



Report on CMM Community Planning Meeting  
and Development of Unconventional Critical  
Campaign

# Unconventional Critical

November 2025

Odeta Qafoku



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Critical Campaign

# **Unconventional Critical**

November 2025

Odetta Qafoku

Pacific Northwest National Laboratory  
Richland, Washington 99354



## Introduction

This report summarizes key outcomes from the Critical Minerals and Metals (CMM) community planning meeting, held in the Environmental Molecular Sciences Laboratory (EMSL) from November 4-5, 2025. Specifically, this report is in reference to the session titled “Biogeochemical Processes Governing Critical Mineral Recovery in Mineral-Dominated Systems,” which hereafter is referred to as “Unconventional Critical.” The session focused on fundamental biogeochemical research needs that should be addressed to help meet the growing demand for CMMs (United States Geological Survey [USGS], Mineral Resources Program) from domestic unconventional sources.

For the purposes of this workshop, unconventional sources of CMMs are considered to be non-soil, mineral-dominated systems, including mine waste streams and Earth system materials that are outside of conventionally developed and targeted ore deposits but contain elevated concentrations of CMMs and represent potentially economic new sources. Examples of unconventional sources include industrial waste such as red mud, mine tailings, coal mining residuals, acid mine drainage treatment solids (AMD), and sedimentary deposits (e.g., black shales). Electronic waste is also considered to be an unconventional source but is outside the scope of this research activity. While critical metal enriched soils are considered to be unconventional sources, they are biologically, geochemically, and hydrologically distinct from the systems considered here and consequently are covered by a separate breakout session topic focused on rhizosphere processes.

Unconventional sources are typically lower in CMM content than conventional sources, but their importance as supplies is expected to increase with time as conventional sources are increasingly depleted. Unconventional sources often represent significant, underutilized potential domestic reservoirs of CMMs that could be accessed using microbiology-driven approaches. Such “biomining” approaches promise far less energy consumption, fewer environmental impacts and lower capital and operational costs as compared to conventional operations (Medin et al., 2023; Park et al., 2020; Vo et al., 2024). Yet, relatively slow leaching kinetics, chemical heterogeneity (i.e., differing chemical properties of CMMs that lead to significant differences in biotransformation pathways), and a broad lack of knowledge about unconventional nanophase CMM host phases and about the mechanisms of geochemical and biomolecular recovery processes create significant barriers to utilizing unconventional sources. Fundamental biogeochemical research is needed to bridge these knowledge gaps. The Department of Energy Office of Science (DOE SC) Biological and Environmental Research (BER) program and EMSL have deep experience in this scientific area.

The objectives of the Unconventional Critical session were to identify key knowledge gaps, define and prioritize science questions and research approaches within the framework of the Environmental Molecular Sciences Laboratory’s (EMSL’s) Environmental Transformations and Interactions science area, identify sites and materials where research could help address knowledge gaps, and develop a framework that leverages EMSL capabilities to generate structured, multiscale molecular data as part of Molecular Observation Network (MONet) that will support AI-driven analysis and discovery of fundamental biogeochemical knowledge relevant to CMM recovery. Participants were charged to identify high-priority research questions and develop science concepts that integrate biological, geochemical, and mineralogical approaches to advance molecular-scale mechanistic understanding of fundamental controls on CMM mobilization from unconventional sources. Participants then were tasked with prioritizing these concepts and outlining groundwork needed to launch an Unconventional Critical community science campaign.

The discussions during the Unconventional Critical session often covered multiple breakout session themes. This report is organized on a topical basis.



## Acronyms and Abbreviations

|          |   |
|----------|---|
| AI       | Artificial intelligence   |
| AMD      | Acid mine drainage  |
| BER      | Biological and Environmental Research                                 |
| CMM      | Critical minerals and materials                                       |
| EMSL     | Environmental Molecular Sciences Laboratory                           |
| MALDI    | Matrix-assisted laser desorption/ionization                           |
| ML       | Machine learning  |
| MONet    | Molecular Observation Network   |
| NanoSIMS | Nanoscale secondary ion mass spectrometry                             |
| NETL     | National Energy Technology Laboratory                                 |
| PPE      | Personal protective equipment   |
| ToF-SIMS | Time-of-flight secondary ion mass spectrometry                        |
| SEM/EDS  | Scanning electron microscopy and energy dispersive X-ray spectroscopy |
| REE      | Rare Earth elements   |
| USGS     | United States Geological Survey                                       |
| XPS      | X-ray photoelectron spectroscopy                                      |



