendation 7:** Develop new tools to allow not just collaborative operational and analytical approaches, but also better collaborative field environments between scientists. This would enable the biogeography of fieldsites to be incorporated into ongoing and complementary studies, such as investigating world-wide localities that are characterized by similar extreme conditions (*e.g.* acidity, salinity, *etc*) [22]. It would also provide a platform to link otherwise separate geobiology research with human space exploration research, following the example of the ongoing Mars Desert Research Station in Utah, USA [53, 54].



### *3.2 What new instrument/analytical capabilities would be useful for space geobiology?*

The transfer of geobiology research and capability into the space environment goes hand-in-hand with the development of new technology, both for deployment in space exploration but also for advancing precursor experimentation.

#### *3.2.1 Existing instrumentation*

There are a large number of instruments already developed for planetary missions, and many that are space-worthy. These instruments include, but are not limited to: 1) mineralogical and elemental analysis by Mössbauer spectroscopy, Raman spectroscopy, X-Ray Diffraction, and X-Ray Fluorescence; 2) organic analysis by pyrolysis, Gas Chromatography-Mass Spectrometry, and deep-

UV Raman spectroscopy; 3) millimetre to micron-scale macro and micro imaging; 4) sample transfer and acquisition tools (*e.g.* drills, abrasion tools, moles, and scoops); 5) cores and cuttings instruments to sample rocks; 6) Atomic Force Microscopy, and 7) Wet-chemistry analytical suites. These instruments, and others, can be modified for use within prototype biomining reactors, space station instrumentation, and lunar wet-geobiology experiments, to allow for real-time and *in-situ* analysis of experiments involving microbe-mineral interactions.

**Recommendation 8:** Existing planetary instruments should be examined for potential use and modification in new geobiology technology and applications to environments such as the ISS. Likewise, construction of spectral libraries of microbial and biomineral material (for example, by Raman spectroscopy and other spectroscopic methods), motivated by astrobiological studies will hugely benefit the geobiology community, much in the same way mineral spectral libraries (such as the online NASA *Reflectance Experiment Laboratory* database) have proven invaluable to ongoing planetary geology research.

*3.2.2 Instrument miniaturisation of laboratory techniques*

New, space-worthy techniques such as Laser-Induced Breakdown Spectroscopy provide important information on energy availability and alteration of rock surfaces, which is useful for geobiology experiments. Other instrumentation for which miniaturised development would be useful for geobiology include Raman spectroscopy, and “life-on-a-chip” instrumentation. Of particular interest to geobiologists are micro-imaging methods and the miniaturisation of these technologies for examining fine-scale microbial interactions with mineral substrates. *In-situ* thin-section preparation of mineral-microbe substrates would also be very useful in the context of the search for past life on Mars or the geological investigation of other planetary bodies within the context of understanding potential biological interactions.

**Recommendation 9**: Sample preparation in the field, particularly by robotic platforms, but also by people could be improved. One example is the development of novel rock cutting, sectioning, and polishing methods that are miniaturised, simplified, and easy to handle, and the integration of this with rapid geochemical analysis.

*3.2.3 New instrument capabilities*

A number of capabilities valuable for geobiology include: a) high resolution Scanning Electron Microscopy (SEM) with energy-dispersive detector (miniaturized), b) capability for cutting depth profiles (for example by ablation) through a rock to characterize each layer, c) Confocal laser scanning microscopy combined with fluorescence spectroscopy, and d) Deep UV Raman Spectroscopy to enhance mineral and biosignature analysis. Other analytical capabilities include improved pH measurements, conductivity, redox potential with aqueous experimental systems. Likewise, sequencing technology has yet to be integrated into space geobiology efforts, yet would provide a valuable and rapid insight into active biological function in response to space environment parameters. With reference to Recommendation 9, the development of high resolution optical imaging techniques in combination with advanced *in situ* sample preparation would provide a valuable new capability in planetary exploration in addition to planetary sample return.



