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EMSL Community Science Campaign Meeting: Critical Minerals and Materials

Rhizo Critical Campaign Breakout Session Report Summary

November 2025

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Background and Charge Questions

The "Critical Minerals Biogeochemistry in the Rhizosphere – Ultramafic Soils (Rhizo Critical)" campaign breakout (BO) session was organized to identify major knowledge gaps and fundamental research needs in rhizosphere microbiology and geochemistry that, if addressed, could transform our ability to recover critical minerals from ultramafic soil systems. We sought to identify significant challenges that must be surmounted in the pursuit of deeper science knowledge. Our ultimate goal is to understand this landscape well enough to identify and prioritize opportunities for EMSL to make the greatest impact with Environmental Transformations and Interactions (ETI) science area research campaigns focused on the biogeochemical processes controlling the behavior of critical minerals and materials in the rhizosphere.

The increasing demand for critical materials and minerals (CMM) in the U.S. has heightened interest in low-grade ores with much attention on ultramafic soils, which contain valuable metals such as nickel (Ni), chromium (Cr), manganese, cobalt (Co), and copper (Lee *et al.,* 2025; DOE CMM Report, 2023) used in advanced battery, magnet, wiring and wind turbines, and stainless steel technologies.

Metal hyperaccumulating plants grown in ultramafic soils can extract economically valuable concentrations of CMMs through the process of phytomining. This technology has evolved from phytoremediation, which involves using plants to cleanse contaminated environments by removing, detoxifying, or stabilizing pollutants like metals and organic compounds. Hyperaccumulator plants are capable of storing metals in their living tissues at concentrations hundreds to thousands of times higher than those found in 'normal' plants. For instance, while the average concentration of Ni in the dry matter of plants growing in typical soils is usually less than 5 $\mu g\ g^{-1}$, Ni hyperaccumulation is defined by concentrations exceeding 1,000 $\mu g\ g^{-1}$ (Corzo Remigio et al., 2020; Reeves *et al.,* 2018). Phytomining research has primarily focused on Ni (Rylott and van der Ent, 2025), for which the U.S. has very limited conventional mines in operation. Most soils typically contain Ni concentrations ranging from 7 to 50 mg kg^{-1}, whereas serpentine soils exhibit significantly higher levels, with Ni content often ranging between 700 and 8,000 mg kg^{-1} (Sobczyk et al., 2017). While more than 500 plant species in over 50 different families have been identified as Ni hyperaccumulators (Kidd *et al*., 2018), Ni phytomining (and phytominng in general) remains largely untested because most studies are short-term, small-scale, and conducted under simplified or artificially enriched conditions, so they fail to capture the low metal concentrations, environmental variability, and management constraints that would be needed for a field-scale demonstration. Few hyperaccumulator species have been validated as true "metal crops," and their biomass production, stress tolerance, and rooting characteristics are usually too poor to yield economically meaningful metal outputs. Critically, the basic mechanisms of metal uptake, transport, and sequestration, especially as shaped by belowground processes such as root exudation, rhizosphere chemistry, and root–microbe interactions that control metal mobility and bioavailability (Montreemuk *et al.,* 2023; Kidd *et al.*, 2018; Durand *et al.*, 2023; Alford *et al.*, 2010), are still only partially understood, and downstream metal recovery from biomass is rarely optimized. Because these limitations stem from gaps in fundamental knowledge rather than from a failure of the concept itself (Rylott and van der Ent, 2025; van der Ent *et al.,* 2015), there is a strong need for basic science that dissects plant metal homeostasis, rhizosphere and microbial processes, and their integration with soil chemistry and process engineering to design more robust, scalable phytomining systems.