## Contents

|  |     |
|--|-----|
| Introduction .....   | ii  |
| Acronyms and Abbreviations .....   | iii |
| 1.0 Breakout Session 1: Knowledge Gaps, from Challenges to Breakthroughs ..... | 1   |
| 1.1 Biomolecular Processes.....  | 1   |
| 1.2 Host-phase mineralogy .....  | 1   |
| 1.3 Priority knowledge gaps.....   | 1   |
| 1.4 Key challenges .....   | 2   |
| 2.0 Breakout Session 2: Approaches .....                                       | 3   |
| 2.1 Chemical Imaging and Molecular Measurements.....                           | 3   |
| 2.2 Experimental Challenges .....  | 3   |
| 3.0 Breakout Session 3: Science to Site Integration .....                      | 4   |
| 3.1 Site Selection.....  | 4   |
| 3.2 Sample Collection .....  | 4   |
| 3.3 Logistical Considerations.....   | 5   |
| 4.0 Breakout Session 4: Science Campaign Concepts .....                        | 6   |
| 4.1 Concept 1: CMM Behavior in AMD Systems .....                               | 6   |
| 4.2 Concept 2: CMM Behavior in Organic Rich Feedstocks.....                    | 6   |
| 5.0 Breakout Session 5: Campaign Structure and Next Steps.....                 | 7   |
| 6.0 Final Outcomes.....  | 8   |
| 7.0 Citations.....   | 9   |
| 8.0 Participants.....  | 10  |



## 1.0 Breakout Session 1: Knowledge Gaps, from Challenges to Breakthroughs

This breakout session focused on identifying key knowledge gaps and challenges in understanding the biogeochemical processes that control extraction of CMMs from unconventional sources, with emphasis on processes relevant to constructed wetland treatment systems, serpentine and lateritic deposits, shales, AMD treatment solids, fly ash ponds, and mine waste. Discussions highlighted the importance of addressing key biogeochemical and mineralogical challenges, including the roles of organic interactions in controlling CMM release. The following processes were prioritized as targets for community science campaigns because improved mechanistic understanding would help drive key advancements.

### 1.1 Biomolecular Processes

Biomolecular processes were highlighted as fundamental drivers of CMM mobilization. In particular, microbially and chemically driven sorption, dissolution, and complexation function in tandem to control metal release; yet microbially-driven hydrolysis or redox transformations, beyond well-characterized specific systems (e.g. Fe cycling), and the effects of various organic compounds released during microbial activity remain poorly understood. Integrating genome-based measurements with high-resolution biogeochemical analyses is important for discovering microbial phenotypes and identifying the organic compounds that influence CMM mobilization, while providing fundamental insights relevant to optimizing recovery strategies.

### 1.2 Host-phase mineralogy

Host-phase mineralogy also governs CMM behavior and recovery potential. The structure, composition, and crystallinity of host phases affect their dissolution and, consequently, the release of entrapped or sorbed critical metals; while the diversity of minerals, their occurrence as nano-phases, the spatial heterogeneity of CMM, and their variability across unconventional sources limit the accuracy of predictions when relying solely on bulk measurements. Therefore, accurate nanoscale characterization of CMM-bearing host phases was highlighted as key for understanding CMM mobilization and release kinetics, guiding effective recovery strategies.

### 1.3 Priority knowledge gaps

1. The effects of co-occurrence of multiple host phases (e.g., iron [Fe], aluminum [Al], and manganese [Mn] bearing solids) on selective incorporation and mobilization of CMMs in highly variable AMD geochemical systems are not well understood.
2. The processes controlling stratification of critical metals in geochemically diverse AMD treatment ponds or vertical flow systems, including the roles of pH fluctuation and redox oscillations in CMM immobilization, release, and transformation, remain a knowledge gap.
3. The chemical and physical form of CMMs within source materials and the roles of poorly crystalline and nanophase minerals in controlling selective partitioning of light, medium, or heavy rare Earth elements (REE) and other critical metals are not fully resolved.
4. The pathways through which microorganisms exert control over processes and rates of CMM mobilization are not well understood in many unconventional field settings.



## 1.4 Key challenges

Key challenges that emerged from this breakout session discussion were:

- Addressing the geochemical complexity and resource heterogeneity of unconventional sources, including multiple diverse mineral phases, dynamically varying solute compositions, and site-to-site variations.
- Accounting for spatial stratification and selectivity of CMM distribution within mineral phases formed in acid mine water treatment systems.
- Accurately identifying the physical and chemical properties of critical metal host phases, including specific minerals, amorphous or colloidal phases, and organic compounds.
- Predicting temporal critical metal release associated with microbial activity and interaction with organic compounds.
- Overcoming the lack of standardization of measurements and protocols including limited access to priority field sites.