**Recommendation 10:** There are a variety of analytical methods that are yet to be miniaturised, but would significantly add to the capacity to examine microorganisms and their interactions with rock substrates in situ and in the laboratory. Efforts should be increased to identify these, and other methods, and support provided to develop them. Geobiology is unique in that it requires both geo- and biochemical *in-situ* technology, and provides a suitable scientific impetus to develop new miniturised instrumentation. To this end, the geobiology community should collaborate more extensively with the physical and engineering sciences to pursue this endeavor.

*3.2.4 Sensors*

A wide diversity of sensor technology is currently available for in-situ analysis of microbe-mineral interactions including: humidity, atmospheric constituents (*e.g.* $O_2$, $CO_2$), temperature, pressure, and radiation dose. Potential areas where new sensors would be useful include small electronic sensors for the complete range of biologically-relevant anions (*e.g.* $SO_4^{2-}$, $NO_3^{2-}$) and cations (*e.g.* $Ca^{2+}$, $Mg^{2+}$, $Fe^{2+}$, $K^+$, $Na^+$), as well as other products of abiotic or biological rock weathering. The ability to deploy these as continuous point analyses, or periodically across a time series, *in situ* will be valuable for small-scale monitoring of mineral-microbe interactions (55).

**Recommendation 11:** New sensor suites should be identified for development, particularly those that allow for the study of ions in small volumes and concentrations. Miniaturization and improvement of robustness of sensors for a wide range of other measurements should be encouraged, particularly where sensors can be integrated into pre-existing and demonstrated experimental technology.



**4. Community Recommendations**

Finally, alongside new scientific experimental avenues and novel technology development is the need for a community-wide response to maximise future opportunities. Geobiology is an inherently cross-disciplinary subject, even more so within the realm of human and robotic space exploration. Within this context, 4 'Community' recommendations were identified.

***4.1 What space mission opportunities should be created for geobiologists in the coming decade?***

Important to advancing our understanding of microbial interactions with geological substrates in space is the availability of suitable space mission opportunities with which to develop testable hypotheses through experimentation, such as with new microbial strains and communities, new planetary analogue substrates, and new instrumentation identified in the Science and Technology recommendations above.

*3.1 New locations for geobiology*

Fundamental questions can be addressed via ground-based experiments using existing lunar rock and soil samples, as a precursor to flight experiments within the space environment, which are typically costly and logistically challenging. A number of analogue materials have been developed for testing robotic instrumentation, particularly for Mars and Lunar exploration (see Recommendation 6, above), and these same materials can be utilised by the geobiology community. From this, the Moon and Near-Earth Objects (NEO) are obvious new targets to send geobiology experiments and instrumentation in the near-term, once ground-based experiments have optimised experimental design.

**Recommendation 12:** Re-usable platforms and associated experiments on Lunar and NEO surfaces should be developed to enable fundamental geobiological processes in the space environment beyond the ISS to be explored through preliminary experiments. Associated experiments that demonstrate technical capability should also be devised. Further work is required investigating the interaction of microorganisms with extraterrestrial materials (and their analogues).

***4.2 What are the priorities for geobiology applied to space exploration?***

Give the vast array of potential new experimental directions (see Science Recommendations) and technical innovation opportunities, it is necessary to identify those areas of geobiology and space-based research that are high priority within the scope of current space exploration.

*4.2.1 Moon, Mars, and asteroids*

Within the inner Solar System, asteroids have received increased attention as an exploration target, in addition to the Moon and Mars. Exploration of the Moon and asteroids have the advantage of less stringent planetary protection requirements compared to Mars, which therefore allow less constrained geobiology activities. The application of geobiology for the search for life is qualitatively different from the other human exploration enabling applications/enabling technologies, and that therefore should be treated or investigated separately.