Held over two days, the Rhizo Critical campaign meeting brought researchers from the user community together with EMSL scientists to articulate the science needs and challenges of phytomining. The focus was to define scientific priorities that could support a focused multi-institutional research effort involving expert researchers and then to develop a concrete framework for an EMSL user program research campaign. To reach this point, participants engaged in five sequential facilitated breakout sessions where they identified major science gaps and challenges, explored methodological approaches, discussed EMSL capabilities, and refined campaign structures that could integrate field and laboratory work. Key objectives discussed included advancing mechanistic understanding of microbial-mineral-hyperaccumulator root interactions in the rhizosphere, establishing standardized protocols for sampling and data collection, and leveraging innovative EMSL tools through the new EMSL user community science campaigns to address questions related to sustainable critical mineral recovery.

Charge questions

Participants were invited to provide their insights on the following charge questions:

(1) What are the key knowledge gaps in studying and understanding the rhizosphere and ultramafic soils processes for phytomining and CMMs biogeochemistry and recovery?

(2) What are the major challenges in investigating rhizosphere and ultramafic soil processes for phytomining and CMM biogeochemistry and recovery?

(3) What capabilities, methodologies, and approaches are necessary to tackle these knowledge gaps and challenges?

(4) How can this EMSL user science community campaign, as a coordinated, multi-institutional effort, effectively address the identified gaps and challenges?

Acronyms and Abbreviations

AI	Artificial intelligence
APRA-E	Advanced Research Project Agency-Energy
BER	Biological and Environmental Research
Co	Cobalt
CMM	Critical minerals and materials
Cr	Chromium
EMSL	Environmental Molecular Sciences Laboratory
EPA	Environmental Protection Agency
ETI	Environmental Transformations and Interactions
nanoSIMS	Nano-secondary ion mass spectrometry
Ni	Nickel
MALDI	Matrix-assisted laser desorption/ionization
MONet	Molecular Observation Network
USGS	United States Geological Survey
XANES	X-ray absorption near edge structure

Contents

1. Breakout Session 1: Knowledge Gaps and Challenges to Breakthrough

The “Knowledge Gaps and Challenges to Breakthrough" session focused on identifying scientific gaps and obstacles related to understanding the mechanisms underlying microbially-driven rhizosphere processes, with a specific focus on microbial-assisted phytomining to accelerate the recovery of Ni and other critical minerals from ultramafic soils.

1.1 Knowledge Gaps

Knowledge gaps emerged in five critical areas:

1. There is an insufficient mechanistic understanding of the coupled biomolecular and pore-scale geochemical processes by which microbes, root exudates, and minerals interact to solubilize Ni (e.g., by controlling specific mineral dissolution, metal complexation, and redox reactions at nanoscale levels under specific conditions).
2. The functional roles of rhizosphere microbial communities, including their interactions with root exudates, in regulating ion mobilization and selectivity amidst toxic metal co-mobilization remain unstudied. Furthermore, it is unclear whether microbial contributions to metal uptake are constitutive or triggered by plant signaling mechanisms.
3. The development of advanced biogeochemical numerical models of rhizosphere-microbe interactions remains underexplored, yet these models are crucial for enhancing our understanding of targeted mechanisms and informing the design of rapid computational and empirical experiments aimed at optimizing critical mineral uptake.
4. The dominant dissolved Ni species (free Ni^{2+}(aq), dissolved Ni–organic complexes, Ni adsorbed to oxides/clays, Ni in mineral lattices) that are taken up by roots of Ni hyperaccumulators under field conditions are poorly known. Moreover, the extent to which root-induced pH shifts and rhizosphere microbiota (e.g. Ni-tolerant bacteria) alter Ni speciation and Ni phases is largely unknown.
5. Our understanding of the affinity and selectivity of metal transporters for different Ni species are limited, particularly under realistic rhizosphere chemistries (variable pH, competing cations, complexing ligands), and it remains unclear whether hyperaccumulator transporters can directly take up Ni complexed with organic ligands or only free Ni^{2+}.
6. There is a significant gap in the comprehensive understanding and documentation of hyperaccumulator species thriving in ultramafic soils within the U.S.. To date, only a handful of natural hyperaccumulators have been identified in the region. Among them, *Odontarrhena chalcidica* (previously known as *Alyssum murale*) and *Odontarrhena corsica* (previously *Alyssum corsicum*), both natural Ni hyperaccumulator species, have been classified as invasive species in the state of Oregon.

