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SYnergy of Soft and Tender X-rays for Earth Research (SYSTER): Multimodal Soft and Tender X-ray Imaging and In Situ Spectromicroscopy for Earth and Environmental Research

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The Earth and environmental sciences (EES) encompass diverse disciplines that investigate processes from the mantle to the atmosphere, addressing both fundamental geochemical cycles and applied environmental challenges. Many critical questions in EES require resolving elemental distributions and chemical speciation within highly heterogeneous natural materials. Synchrotron-based X-ray microscopy provides this capability across soft and tender energy ranges, enabling access to elements from carbon, oxygen and nitrogen to sulfur, iron, and beyond.

To expand access to these essential techniques to EES community, NSF Synchrotron Earth and Environmental Science (SEES) establish the SYnergy of Soft and Tender X-rays for Earth Research (SYSTER) program in Advanced Light Source (ALS). SYSTER integrates complementary capabilities including soft and tender X-ray scanning transmission X-ray microscopy (STXM; BL 5.3.2.2), *operando* STXM (BL 11.0.2.2), coherent imaging and ptychography (COSMIC; BL 7.0.1.2).

In this presentation, we will provide updates on the newly added tender X-ray fluorescence nano-probe at COSMIC BL, as well as recent developments in carbon and iron in situ measurement at BL 5.3.2.2 and 11.0.2.2. The tender X-ray fluorescence nano-probe enables high-sensitivity detection and nanoscale mapping of trace elements such as low-concentration Fe in ocean surface waters, and phosphorus in hydroxyapatite biomineralization pathways in organisms such as yeast.

In-situ STXM offers powerful opportunities to observe dynamic geochemical reactions. However, its broader adoption within the EES community has been limited due to the complexity of energy-dependent microscope alignment, sample preparation and loading, and precise control of reaction environments. Through collaboration between SEES and ALS staff, we have developed and optimized in-situ C and Fe spectromicroscopy methods at BL 5.3.2.2 and BL 11.0.2.2. The In-situ STXM enables investigation of soil organic matter transformations and Fe-sulfide mineral oxidation under continuous flow conditions at different pH and redox regimes. By enabling time-resolved measurements under controlled reaction environments, these capabilities allow us to capture transient intermediates and reaction pathways that are often missed in conventional ex-situ analyses.