Micro-scale SIMS and LA-ICP-MS analyses reveal fracture mineral infillings are archives for 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 mixture of fluids of different kinds, redox transitions and microbial activity may invoke supersaturation and hence precipitation of various fracture coating minerals. If this mineral record withstands alteration in the form of dissolution, re-crystallization or diffusion driven modifications, the composition will retain important paleofluid information, essential to understand pieces of low temperature history that are not left in the country rock record. In the last years, 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/in situ 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 strongly ^{13}C-enriched calcite reflecting methanogenesis that predate the BSR, to ^{13}C-depleted values reflecting organotrophic BSR (Drake et al., 2021). In situ U-Pb dating using LA-ICP-MS of the same calcite crystals and growth zones targeted using 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 (Nisson et al., 2022), as well as serving as important astrobiological analogues (Onstott et al., 2019).

To conclude, key findings so far, with far-reaching interest in the research community include recent discoveries and exploration of: 1. Widespread occurrence of extremely isotopically varied pyrite and calcite ($\delta^{34}S_{pyrite}$ and $\delta^{13}C_{calcite}$), including the largest variability of these widely used isotope proxies yet reported on Earth. 2. Widespread evidence of microbial formation and consumption of the greenhouse gas methane in Precambrian shields. 3. Geochronological constraints of microbial processes at an unprecedented level of detail, that allow delineation of metabolic shifts. 4. Organic molecule- and compound-specific C-isotope evidence of bacterial sulfate reduction from the deep igneous biosphere. 5. Fossilized findings of fungi and proposed syntrophic relationships with prokaryotes. 6. A thermochronological framework for the longevity of deep ancient life in cratons on Earth. 7. A combined approach of studying isotopic inventories of dissolved gases and liquids, with microbial communities as well as biosignatures of fracture coating minerals from isolated borehole sections.

References

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