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Sulfur as the link between geochemistry, mineralogy, and microbial life in submarine hydrothermal systems

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Submarine hydrothermal vents are hotspots of life, where mineral formation and microbial activity closely interact. These systems are characterized by steep geochemical gradients that affect the precipitation of minerals and the microbial communities that thrive in these extreme environments. To study the complex interactions between geochemistry, mineralogy, and microbiology in hydrothermal systems off Milos (Greece) sampled during research cruise M192, we utilized three sediment cores with varying hydrothermal influence and nine chimneys from water depths of 100 to 210 m. We combined extensive porewater and fluid geochemistry (pH, Eh, major anions, and trace elements) as well as mineralogical data (XRD for mineral phases, µXRF for elemental mapping, and SEM-EDX for high-resolution imaging and elemental analysis) with variations in lipid biomarkers (ether-bound core lipids and fatty acids). Lipids, essential components of all living organisms, serve as molecular fingerprints, preserving evidence of microbial activity long after the communities themselves have disappeared. Non-metric multidimensional scaling analysis identified clear statistical patterns linking sulfate and dissolved inorganic carbon concentrations in porewater to lipid distributions in the sediment cores ($R^2 \geq 0.75$, $p \leq 0.001$), indicating the importance of autotrophic sulfur-metabolizing microorganisms. Mineralogical data from all samples (sediment cores and chimneys) further support this link, with elemental sulfur and sulfide minerals correlating with lipid variability ($R^2 \geq 0.41$, $p \leq 0.008$). SEM-EDX analyses revealed unusual sulfide minerals (antimony sulfides covered with arsenic sulfides) with dissolution pits (Fig. 1)—distinct features indicative of microbially influenced mineralization rather than purely abiotic precipitation. Our findings highlight sulfur cycling as a dominant metabolic process in shallow hydrothermal systems, shaping microbial lipid signatures and mineral assemblages. Since minerals persist over geological timescales, their biosignatures can serve as proxies for past life, even where lipid biomarkers have long since degraded. Therefore, understanding these microbe-mineral interactions provides a framework for reconstructing hydrothermal processes and identifying biosignatures in ancient terrestrial systems or potential extraterrestrial settings.