These challenges complicate prediction, transferability, and reproducibility of insights derived from different unconventional sources.

To address these knowledge gaps and challenges, participants identified several research directions, including:

- i) Addressing methodological, logistical, and collaborative barriers such as limited metadata, inconsistent workflows, restricted access to priority sites, absence of standardized protocols, and the need for collaborative efforts leveraging advanced capabilities, including synchrotron-based X-ray methods with high-resolution spectroscopy workflows
- ii) Developing strategies to manage sample heterogeneity by focusing research on well-defined systems or specific mechanisms, including ligand-driven dissolution, redox processes, or pH-controlled processes, to improve comparability and reduce variability across studies
- iii) Implementing standardized analytical measurements and protocols, supported by adaptive, manipulative laboratory experiments for reproducible and comparable mechanistic outcomes
- iv) Developing AI-structured data to enable machine learning (ML) approaches for pattern recognition, identification of common trends and mechanisms, and improved prediction across diverse unconventional sources

The breakout session underscored the importance of advancing biogeochemical understanding that can support exploitation of unconventional CMM sources while minimizing unintended consequences, such as contaminant mobilization (e.g., chromium [Cr]).



## 2.0 Breakout Session 2: Approaches

The “Approaches” breakout session discussed EMSL capabilities, measurements, and identified additional data types that could be incorporated into campaigns. Participants emphasized that standardization of measurements and protocols is essential for ensuring measurement consistency, reproducibility, scalability, enablement of cross-site comparison, and simultaneous capture of rich process-level metadata. Data standardization is critical for generating high-quality, searchable data that will be made available to the BER research community for AI-guided analysis and modeling through the MONet database.

### 2.1 Chemical Imaging and Molecular Measurements

Participants evaluated how existing MONet data and additional EMSL capabilities align with the goals of the Unconventional Critical campaign and recommended methods that are feasible to standardize within budget constraints. Biogeochemical imaging was emphasized as a high priority for resolving spatial distributions of CMMs and their associations with microbes and/or organic components at scales of nanometers up to hundreds of micrometers. Key capabilities for the Unconventional Critical campaign included time-of-flight secondary ion mass spectrometry (ToF-SIMS) and nanoscale secondary ion mass spectrometry (nanoSIMS), integrated with scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM/EDS), along with matrix-assisted laser desorption/ionization (MALDI) for metabolites and microbial exudates imaging. In addition, EMSL’s TerraForms platform, a configurable pore-scale micromodel device that can be controllably embedded with minerals and microbes, was emphasized as a unique capability for conducting adaptive manipulated experiments. When TerraForms are integrated with downstream analyses, such as ToF-SIMS, nanoSIMS, SEM/EDS, MALDI, and X-ray photoelectron spectroscopy (XPS), this platform enables targeted investigation of biogeochemical transformations and spatial redistribution of CMMs following pH, organic ligand, microbe, or redox manipulations. This is a unique capability that strongly complements the capabilities of synchrotron light sources and other DOE laboratories.

### 2.2 Experimental Challenges

Participants identified challenges associated with characterizing poorly crystalline or amorphous nanophase precipitates (e.g., Fe, Al, or Mn oxides) formed during neutralization of AMD waters along with detecting CMMs, which are often concentrated in these phases (hundreds of ppm, but difficult to detect due to complex matrices and overlapping spectroscopic signals). The complexity of host phases poses challenges for quantitative analysis, as signals from target elements often overlap (e.g., XRF signals from light to heavy REEs overlap with barium [Ba], vanadium [V], titanium [Ti], Mn, Fe). Multiple characterization techniques, such as ToF and nanoSIMS are typically needed to confirm CMM-host phase relationships. Proposed actionable steps included advanced denoising and signal enhancement strategies to improve detection sensitivity in these complex matrices. Discussions in this breakout session also focused on applying AI and ML mineral screening to enhance processing of large, multimodal datasets, improve ppm-level detection accuracy, and support more robust mineral phase identification.

In conclusion, participants emphasized the importance of integrating field observations with manipulation experiments to resolve biogeochemical processes key to governing CMM speciation in unconventional sources. Well-structured data were recognized as foundational for maximizing the impact of experimental, field-based research, and AI-driven discoveries.



## 3.0 Breakout Session 3: Science to Site Integration

The "Science-to-Site Integration" breakout session focused on identifying effective strategies for site selection, sample collection methods, and logistic site considerations to support the Unconventional Critical campaign.

