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Mineralogical biosignatures: what can we learn from more data? - *EMU Research Excellence Medal Lecture*

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Reconstructing the multi-billion-year history of microbial life on Earth relies heavily on our ability to accurately interpret the geological record. Minerals formed in low-temperature aqueous environments are primary targets for this endeavor, as they potentially archive information regarding local microbial activities and the prevailing geochemistry at the time of their formation. However, mineral precipitation in natural settings occurs within highly complex systems where a multitude of physicochemical variables, such as temperature, pH, and solution composition, interact with biological drivers, including organic molecules and active microbial metabolisms. These factors collectively influence mineral properties, including particle morphology and texture, crystal structure, and composition. Consequently, distinguishing between primary biological signatures and abiotic environmental influences remains a significant challenge, often leading to ambiguous interpretations of the fossil record.

To address this challenge, we present a novel high-throughput experimental and analytical framework designed to characterize (bio)mineralization across a vast parameter space. By using a combination of in-situ microscopy, automated image analysis, and Raman spectromicroscopy, we have developed a pipeline to conduct and analyze hundreds of miniaturized microbial biomineralization and organomineralization experiments simultaneously. This approach allows for the systematic mapping of mineralogical signatures formed under diverse geochemical regimes and in the presence of varying microbial strains and organic molecules. We now aim to develop and train Machine Learning (ML) algorithms to analyze these high-dimensional datasets, in order to decouple overlapping physicochemical and biological signals.

Using examples from calcium carbonate and elemental sulfur (bio)mineralization systems, we demonstrate how this approach can be used to identify which specific mineralogical traits can serve as potential biosignatures versus those that are primarily shaped by environmental background. These results will provide a more rigorous statistical foundation for identifying traces of life in ancient terrestrial and extraterrestrial samples, ultimately refining our understanding of how microbial processes have shaped Earth's surface environments throughout geological time.