*4.2.2 Human related priorities*

Many of the envisioned applications are already in use on the Earth, such as biomining. However, much better understanding of the processes on the Earth would be needed before realistic application for space exploration could be foreseen. Furthermore, when considering geobiological applications for human exploration, priority must be given to those that contribute to the most essential requirements by humans, such as the production of oxygen, water, nitrate, food, as well as addressing and mitigating hazards to humans. Nevertheless, the interest in applications like biomining for pure economic benefit and general exploitation of planetary resources is likely to increase in the future, and should therefore be utilised by the research community.

*4.2.3 Priorities related to the search for life*

Geobiological research contributing to the search for life elsewhere and the identification and definition of biosignatures is a high priority, forming the focus of current and upcoming planetary exploration. Not only is this relevant for robotic missions in the near term, but more information is needed in preparation of human missions. For example, those planetary environments that may, albeit transiently, support microbial life, can be robotically investigated. If an absence of life is subsequently detected this region could become the target for manned exploration to enable further (possibly rover-aided) exploration of the region. Regarding the technologies used to detect such biosignatures, an international standardised quality assessment would provide a structured evaluation of the capabilities of candidate probes/techniques, including the use of the same planetary analogue field sites and sample materials for this purpose.

**Recommendation 13:** Research priorities include the use of Lunar and asteroid exploration for new geobiology investigations, a significantly increased understanding of geobiology space-applications in terrestrial settings, and international coordination for the rigorous development of biosignatures.

### *4.3 What new practical uses can be envisaged to use geobiology to advance human space exploration and settlement?*

Practical applications of geobiology in the advancement of human space exploration include a number of unexplored research avenues beyond biomining and ISRU. Microbes can, for example, be used for energy production in microbial fuel cells. Likewise, microbes from the deep subsurface and cave environments have been shown to be able to utilise hard to digest carbon sources such as plastic [56]. Moreover, such communities could feed off plastic waste during long-term space missions. Two new areas to apply geobiology research include the use of microbes as biosensors for the detection of hazards for humans, such as decreasing oxygen availability, or radiation increases, and the use of microbes for construction of habitats through biocementation [57] of regolith materials.

**Recommendation 14:** The applications of geobiology are diverse and continued efforts should be made to identify ways in which microorganisms, and their transformative interactions with extraterrestrial materials can be used in space exploration. An analysis of Earth-based geobiology processes such as biomining should be undertaken to assess more accurately how these processed can be modified for space application and which parts of these processes can be used in space exploration and development.

***4.4 What ways can space geobiology contribute to earth-based studies?***

Just as terrestrial studies can be applied to space exploration and research, the design of new technologies, instrument miniaturisation, and greater understanding of biogeochemistry through space-based geobiology experiments can directly contribute to terrestrial science. In particular, the necessity to develop novel technologies or techniques to undertake space-based experiments provides a strong link between fundamental, discovery-led science, and the applied sciences. Several areas of terrestrial science will benefit from the study of microbe-mineral interactions in the context of space exploration. Examples of areas that can benefit are microbial survival in extreme environments, which can be transferred to industrial environments and processes, the bioremediation of soils (advanced by the search for chemolithotrophs or metal respirers in extreme environments), biomining advanced by organisms capable of breaking down/redox cycling heavy metals and toxic bi-products [10], synthetic biology advanced by identifying genes that microbes use to cycle or extract elements and compounds from geological substrates [14], agriculture and soil evolution by understanding the microbial contribution to global biogeochemical cycles [58], and archaeology advanced by the study of the effects of microbiology/microbe-mineral interactions on man-made structures and archeological artefacts, including bioweathering of stone buildings [59].

A large number of such technologies include, but are not limited to *(i)* the development and refinement of mixing technologies to overcome problems of micro- and partial-gravity with applications to optimization of biomining reactors, *(ii)* the development of micro-arrays and other bioinformatic tools for studying microbes and their responses to space conditions that could be applied to Earth-based studies of microbial genetics in extreme or inaccessible environments, and *(iii)* development of life support technologies for space applications that will enable self-sustaining conditions for exploring extreme environments on Earth (*e.g.* Antarctica) to be developed.

