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Astrobiology Lab. at the University of Bologna: ongoing projects and perspectives

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Abstract. The Astrobiology Laboratory at the Università di Bologna has diverse interests in multiple areas of research, including the study of planetary field analogues for space exploration, the geomicrobiological characterisation of biosignatures in modern and ancient extreme environments, and the analysis of Earth's oldest traces of life using high-resolution correlative microscopy approaches. This research is focussed on developing methods for life detection, with a particular focus on the search for fossilised life on Mars, which is considered the primary astrobiology target for the coming decades. This contribution briefly reviews the research accomplished by the group and describes ongoing projects.

Key words. Early life – planetary field analogues – extreme environments – biosignatures – life in the Universe.

1. Introduction

Astrobiology a highly interdisciplinary endeavour involving the study of the origins and evolution of life and its distribution throughout the Universe. It concerns understanding the history of life on Earth and the possibility of life elsewhere. At present, numerous Solar System bodies are considered targets for astrobiological searches; thus, constraining the nature of possible life on these bodies is of paramount interest, as is understanding how living organisms may enter into the fosssil record over geological timescales. The Astrobiology Lab. at the Università di Bologna addresses these challenges using a combination of planetary analogue field sites, geomicrobiological biosignatures from polyextreme environments, and exceptionally well-preserved traces of ancient life. Herein, we describe the research conducted by the Lab. since its founding in 2017 and highlight ongoing collaborations in each of our major research themes.

2. Field Analogues

The exploration of terrestrial surface and subsurface environments exhibiting extremes in one or more physical or chemical conditions has revealed an incredible microbial diversity, and has shown new frontiers of existence and adaptation of life, thereby expanding the known boundaries of habitability in our Solar System and beyond (Cavalazzi et al. 2019). Exploring extremophilic communities can further our understanding of the range of conditions capable of supporting Earth-like life and can help identifying the planetary processes sustaining potentially habitable worlds. Extreme environments and ecosystems are commonly used as model systems, termed analogue sites, to refine strategies for life detection and characterization elsewhere. Analogue sites are places on Earth sharing physical, chemical, or geological similarities with extraterrestrial environments or approximate conditions or features found on other planetary bodies (Cavalazzi et al. 2019). Although the study of analogue sites on Earth may not hold all the answers necessary to address the search for life on other planetary bodies, and although no Earth analogue is perfectly identical to any location on another planet, analogues are nonetheless critical in planetary science and space exploration, especially in astrobiology, since no known extraterrestrial life exists. Expanding our knowledge of diverse terrestrial analogues, particularly through the study of geological processes in extreme environments coupled with their potential for habitability, is considered crucial in determining the physical and chemical boundaries within which life can exist (Cavalazzi et al. 2019). Analogues are further crucial to understand the formation and preservation of biosignatures in both ancient and modern systems (Cavalazzi and Westall 2019). The NASA Mars 2020 Perseverance rover and ESA-Roscosmos ExoMars Rosalind Franklin rover are upcoming astrobiology space missions with targets of finding life beyond Earth, both focussed on Mars. For such missions, the study of terrestrial analogue environments is a valuable, often essential, platform for preparatory research. The UNIBO Astrobiology Lab. has been working and is developing a number of planetary field analogue sites (Fig. 1) in which extreme physical and chemical boundaries for life coexist; these sites have been and are being developed in collaboration with the University of Mekelle (Ethiopia), BIUST (Botswana), Cadi Ayyad University (Morocco), the University of Johannesburg (South Africa), the Open University (UK), INAF-Roma (Italy) and the University d'Annunzio (Italy). Ongoing field analogue studies are particularly related to modern acidic lakes, and alkaline crater lakes in Ethiopia, high- and low-temperature hydrothermal systems in Ethiopia, modern arid salt plains in Botswana, Ethiopia and Morocco, fossil and modern stromatolites in Ethiopia, and early traces of life in South Africa.

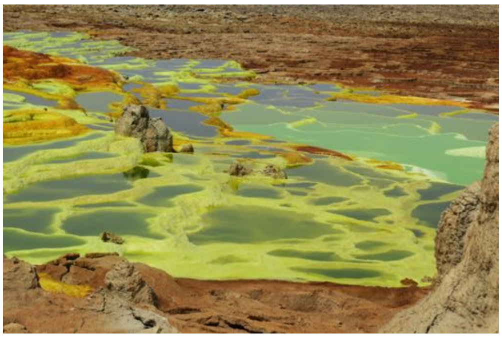

Fig. 1. Photograph of Field of metre-scale sulphur-halite terrace morphologies at the Dallol Hot Springs site, Afar, Ethiopia.