1.2 Practical Challenges

The five key challenges that emerged from these discussions were:

(1) Restricted access to ultramafic soil field sites due to regulatory and ownership barriers which creates difficulty for sampling and land use for Ni recovery.

(2) Limited availability of field sites with vegetation containing known hyperaccumulators, which restricts access to rhizosphere soils for exploratory studies.

(3) The inherent complexity of these soils' mineralogical heterogeneity within and across different sites gives rise to multiple sets of Ni-containing host phases, processes, and rates.

(4) Such a heterogeneity, scaling, and translating from one site to others requires highly standardized sampling approaches to facilitate "apples-to-apples" comparisons across these environments.

(5) Difficulties remain in translating findings from metaG and metaP experiments—whether conducted with natural or synthetic microbial consortia—into real soil environments. These challenges stem from limited understanding of the biosynthetic pathways underlying microbial secondary metabolite production, including siderophores and chelators, within complex microbial communities. In actual soil systems, these pathways are further influenced by heterogeneous mineral matrices that contain non-standard minerals, diverse chemical substitutions, and substantial physicochemical variability. Together, these factors significantly shape microbial metabolism and mediate interactions among community members.

To address these challenges, participants proposed several technical advancements. These included:

(1) Adopting standardized rhizosphere soil and root sampling and field experiments across different field sites to enable better translating across sites

(2) The creation of a systematic soil database encompassing ultramafic soil profiles, chemistry, and specific mineral phases across various sites including the U.S. Geological Survey (USGS) serpentinite and laterite soil sites (Note: while such a database would be outside the scope of this campaign, the sampling described in step 1, coupled with the systematic standardized analyses inherent to the Molecular Observation Network (MONet), would produce a systematic data base of soil molecular phenotype data for ultramafic soil profiles)

(3) High-throughput screening approaches to identify diverse hyperaccumulator (HA) plants (in collaboration with ongoing initiatives within the science user community, such as the recently funded Advanced Research Projects Agency-Energy (ARPA-E) projects by the U.S. Department of Energy (ARPA-E, 2024)), microbial and plant siderophores, and associated microbial consortia to uncover novel mechanisms driving microbial-assisted phytomining processes. (Note: given the limited availability of known HA plants in ultramafic field sites in the United States, high-throughput screening approaches to identify diverse HA species are highly valuable and should be actively pursued. Although this activity falls outside the scope of the current campaign, EMSL's Rhizo Critical campaign is uniquely positioned to support and accelerate such efforts through strategic partnerships and collaborative projects with the broader scientific user community).

Complementary mechanistic laboratory experiments and AI-driven datasets—aligned with the broader, long-term scope of the Rhizo Critical campaign—were highlighted as essential components for advancing machine learning models to improve reproducibility and scalability. Discussions also stressed the need to unravel biomolecular mechanisms underlying metal solubilization, metabolite production, and mineral transport within in situ environments.

The session also underscored the importance of advancing hydrobiogeochemical models of rhizosphere-microbe interactions to provide improved theoretical tools for generating insights and exploring specific mechanisms to enhance critical metal uptake (e.g., Ni, Co, and Scandium) while minimizing unintended effects, such as phytotoxicity or ecosystem pollution. Ultimately, the breakout session emphasized systematic collaboration and technological integration to develop reproducible, scalable approaches for microbial-assisted phytomining and critical mineral biogeochemistry in ultramafic soils.

2.0 Breakout Session 2: Approaches

The "Approaches" breakout session explored EMSL's capabilities and prioritized measurements and data types that could be standardized to advance fundamental rhizosphere research relevant to microbial-assisted phytomining in ultramafic soils. Standardization of measurements to facilitate data consistency and reproducibility, as well as to capture rich process metadata, is critical to ensuring that high-quality searchable data can be delivered (via the MONet database) to the Biological and Environmental Research (BER) research community for use in AI-guided analysis and modeling activities.