**Recommendation 15:** Space agencies and other organizations should be made aware of the huge number of terrestrial technology applications of geobiology applied to space exploration and settlement. Further uses and demonstrations of technology in terrestrial applications should be identified and developed. Furthermore, the strong connection between space geobiology and spin-off technology should not just be serendipitous, but form an integral component of planned experimental programmes. These represent immediate applications and opportunities to advance the scope of geobiology in space exploration, but at the same time to benefit Earth applications. By creating these Earth-space synergies the scope of support (financial and otherwise) for geobiology in general could be developed.



**5. Conclusions**

The discussions supported the original motivation for the workshop – that the interactions of microbes with minerals, although constituting the specialized field of geobiology, have an extraordinary range of applications to space exploration and settlement. This perhaps is not surprising in view of the fact that the major focus of robotic space missions in locations such as Mars is the study of past habitability and life, and the successful establishment of a permanent human presence in space will depend on the ability for humans to interact with, and use, the local planetary regolith and rocks. The break-out sessions were necessarily limited by the time available and the duration of the workshops, however, they were successful in identifying a large variety of areas of geobiology that could be developed and improved and these discussions led to well-defined recommendations. These recommendations are not exhaustive and their details almost certainly need more investigation. However, the workshops successfully identified some of the critical science and technology areas that can be developed and the recommendations provide clear avenues for the development of both ground and space based experiments.

**6. Workshop Participants**

Abigail Allwood, Oliver Angerer, Katinka Apagyi, Cesare Barbieri, Roberto Barbieri, Marie-Paule Bassez, Loredana Bessone, Ute Boettger, Penny Boston, Bo Bylos, Sherry Cady, Rosie Cane, Barbara Cavalazzi, Charles Cockell, Benilde Costa, Claire Cousins, Maria Cruz, David Cullen, Illenia D'Angeli, Fabio Demasi, Jean-Pierre de Vera, Jo De Waele, Susana Direito, Alexey Dodsworth, Dainis Dravins, David Duner, Howell Edwards, Juergen Eichholz, Kai Finister, Lauren Fletcher, Fulvio Franchi, Brian Glass, Walter Goetz, Adriano Guido, Fariha Hasan, Ernst Hauber, Martin Hilchenback, Chidiebere Ibegbu, Tomoaki Ichijo, Magnus Ivarsson, Józef Kazmierczak, Goestar Klingelhoefer, Gerhard Kminek, Barbara Kremer, Sydney Leach, Johannes Leitner, Stefan Leuko, Sara Tiziana Levi, Natalie Leys, Kennda Lynch, Rocco Mancinelli, Valentina Marcheselli, Max Mergeay, Hugo Moors, Uwe Motschmann, Leslie Mullen, Natasha Nicholson, Sophie Nixon, Karen Olsson-Francis, Francis Olunwa, Silvano Onofri, Gian Grabiele Ori, Donald Pan, Milva Pepi, Erik Persson, Petter Persson, Brandi Reese, Vincent Rennie, Petra Rettberg, Arianna Ricchuiti, Luisa Rodrigues, Riccardo Sabbadini, Toby Samuels, Christian Schröder, Janet Siefert, Kamal Taj-Eddine, Fabio Tosti, Vivi Vajda, Julio Valdivia Silva, Rob Van Houdt, Geri Weitzman, Angelo Vermeulen, Elena Vorobyova, Daniela Zara.

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**Figure Captions**

**Figure 1.** Applications of geobiology in human and robotic space exploration as a result of the interaction between microorganisms, phage, and enzymes with mineral substrates. Adapted from [13].

