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Anoxic Energetic Convergence Nodes and Microbial Adaptations in the High-Altitude Lirima Hydrothermal System, Chilean Andes

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High-altitude hydrothermal systems in Chile's Tarapacá Region operate under reduced atmospheric pressure (~0.6 atm) at elevations above 4,000 m, providing exceptional natural laboratories for examining biogeochemical processes. The Lirima hydrothermal system, situated at 4,200 metres in the Chilean Andes, establishes distinct gas-water equilibrium conditions governing chemical speciation and biogeochemical cycling, creating environments paralleling proposed early Earth conditions. This study aimed to identify temperature-dependent energetic convergence nodes (ECN) where multiple metabolic pathways achieve equivalent thermodynamic yields, integrating water geochemistry with chemical activity modelling, microbial community assessment, and sedimentary organic matter isotope measurements.

Physical and chemical parameters were measured across seven hydrothermal pools exhibiting thermal gradients (40-80°C), pH variations (6.5-7.2), and electrical conductivity (<2,000 µS/cm²). Water samples underwent geochemical analysis using ICP-OES, with dissolved gases quantified via GC-FID. Sedimentary organic matter isotopes ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$) were analysed using a Pyrocube elemental analyser coupled to mass spectrometry. Microbial community composition was assessed through 16S rRNA gene sequencing. Thermodynamic calculations focused on inorganic carbon and sulphur reactions under anoxic conditions, employing PHREEQC simulations for chemical activities.

We identified distinct ECN centred at 63-65°C where carbon and sulphur reaction pathways achieve equivalent thermodynamic yields. Carbon isotopes showed progressive depletion (-17.2‰ to -27.7‰), while sulphur isotopes transitioned from negative to positive values (-19.4‰ to +11.45‰), coinciding with ECN formation. These isotopic shifts corresponded with decreasing carbon-to-sulphur ratios (from ~10.0 to <0.1), demonstrating that microbial communities prioritise physiological stability over energetic optimisation. Significant correlations were observed between microbial activity and environmental parameters, with distinct hydrogeochemical facies indicative of water-rock interactions.

Our findings reveal fundamental patterns of biogeochemical organisation through ECN, offering insights into microbial adaptation in extreme environments. This framework bridges the gap between theoretical predictions of habitable zones and actual physiological constraints, demonstrating microbial communities' preference for metabolic stability over energy yield maximisation. These insights advance our understanding of early Earth conditions while providing quantitative markers for identifying potential biosignatures in terrestrial analogues and extraterrestrial hydrothermal systems.