Volcanic lakes as extreme habitats for astrobiological exploration: the HELENA project

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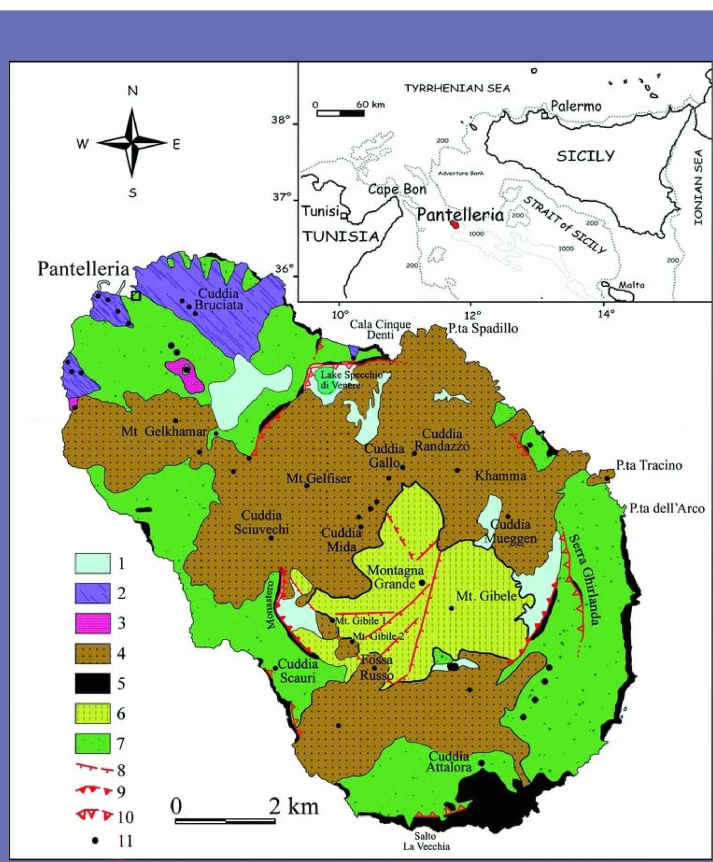
Volcanic lakes in astrobiology

Extreme terrestrial environments, once thought to be devoid of life, have been found to be inhabited by extremophilic microorganisms, expanding our view of the limits of habitability and spurring the exploration of such environments in the context of the search for life on Mars (Schulze-Makuch et al., 2008). Evidence of an active hydrological cycle in Mars' past has come from the investigation of diagenetic episodes by aqueous alteration at Gale Crater by the Curiosity rover (Fraeman et al., 2020; David et al., 2020; Achilles et al., 2020), along with geomorphological features indicating lakes (Fairén et al., 2003) and shallow sediments (Rapin et al., 2019).

Bagno dell'Acqua & the HELENA project

The HELENA (Habitat Estremi di Laghi Vulcanici per l'Esplorazione Astrobiologica) project aims to characterize the Bagno dell'Acqua Lake on the island of Pantellerìa (Sicily) from an astrobiological perspective. A lake of volcanic and hydrothermal origin located inside a caldera, it is host to polyextreme environments controlled by the arid climate and intense seasonal evaporation. It is characterized by high thermal water temperatures, a variable pH from slightly acidic to strongly alkaline, high salinity as a consequence of evaporation, and high concentrations of metals and other chemical elements due to the interaction of water with volcanic products (i.e., rocks, gases, and thermal fluids). The lake is marked by actively growing microbialites rich in calcium carbonates and silica precipitates.



Location of Pantelleria and simplified geological map of the island (modified after Rotolo et al. 2007). Green Tuff eruption: 44 ka

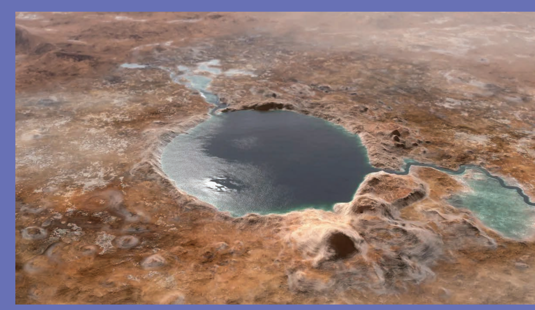
1. Alluvium and fill, 2. Post-Green Tuff basalts, 3. Pre-Green Tuff basalts, 4. Post-Green Tuff pantelleritic pumice falls and lava flows, 5. Pre-Green Tuff pantellerites, 6. Trachyte lavas, 7. Green Tuff, 8. Faults, 9. Cinque Denti caldera rim, 10. La Vecchia caldera rim, 11. Principal eruptive vents

Volcanic lakes are early Earth and Mars analogue environments

Terrestrial volcanic lakes serve as Noachian Mars analogue environments. They can help us in assessing and interpreting the potential biological history of Mars and in developing exploration strategies for ESA ExoMars and Mars Sample Return missions.

Volcanic lakes could also provide us with an analogue to study primordial or prebiotic habitats: the accumulation of phosphates along the coasts of primordial alkaline lakes due to evaporation cycles may be a process capable of favoring the origin of life (Toner and Catling, 2020).

