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Fracture mineral infillings as archives for deep intermittent paleo fluid-flow and ancient microbial activity

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Fractures and fracture zones are important conduits for advective fluid flow in the crust. Certain processes and environmental conditions, such as mixture of fluids of different kinds, redox transitions and microbial activity may invoke supersaturation and hence precipitation of fracture coating minerals. If this mineral record withstands dissolution, re-crystallization or diffusion driven alteration, it will retain paleofluid information essential to understand pieces of low temperature history that are not left in the country rock record. Recent significant analytical improvements, particularly in the field of *in situ* micro-analyses and -mapping, facilitate fine-scaled determinations of stable isotopes, trace elements, radioisotopes and preserved organic molecules, enabling detection of past episodes of microbial activity and fluid chemistry fluctuations at an unprecedented level of detail. The toolbox is further expanding in the form of fine-tuned clumped isotope measurements and synchrotron based imaging/analysis. As an example, when applied to single crystals of calcite and pyrite, SIMS ion imaging for $\delta^{34}S$ and transects of spot analyses of $\delta^{13}C$ and $\delta^{34}S$ through crystals with intense growth zonation, from a fracture sampled in an abandoned mine in Sweden, showed bacterial sulfate reduction (BSR)-related fine-scaled isotope variability of almost 130‰ for $\delta^{34}S_{pyrite}$ and an evolution from strong ^{13}C-enriched calcite reflecting methanogenesis that predate the BSR, to ^{13}C-depleted values reflecting organotrophic BSR[1]. In situ U-Pb dating of the same calcite crystals used for SIMS showed that methanogenesis occurred at 50-30 Ma, whereas BSR occurred at 19-13 Ma when more sulfate rich water infiltrated. This shows that it is possible to distinguish and date shifts in microbial metabolisms and fluid chemistry in a single bedrock fracture. This opens up for widespread exploration of bedrock fractures for discrete periods of fluid flow, and particularly for tiny traces of a significantly understudied "ancient deep biosphere" that may shed light on the evolution of extremophilic microbial life on Earth, such as recent works in Archaean rocks in South Africa[2], as well as serving as important astrobiological analogues[3].

[1] Drake, H.,et al., 2021. Communications Earth&Environment 2, 102

[2] Nisson, D.M.,et al., 2023. Geochim Cosmochim Acta 340, 65-84

[3] Onstott, T.C.,et al., 2019. Astrobiology 19(10), 1230-1262.