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Spatial and temporal variances in geochemical signatures and soil gas emissions along an extreme redox gradient are indicative of subsurface interactions with euxinic spring waters

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Zodletone spring, Oklahoma, USA is a sulfidic, hydrocarbon-associated brine where the surrounding regolith features a strong redox gradient mediated by the euxinic waters interacting with the surrounding soils making it valuable for studying the signatures of (bio)geochemical cycling in euxinic environments that existed on early Earth and Mars. In summer and fall of 2024, 3 sites surrounding the spring were established to study its redox biogeochemistry. These sites, ZT-1, ZT-2, and ZT-3, vary in depth to euxinic groundwater, from within 1 m of the surface at ZT-1 to over 4 m at ZT-3. In 2024, we installed groundwater monitoring wells and soil gas wells. Soils and regolith were sampled in 10 cm increments during installation. We used groundwater sensors, platinum electrodes, and time-domain reflectometry (TDR) probes to monitor groundwater level, electrical conductivity, temperature, soil redox potential (Eh), and soil moisture. Groundwater samples, soil gas samples, and soil carbon dioxide (CO_2) efflux measurements were collected seasonally. Water samples were analyzed for major anions, cations, and metals. Soil gas samples were analyzed for pCO_2, oxygen (pO_2), and methane (pCH_4). Soil bulk mineralogy was characterized by XRD and Fe mineral speciation via selective dissolution extractions. The soils featured oxidized forms of Fe above the depth of groundwater fluctuation, where pyrite was observed. Metastable FeS formed in saturated soils. We correlate site depth to euxinic water to significantly higher pCH_4. At ZT-1, pCH_4 reached nearly 5% at 60 cm. At ZT-2, pCH_4 reached 4300 ppm at 140 cm with lower pCH_4 at shallower depths suggesting methane oxidation occurs. pCH_4 was negligible at ZT-3. ZT-1 and ZT-2 groundwater samples contained elevated concentrations of Sr and Ba, similar to the spring. pCO_2 and pO_2 featured seasonal shifts, and pCO_2 increased with depth as O_2 decreased. CO_2 efflux was lowest at ZT-1. Eh values reaching -120 mV relative to the standard hydrogen electrode, corresponded to higher groundwater levels at ZT-1 while ZT-2 and ZT-3 remained between 200-500 mV. Overall, we find clear signatures of redox activity driven by interaction with groundwater, providing rare insight into the biogeochemistry of soils affected by interactions with euxinic fluids.