By studying the mechanisms of biosignature formation present in volcanic lakes, we can better interpret the features we observe on Mars and in the terrestrial rock record.



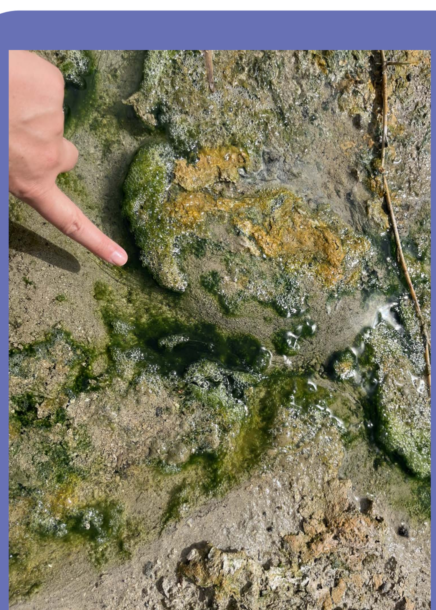
Depiction of Jezero Crater as it might have appeared billions of years ago when it was perhaps a life-sustaining lake. (NASA/JPL-Caltech)

Earth's landscape, as it may have looked more than 2.5 billion years ago. (Peter Sawyer, the Smithsonian Institute)

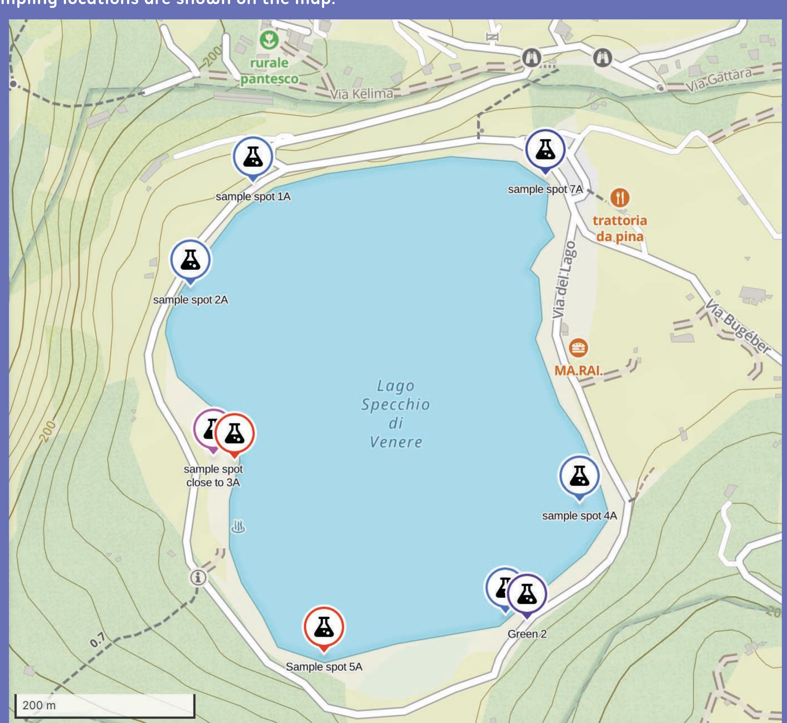
Rock examined by Perseverance on Mars. The leopard spot-like features speckling the clay-colored part of the rock resemble structures in Earth rocks that are associated with life. (MSSS/NASA/JPL-Caltech)

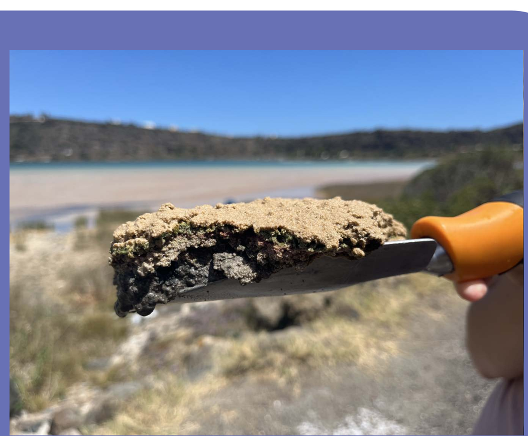
Geomicrobiology of volcanic lakes

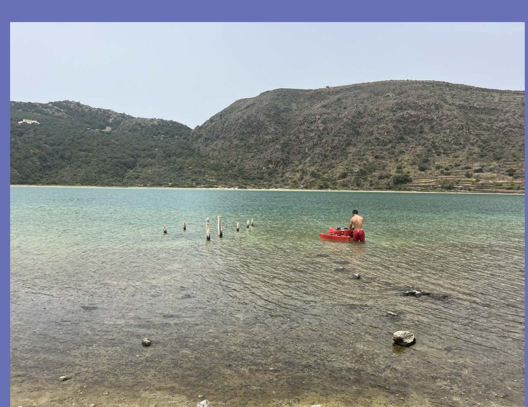
Volcanic lakes are rapidly changing and extreme environments, which result in fascinating microbial physiology and community dynamics. Geochemical characteristics, including pH levels and the presence of sulfur and iron compounds in crater lakes, are the primary factors influencing the makeup of native microbial communities. Iron, in particular, holds a crucial role in the biogeochemistry of numerous volcanic ecosystems and likely played a significant part on early Earth (Weber et al. 2006). Evidence of acidic water systems with redox cycles driven by iron and sulfur has also been identified on the Martian surface (Bibring et al. 2007). Understanding the biogeochemical cycling of volcanic lakes may prove useful in our search for life on Mars and the earliest life on Earth.



