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Anticipating temporal variability in hydrothermal ecosystems using geochemical tracers

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Hydrothermal ecosystems occur where interactions among groundwater, precipitation, subsurface geological processes, and volcanic activity support microbial life. In Yellowstone National Park (YNP), snowmelt interacting with rocks at high temperatures, and undergoing phase separation, mineral deposition, and mixing with groundwater, leads to surficial hot springs ranging in pH from about <2 to >9 with temperatures up to 95°C. Over a century of research using geochemical tracers (e.g., chloride, sulfate, $\delta^{18}O$, $\delta^{2}H$, and trace solutes) reveals that YNP hot springs are mixtures of deep hydrothermal (DH) fluids, with likely residence times of hundreds of years, and fluids preserving more recent shallow meteoric signatures (SM). Despite this progress, it remains uncertain how hot springs of differing fluid signatures change over time, yielding variable consequences for microbial ecosystems.

Integrating decades of samples from springs exhibiting diverse fluid compositions reveals some fluid types are geochemically consistent over multiyear timescales while other fluid types are highly variable. Laboratory-measured geochemistry can be mapped onto field-measurable dimensions, enabling quick field identification of variability hot spots for further investigation. As an example, chloride concentrations, tracing water-rock interaction and meteoric dilution, of fluids above pH 3 and between 1500 and 2000 µS/cm specific conductance have a coefficient of variation (CV) below 50% while other combinations of pH and specific conductance can have chloride CV in excess of 225%. Sulfate concentrations, tracing volcanic gas input, of fluids between pH 1.5–2.0 and up to 6000 µS/cm specific conductance are below 50% CV while other combinations exceed 100%.

Using multiyear trends to select fluid types for finer temporal resolution sampling (approximately monthly) allows identification of shorter-term geochemical behavior. DH-signature fluids remain geochemically consistent across 16 months while SM-signature fluids exhibit erratic or cyclic behavior. These patterns persist years after initial documentation.

In addition to conservative tracers, redox-sensitive species (e.g., iron, sulfide, dissolved oxygen) and dissolved organic carbon fluctuate in SM-signature fluids while remaining consistent in DH-signature fluids. These results demonstrate that hydrothermal fluid variability is determined by the pathways through which water reaches each spring, as classified by geochemical tracers, and fluid composition variability generates shifting niche spaces for microbial community members.