2.1 Priority Methods

Participants reviewed how existing EMSL capabilities and methodologies align with scientific objectives identified by the knowledge gaps, while balancing technical feasibilities. Chemical imaging and bioimaging were noted as “high importance” to resolve biomolecular pathways and the linked geochemical processes at the pore scale for soil-root interfaces. Specifically, spatial metabolomics, including matrix assisted laser desorption/ionization (MALDI) mass spectrometry, and elemental imaging via nanoscale secondary ion mass spectrometry (nanoSIMS) were highlighted for analyzing rhizosphere chemical signaling and microbe-metal interactions at high spatial resolutions. Moreover, participants recommended using integrated omics including metagenomics, meta-transcriptomics, meta-proteomics, and metabolomics to study metallophore production and microbial roles in mineral uptake. Specifically, EMSL’s advanced (meta)proteomics approaches could be prioritized to uncover biomolecular pathways and microbial functions involved in microbial-assisted CMM transport and recovery in the rhizosphere. Additionally, technologies like EMSL’s RhizoChip and pore-scale micromodel TerraForms could be used to conduct controlled studies of plant-microbe interactions in situ and subsequently observe biogeochemical processes at microscale levels through time. Imaging techniques, such as micro X-ray fluorescence, were highlighted as essential for understanding mineral phases and coatings in complex ultramafic soils, while detecting mineral phytoavailability (through sequential chemical extraction methods) was proposed for studying critical mineral phases.

2.2 Experimental Challenges

Challenges included aligning field methodologies with lab tools due to soil variability, high costs for rare Earth element analysis, and maintaining microbial persistence in field trials without triggering adverse cascading effects. Participants proposed actionable steps to address these issues, including expanding investment in imaging tools compatible with synthetic soil habitats like RhizoChips and field deployable micromodels for mechanistic studies, developing standardized workflows linking field and laboratory results, and establishing comprehensive soil and microbiome-metallophore databases. Participants and other BER user communities were encouraged to develop collaborative proposals aimed at unifying researchers focusing on ultramafic soils and hyperaccumulator biology. These efforts strive to facilitate the creation of AI-ready datasets and scalable modeling workflows, fostering advancement in this interdisciplinary field.

3.0 Breakout Session 3: Science-to-Site Integration

The "Science-to-Site Integration" session focused on defining effective strategies for field site selection, sampling methods, and logistics to support rhizosphere and ultramafic soil research under the Rhizo Critical campaign. This discussion is necessary to identify and begin developing standardized sample collection, shipping, handling, and processing approaches in advance of the research campaign.

3.1 Sampling Sites

Field sites in California and Oregon were suggested for sampling (e.g., in collaboration with USGS), with a focus on rhizosphere soil and ultramafic soils hosting Ni-phase minerals. Obtaining access to sites under the Bureau of Land Management or private ownership was highlighted as a considerable hurdle, requiring permits, agreements, or collaboration with organizations such as the USGS and Environmental Protection Agency (EPA).

3.2 Logistical Considerations

Sample shipment discussions identified best practices including precise protocols to prevent contamination, ensure preservation, and standardize metadata documentation. Integrating laboratory and field studies via shared datasets and AI-ready platforms was recognized as essential to bridge gaps between the two research environments.

To address logistical challenges, participants proposed actionable steps such as optimizing soil sampling tools, designing standardized sampling protocols, and leveraging partnerships with land managers and government entities to gain site access. Field-to-lab alignment through systematic soil characterization databases and mechanistic testing frameworks was considered vital for reproducibility and scalability. Establishing metadata uniformity and generating predictive models using integrated datasets were noted as critical next steps.

The session concluded with an emphasis on the importance of unified approaches to field site selection, sampling optimization, and data standardization under the Rhizo Critical campaign. These efforts aim to streamline research workflows, resolve technical and logistical barriers, and enhance understanding of rhizosphere-driven biogeochemical processes in ultramafic soils.