3. Early life

Fossil evidence for life on Earth extends unambiguously to almost 3.5 Ga in the Archaean cratons of southern Africa and Western Australia. The earliest traces of life are manifold, and provide compelling evidence that a diverse biosphere had developed by the Early Archaean (Hickman-Lewis et al. 2018a). Traces of life include microbial cellular fossils, microbial mats and microbially induced sedimentary structures (Hickman-Lewis et al. 2018a; **?**, 2020a; Greco et al. 2018), stromatolites (Hickman-Lewis et al. 2019), C–N–S isotope geochemistry, aliphatic carbon chemistry (Hickman-Lewis et al. 2020a), biominerals, and trace element biosignatures (Hickman-Lewis et al. 2019, 2020b). Although subject to metamorphism and alteration, biogeochemical information garnered from numerous bulk and high-resolution in situ approaches indicate complex Archaean ecosystems. The search for ancient life on Earth has demonstrated the importance of studying fossilized biology using multiple morphological and (bio)geochemical biosignatures and, in some cases, proving experimentally that the evidence for life is exclusively of biological origin. In particular, the UNIBO Astrobiology Lab. is interested in using new techniques for life detection and understanding the co-evolution of Earth and Life at major junctures in Earth history, of which μPIXE (Hickman-Lewis et al. 2020b), computed tomography (Hickman-Lewis et al. 2019), FTIR (Hickman-Lewis et al. 2020a) and LA ICP-MS (Hickman-Lewis et al. 2020c) are key examples. Proposals for astrobiology mission instrument payloads by multiple space agencies include the design and development of miniaturized instruments similar to advanced laboratory instruments on Earth, which are capable of detecting and characterizing potential biosignatures. A more recent development in astrobiology search strategies includes the development of systems capable of caching extraterrestrial materials for sample return missions, where more sophisticated instrumentation in laboratories on Earth can be used to interrogate potential signatures for life. The UNIBO Astrobiology Lab. has numerous on-going projects concerning early life (Proterozoic to Archaean) in collaboration with the CNRS-CBM (France), The Natural History Museum (UK), the University of Johannesburg (South Africa), INAF-Florence (Italy) and the University of Mekelle (Ethiopia). These projects concern the nature and occurrence of early life, understanding early microbial diversity and metabolic landscapes, achieving mechanistic constraints on stromatolite growth processes, and decoding the history of atmospheric and oceanic oxygenation.

4. Biosignatures in rocks

Among the central concerns in astrobiology is life detection. The earliest and dominant life forms of life throughout Earth's history were microbial, and understanding their modes of life and preservation potential in extreme environments considered Mars analogues will guide life detection strategies for astrobiology missions. The ensemble of evidence of past or present life is commonly referred to as biosignatures (Cavalazzi and Westall, 2019). A biosignature can denote an object, substance, and/or pattern whose origin requires a biological agent (Des Marais et al., 2008). Examples include (i) primary and diagenetically altered biosynthetic molecules; ii) carbonaceous cellular and extracellular remains that retain biologically fractionated isotope patterns; (iii) biologically concentrated elements, biominerals, and mineral assemblages in chemical disequilibrium due to biological activity (Cavalazzi et al., 2014); (iv) non-racemic concentrations of chiral molecules; and (v) microbially influenced sedimentary fabrics and structures (Hickman-Lewis et al., 2019). The validity of a biosignature is determined not only by the probability of life producing it, but also by the improbability that non-biological processes did so. The search for life beyond Earth rests upon the premise that biosignatures will be recognizable within the contexts of their planetary environments. Astrobiological investigations must there therefore consider how biosignatures might be generated, preserved, and/or detected within their geological contexts.

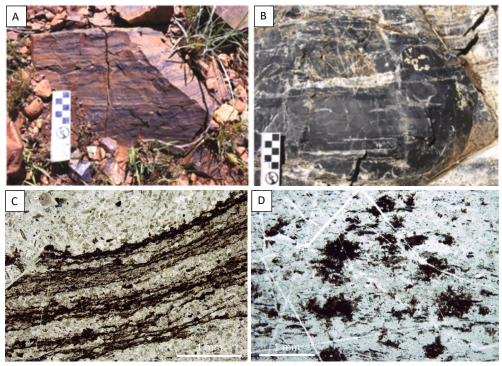

Fig. 2. A–B) Field photographs of 3.3–3.5 billion-year old cherts from South Africa: the Middle Marker horizon (A) and Josefsdal Chert (B). C–D) Photomicrographs showing microbial biosignatures within these cherts: microbial mats (C) and biogenic carbonaceous clots (D).

One of the main targets of the UNIBO Astrobiology Lab. is the detection and characterization of biosignatures in space and time which includes among others i) early life biosignatures such as biominerals and -metals concentrated in ancient organic matter (Cavalazzi et al., 2014; Hickman-Lewis et al., 2018, 2019, 2020c); ii) characterization of cellularly preserved fossils and organic structures in the fossil record (Cavalazzi, 2007); and iii) the response of microorganisms to irradiation under simulated Martian conditions. We collaborate with CNRS-CBM (France), the Natural History Museum and Open University (UK), the University of Johannesburg (South Africa), INAF (Italy), and the University of Mekelle (Ethiopia).

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