### 3.1 Site Selection

The discussions emphasized that campaigns should focus on well-chosen samples that directly address the campaign's key objectives. While geographic field site selection remains critical for leveraging existing field locations, participants suggested considering samples based on their chemical, physical, or biological attributes, rather than strictly by location. This approach provides a platform to capture system diversity across field sites, mined or transported materials, and laboratory generated samples, advancing research on CMM recovery and the microbial and geochemical mechanisms that govern it. Site selection should occur during or after campaign hypotheses are clarified, ensuring that each location directly addresses the campaign's key objectives. When multiple locations satisfy the key objectives, preference should be given to locations where participants already have site access or have existing materials (reducing lead time). It would be desirable for each site to have an agreed-upon sampling area (e.g., mapped plot or transect) where repeat sampling can occur over time and can be documented with a concise site sheet describing coordinates, land ownership or management (public, private, industrial), and any known or suspected contaminants. It was suggested to have one site designated as a "reference site," from which a bulk material archive will be created and distributed to laboratories so that teams can work on representative material and a common feedstock for cross-campaign comparison.

### 3.2 Sample Collection

Sample collection should prioritize standardized practices. With this goal in mind, sampling efforts should use simple, field portable tools that small teams (2–3 people) can carry and operate without heavy machinery, typically in a single day. The primary sample types will be grab or composite samples, or shallow cores where feasible and for materials that retain vertical structure. For unconsolidated materials, non-energized hand powered cores (e.g., slide hammer or push tube cores) can be used to collect cores to specified depth intervals. In rocky, gravelly, or shallow profiles where coring is impractical, small shovels can be used to collect grab samples from the same target depth; where necessary, lightweight mechanical tools (e.g., manual post driver or hammer) may be used to drive coring tubes. At each depth interval, field teams should collect a standard set of samples, such as three replicate cores or composite grabs, with a target minimum mass per depth (see details below) to ensure sufficient mass for geochemical, mineralogical, biological, and imaging analyses. Standardized collection protocols are essential to enable consistent, comparable, and reproducible measurements across sites. In general, samples that cannot reliably yield sufficient material to meet the minimum mass requirements for standardized measurements (e.g., pH, DNA, total phosphorous, extractable organic material, and imaging methods) may be excluded, as they limit analytical replication and reproducibility and may raise questions about potential economic viability as sources of CMMs. All samples should be placed directly into pre-labeled, airtight, sealable containers with labels indicating site identification (ID), sample ID, and date. A short metadata form must be completed for each sampling point, capturing GPS coordinates, sampling method (core vs grab), visible site conditions (e.g., moisture, coarse fragments, standing water, disturbance), depth interval, collector initials, and notes or images capturing any unusual site or/and sample features. Existing MONet workflows, which emphasize soil cores and standardized metadata, will be used as a template and when necessary adapted, for example, accommodating grab samples where coring is not possible. Sampling needs should be scheduled when sites are accessible (avoiding snow cover, flooding, extreme heat), and shipping should be arranged so that samples reach EMSL within defined schedules for analysis. Where



contaminants are known or suspected, appropriate personal protection equipment (PPE), safe handling procedures, and documentation of potentially contaminated materials must be implemented and recorded.

### 3.3 Logistical Considerations

Before sampling begins, each site should have a protocol and documentation to specify access requirements and permitting. This content will elaborate who owns or manages the land; whether formal permits, access agreements, or safety briefings are required; and any seasonal access restrictions (e.g., snow closures, flooding, fire risk closures). Known hazards such as industrial activity or suspected contamination should be identified along with any required PPE, training, or other safety measures. Field teams should be designated in advance for each site, with clarity on who can perform sampling and any required specialized training. Sampling windows will be coordinated in advance with the EMSL team to prevent bottlenecks, with field work planned when sites are accessible to ensure steady campaign progress and samples routed to EMSL team for receiving. Sample shipping protocols will be defined ahead of time, including packaging (double bagging, use of coolers, etc.), labeling conventions, and stated address for the EMSL facility. Overall, logistics approaches can be replicated across multiple sites without long lead times, ensuring that field activities support the scientific campaign.



## 4.0 Breakout Session 4: Science Campaign Concepts

In this breakout session, participants built on discussions from the three preceding breakouts to develop “straw-person” concepts that could form the basis for multi-institutional, multi-investigator science campaigns. Participants emphasized the importance of framing the campaign around central, overarching scientific objectives that are challenging and large in scope and require coordinated contributions from multiple investigators to advance science. The session outlined two research concepts that address key challenges and gaps in CMM resource recovery and provide a framework for the Unconventional Critical multi-user science campaign.