4.0 Breakout Session 4: “Straw Person” Campaign Framework

The "Straw Person" Campaign Framework session laid the groundwork for identifying key research questions, concepts, and methodologies that could define the scope of work of a Rhizo Critical multi-user science campaign. Discussions focused on addressing knowledge gaps surrounding rhizosphere processes, ultramafic soil biogeochemistry, and microbial-plant interactions critical to phytomining and mineral recovery.

4.1 Science Questions

Participants outlined specific fundamental science questions, including how hyperaccumulator plants influence microbial community composition and functional guilds, and the role of root exudates, such as organic acids and siderophores, in metal solubilization and microbial metabolism. Deeper mechanistic understanding of biomolecular pathways for mineral solubilization and Ni uptake, and the relative influence of microbial processes and geochemical reactions (e.g., mineral phases dissolution/precipitation/leaching, impact of pH on redox, mineral solubility, and microbial viability) were emphasized as central to advancing rhizosphere biogeochemistry of Ni and other critical minerals. Seasonal and spatial dynamics were also noted as important scientific factors affecting rhizosphere processes and critical mineral mobilization. Proposed hypotheses included that root exudates are primary drivers of metal mobilization, and hyperaccumulators exhibit unique exudation profiles enhancing mineral solubility compared to non-hyperaccumulators.

4.2 Target Organisms

Hyperaccumulator plants, primarily species within Brassicaceae, were proposed as strong candidate model systems for investigating rhizosphere-mediated mineral uptake, with comparisons to non-hyperaccumulators. Specific hyperaccumulator plants suggested by participants included *Odontarrhena chalcidica* (formerly *Alyssum murale*), *Odontarrhena corsica* (formerly *Alyssum corsicum*), and *Streptanthus polygaloides*. Research could focus on identifying microbial metabolites (e.g., metallophores), gene pathways, and transport mechanisms driving biogeochemical processes, while analyzing soil composition and chemical gradients critical to ultramafic systems. Integrated lab and field strategies were stressed to refine mechanistic insights and align findings across scales.

4.3 Target Minerals

Ni was identified as the primary target critical mineral for this campaign due to its exceptional accumulation ability in certain hyperaccumulator plants, with concentrations reaching up to 4 wt% in leaves and up to 25 wt% in sap—among the highest recorded metal concentrations in living tissues (Przybylowicz et al., 2015). Co was recommended as a secondary focus, as it is often co-located with Ni in ultramafic soils and has growing economic importance due to its role in lithium-ion battery production for electric vehicles, which are critical for transitioning to a low-carbon economy.

4.4 Target Methods

Recommendations included leveraging omics technologies (meta-genomics, transcriptomics, proteomics, and metabolomics) and high-throughput exudate profiling to uncover microbial functions and pathways, alongside advanced imaging techniques (e.g., MALDI, nanoSIMS, X-ray absorption near edge [XANES] structure) for nanoscale visualizations of chemical and microbial interactions.

4.5 Target Field Sites

Discussions centered on identifying sites with ultramafic soils and hyperaccumulator plant populations such California's Sierra Nevada foothills and Northern California (e.g., Klamath region), serpentine and ultramafic soils in Southern Oregon and legacy mining sites near Riddle, Oregon, and native growing hyperaccumulator plant (Streptanthus polygaloides) field sites in Paradise, California. Additional field sites will be identified in collaboration with the user community when we launch the campaign.

4.6 Model System Experimental Studies

Collaborative use of EMSL resources, including TerraForms tools like SubTap, RhizoChips, and pore-scale micromodels, will further refine experimental workflows. Participants further emphasized the importance of harmonizing field and lab methodologies, implementing standardized protocols for sample collection and characterization, and building AI-ready datasets to streamline predictive modeling.