Sampling campaign at the Bagno dell'Acqua in June, 2024, where we measured the geochemical paramethers of the lake and collected samples of lake bottom and paleoshore sediements. Sampling locations are shown on the map.







Initial field work

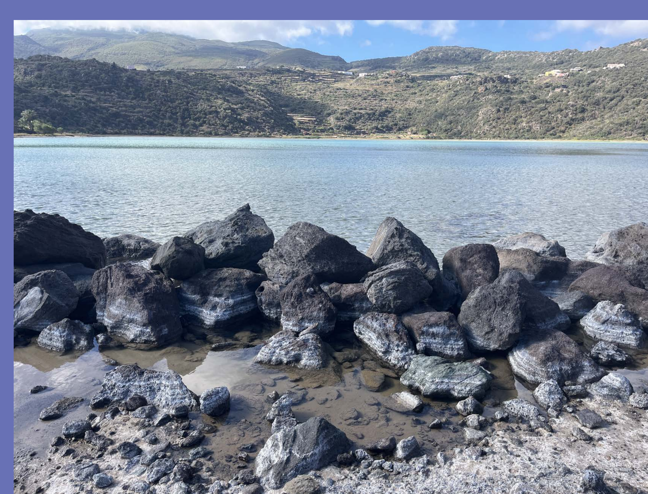
During an initial sampling campaign in June, 2024, we collected sediment samples in six locations around the Bagno dell'Acqua lake. In addition we measured the pH, temparature and salinity at each sampling location, and mapped the bathimetry of the lake with a submersible.

The sediments from both the lake floor and the paleoshore showed discrete layering of black and green layers, indicating the presence of black fungi and cyanobacteria.

Microbe-mineral interactions in volcanic lakes

In understanding the microbial biodiversity (prokaryotic and eukaryotic) in the context of this relatively little known polyextremophile, we can identify new endemic extremophiles or polytolerants. Furthermore, the study of biosignatures and mineral/microbe interactions is advantageous in this environment since the terraced structures preserve portions of the paleo-lake, which allows for a comparative study on (sub)fossil counterparts to verify the potential for preserving biosignatures over time. We plan to characterize the microbial abundance and diversity associated with the depositional environment and to identify the distribution of habitats and paleohabitats and associated geobiofacies through paleoenvironmental reconstructions.

Varying micro-environments visible at the Bagno dell'Acqua in Pantelleria (Sicily)



Evaporation cycles evident on the north side of the Bagno dell'Acqua

Areas of high productivity and iron accumulation on the south side of the Bagno dell'Acqua

Volcanic lakes like the Bagno dell'Acqua receive phosphorus-rich inputs, typically found in low pH environments where the phosphorus comes from the dissolution of volcanic rocks. Phosphorus is removed from the water when a phosphate mineral reaches saturation or when P-oxyanions are adsorbed onto a precipitating host phase, often rich in iron. When phosphorus enters a volcanic lake, it can enhance biological productivity. A previous study on the lake demonstrated the role of the microorganisms in mediating calcium carbon precipitations, parallel to phosphate precipitation (Mazzoni et al., 2024).

The HELENA project will characterize the Bagno dell'Acqua volcanic lake on the island of Pantellerìa (Sicily) from an astrobiological perspective. This polyextreme planetary analogue will help us understand the biodiversity, geobiofacies, and biosignatures present in the lake in the context of Mars exploration and origin of life studies.

TO FOLLOW OUR PROJECT CHECK OUT OUR WEBSITE! HERE WE WILL KEEP YOU UP TO DATE WITH RESULTS, PUBLICATIONS, AND FIELD WORK PHOTOS.

References: Achilles, C., E. et al. (2020), Journal of Geophysical Research: Planets 125, e2019JE006295; Bibring, J. P., et al., (2007), Science, 317(5842), 1206-1210; David, G., et al. (2020), Journal of Geophysical Research: Planets 125, e2019JE006314; Fairén, A. G., et al. (2003), Icarus 165, 53–67; Fraeman, A. A., et al. (2020), Journal of Geophysical Research: Planets 125, e2020JE006527; Mazzoni, C., et al.,(2024), Frontiers in Microbiology, 15, 1391968; Rapin, William, et al. (2019), Nature Geoscience 12.11: 889-895; Schulze-Makuch, D., et al. (2008), International Journal of Astrobiology 7, 117–141; Toner, J. D., & Catling, D. C. (2020), Proceedings of the National Academy of Sciences, 117(2), 883-888; Weber, K. A., et al., (2006), Nat Rev Microbiol 4:752–764.