### 4.1 Concept 1: CMM Behavior in AMD Systems

This research concept aims to advance fundamental understanding of CMM behavior in AMD systems, with particular emphasis on recovery of light, medium, and heavy REE as high value target elements from AMD treatment ponds. The focus would be on the coupled roles of poorly crystalline and nanophase minerals, mineral-microbial interactions, and organic ligands in driving selective binding, complexation, partitioning, and mobilization of CMMs. The research would also advance understanding of CMM transformation pathways, including how mineral phase transitions, from amorphous to crystalline states over time, may influence CMM retention and mobility. Biogeochemical analyses will integrate controlled manipulation experiments using microfluidic-based platforms (TerraForms) with high-resolution mass spectrometry, metagenomic analysis, and advanced spatially resolved geochemical characterization to resolve processes governing critical metal entrapment, transformation, and release, including the behavior of Al, Fe, and Mn oxides under varying pH, organic ligands, and microbial activity.

### 4.2 Concept 2: CMM Behavior in Organic Rich Feedstocks

This research concept aims to elucidate the molecular-scale mechanisms governing CMM behavior in organic rich feedstocks (> 5% organic carbon), including black shales, coal mining wastes, lignite, etc. In these systems, both resident organic matter and microbially derived exudates strongly influence critical metal solubilization, speciation, and transport through ligand complexation reactions and by regulating redox potential and mineral host dissolution kinetics. The research would focus on critical metal release from reduced host phases (e.g., pyrite, Fe(II) bearing clays, siderite) and on their transformation across microbially mediated redox gradients. Key processes include chemolithotrophic host mineral oxidation and heterotrophic organic matter oxidation, which together regulate critical metal binding and release. Redox-controlled manipulation experiments (e.g., TerraForms) will test hypotheses of how organic functional groups and microbial communities control critical metal speciation, mobility, and recovery. These experiments will be integrated with biogeochemical analyses as described in Concept 1 to resolve processes governing CMM transformation and release under varying redox conditions, ligand compositions, and microbial communities.

Participants recommended coupling concepts where feasible to connect processes and mechanisms that could inform and guide subsequent manipulation experiments, while recognizing that the concepts represent fundamentally different systems. Collaboration with the DOE’s Mine of the Future [DOE, Hydrocarbons and Geothermal Energy Office] and HERMES (National Energy Technology Laboratory [NETL], Critical Minerals and Materials) initiatives were seen as important opportunities to leverage DOE investments to accelerate progress.



## 5.0 Breakout Session 5: Campaign Structure and Next Steps

During this breakout session, participants discussed potential campaign science frameworks and project structures, emphasizing the need for systematic planning including logistics in sampling strategies.

Participants' recommendations and "straw-person" concepts will guide refinement of the Unconventional Critical campaign science framework, help prioritize data needs, and streamline measurement workflows.

The group recommended adopting a team-based approach that fosters collaboration, broad participation, and effective sharing of ideas and resources.



## 6.0 Final Outcomes

1. Key science thrusts and early strategic opportunities were identified to demonstrate campaign feasibility and produce impactful scientific outputs.
2. Community-driven recommendations were finalized, addressing field site selection, standardized sampling protocols, integration of lab and field studies, and the use of EMSL's advanced capabilities to tackle core mechanistic science questions.
3. A conceptual framework was established to guide the campaign, detailing collaboration among campaign leads, participants, and the EMSL team. Campaign leads will be supported through campaign organization, training, data processing and other EMSL resources to enable multi-scale, multidisciplinary research on critical materials.



## 7.0 Citations

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## 8.0 Participants

### External

Andrea Foster – U.S. Geological Survey  
Annushka Mishra – Duke University  
Benjamin Legg – Pacific Northwest National Laboratory  
Demosthenes Pua Morales – Los Alamos National Laboratory  
Emiley Eloie-Fadrosch – Joint Genome Institute  
Heileen Hsu-Kim – Duke University  
Mengling Stuckman – National Energy Technology Laboratory  
Xin Zhang – Pacific Northwest National Laboratory  
Anthony Chappaz – Central Michigan University  
Yoshiko Fujita – Idaho National Laboratory  
Zoe Elizabeth Havlena – Los Alamos National Laboratory

### Internal

Odeta Qafoku – Unconventional Critical Campaign Leader  
John Bargar – Environmental Transformations and Interactions Science Area Leader  
Sarah Liechty – Project Manager  
Kaizad Patel – Earth Scientist  
Arunima Bhattacharjee – Earth Scientist  
Jeremy Bougoure – Chemist  
Dusan Velickovic – Rhizosphere Group