5.0 Breakout Session 5: Priority Science and Next Steps

The "Priority Science and Next Steps" session synthesized ideas from prior discussions to evaluate potential cohesive frameworks for the Rhizo Critical campaign, addressing key science concepts, experimental approaches, and operational priorities for advancing rhizosphere biogeochemistry and ultramafic soil research. The session emphasized research that provides mechanistic understanding of the roles of metabolites (e.g., organic acids and metallophores) alongside microbiome functions as controls on nickel uptake and mineral mobilization in hyperaccumulator compared to non-hyperaccumulator plants. Participants also discussed the distinct biogeochemical characteristics of soils naturally hosting hyperaccumulators versus those lacking such vegetation, highlighting the interdependence of biotic and abiotic parameters.

5.1 Campaign Approaches

1. The integration of controlled laboratory experiments with field surveys was proposed as critical to bridging mechanistic studies and environmental variability. Laboratory work would refine understanding of rhizosphere processes, while field studies at diverse ultramafic soil locations—such as the Klamaths, Sierra Foothills, and Riddle Legacy Mine—would capture variability in mineral phases, climate impacts, and vegetation. Participants advocated for developing a shared reference field site to standardize reproducibility across studies, supplemented by work at diverse ultramafic soils to ensure holistically representative findings. Collaborative efforts with USGS to map unexplored sites were encouraged to expand campaign scope.
2. Shallow soil cores targeting layers rich in plant root interactions with ultramafic soil minerals was recommended as a key sampling strategy. Native hyperaccumulator sites would require strategic manual extraction methods to target rhizosphere processes at their most dynamic levels. Leveraging EMSL's expertise with MONet, standardized protocols for sample collection, preservation, and shipment to EMSL were recommended to guarantee reproducible analyses. Additionally, sampling at multiple seasonal intervals was proposed to capture temporal changes in rhizosphere chemistry and microbial activity. 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 (collected by participants) routed to the EMSL team for processing and analysis.
3. Participants recommended a campaign framework that develops mechanistic insights in balance with data accumulation. Participants recommended workflows that integrate field observations with laboratory mechanistic studies while enabling collaborative data-sharing platforms. Experimental designs would pair standardized model hyperaccumulator plant systems with ultramafic field surveys, enabling scalable and reproducible studies of rhizosphere biogeochemistry. Technologies including metaproteomics, metabolomics, XANES, and MALDI and tools like TerraForms (micromodels, SubTap, and RhizoChips) were identified as essential for characterizing microbiome-metal-plant interactions and refining methods.

Breakout Session 5 reinforced the need for approaches that align field and lab research through standardized methods and collaborative networks. By fostering reproducibility, scalability, and mechanistic understanding, the Rhizo Critical campaign aims to address foundational questions necessary for advancing rhizosphere-driven mineral biogeochemistry in ultramafic soils while ensuring practical applications in areas such as phytomining and sustainable resource recovery.

6.0 Final Outcomes

1. Participants identified major science gaps and challenges related to studying and understanding rhizosphere and ultramafic soil processes in the context of microbial-assisted phytomining and critical mineral and materials biogeochemistry and recovery.
2. The role of EMSL user science community campaigns, specifically the Rhizo-Critical campaign, in addressing these scientific gaps and challenges was emphasized. This includes prioritizing EMSL's advanced approaches, such as integrated imaging, omics, computational modeling capabilities, and the utilization of synthetic soil habitats (TerraForms), as key areas for future investment.
3. Community participants identified the following key science thrusts and early strategic opportunities to demonstrate campaign feasibility and produce impactful scientific outputs:
    - Build mechanistic understanding of how metabolites and microbiomes control Ni uptake and mineral mobilization in hyperaccumulators vs. non-hyperaccumulators.
    - Create integrated field-lab framework with shared reference sites, standardized rhizosphere sampling, and seasonal campaigns.
    - Develop coordinated and standardized workflows using model systems, advanced omics/imaging, and shared data platforms for reproducible, scalable studies.
4. A conceptual framework was established to guide the campaign, detailing collaboration among campaign leads, participants, and EMSL to support multi-scale, multidisciplinary research on critical materials.
5. 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.

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