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Black Shales as Biogeochemical Archives: Reading the Record from Basin Scale to Microscale

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Black shales have long occupied a central role in both Earth system science and energy resources. These organic-rich mudstones archive Earth's climatic evolution—particularly extreme intervals such as Ocean Anoxic Events (OAEs)—while also forming the backbone of hydrocarbon systems. Beyond their paleoenvironmental significance, black shales are increasingly recognized as unconventional repositories of critical elements essential for modern technologies and the global energy transition. Many contain elevated concentrations of lithium, vanadium, uranium, molybdenum, cobalt, nickel, niobium, rare earth elements, and platinum group elements. These enrichments are governed by redox-controlled sequestration, organic matter complexation, sulfide precipitation, and adsorption onto clay and organic substrates. Because redox-sensitive metals are preferentially concentrated during episodes of extreme reducing conditions, black shales serve as both geochemical sinks and archives of ocean–atmosphere metal cycling through geologic time.

Globally significant examples include the Alum Shale of Scandinavia, the Chattanooga, Bakken, and Marcellus formations in the United States, the Talvivaara black shales of Finland, and the Kupferschiefer of Central Europe. While their resource potential is substantial, extraction presents challenges related to mineralogical complexity, environmental risk, and energy-intensive processing. Advanced analytical tools—such as ICP-MS, LA-ICP-MS, MC-ICP-MS, and synchrotron-based micro-XRF and XANES—have significantly improved our understanding of metal speciation, spatial distribution, and mineral associations, enabling more targeted and sustainable recovery strategies.

In this presentation, I examine selected stratigraphic intervals of metalliferous black shales to illuminate their role within evolving biogeochemical cycles. I will demonstrate micro-scale CT scan images of biological activity and metal association under extremely anoxic shales and bring insights for future directions of bio-metal associations. By integrating trace element geochemistry, isotopic systematics, and redox-sensitive metal distributions, I demonstrate how these deposits record fundamental transitions in oceanic and atmospheric chemistry that regulated metal sequestration under oxic and anoxic conditions. Ultimately, I highlight how multi-scale geochemical analysis—from basin architecture to microscale mineral associations—can refine exploration strategies and inform resource development as society confronts escalating demand for critical elements in the energy transition.