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Figure 1 (colour - online)

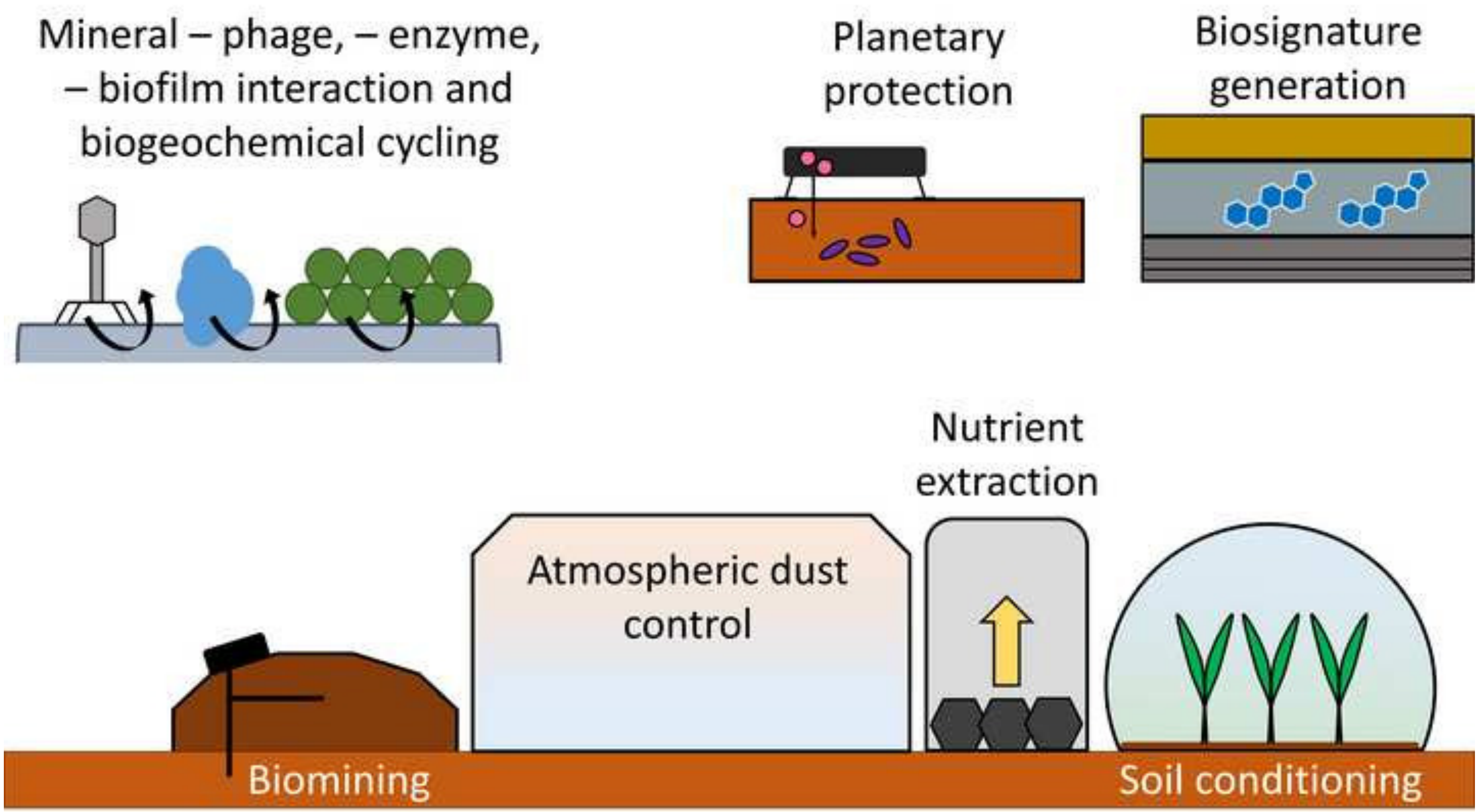

Figure 1 (greyscale - print)