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LASER ABLATION ICP-MS TRACE ELEMENT MAPPING OF HEAVY METAL DISTRIBUTION IN MINING-IMPACTED SEDIMENTARY ROCKS

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Abstract

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) has emerged as a transformative analytical technique for investigating the spatial distribution of heavy metals in mining-impacted sedimentary rocks. Unlike conventional bulk chemical analyses, which provide only average elemental concentrations, LA-ICP-MS enables high-resolution in-situ mapping of trace elements, preserving the mineralogical and textural context of contamination. This review examines recent advancements in laser ablation technology, aerosol transport systems, mass spectrometric architectures, and quantitative calibration strategies that have significantly improved analytical accuracy and spatial resolution. Special emphasis is placed on the advantages of 193 nm excimer lasers, low-dispersion ablation cells, and time-of-flight ICP-MS systems for rapid multi-element imaging. The study further explores the geochemical mechanisms controlling heavy metal sequestration, including adsorption, mineral substitution, and redox-driven remobilization processes in sedimentary environments affected by mining activities. Emerging computational approaches such as machine learning, dimensionality reduction, and automated mineral classification are also discussed as powerful tools for interpreting high-dimensional elemental datasets. Several case studies from major mining regions, including the Athabasca Basin, Sullivan Mine, and Qaidam Basin, demonstrate the practical applications of LA-ICP-MS in environmental forensics, critical metal recovery, and contamination source apportionment. In addition, developments in three-dimensional voxel mapping and correlative microscopy highlight the growing capability of the technique to investigate subsurface transport pathways and mineral-scale weathering processes. Overall, LA-ICP-MS mapping represents a major advancement in environmental geochemistry, offering unparalleled insight into heavy metal behavior, environmental risk assessment, and sustainable resource management in mining-impacted geological systems.

1. INTRODUCTION

The characterization of heavy metal distribution within sedimentary rocks represents a fundamental challenge in environmental geochemistry and mineral resource geology. Historically, the assessment of mining-impacted landscapes relied heavily on bulk chemical analysis, where entire rock volumes or sediment samples were digested into solution and analyzed via Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Atomic Absorption Spectroscopy (Jarvis, 2021). While these methods provided precise average concentrations, they effectively "erased" the spatial architecture of the sample, obscuring the critical relationships between toxic elements and their mineral hosts (Sylvester & Egins, 2022). In the context of the Anthropocene, where the global production of mining waste now exceeds 100 billion tons per year, the need for spatially resolved data has become acute. Sedimentary rocks, acting as the primary repositories for environmental contaminants, preserve a heterogeneous record of sequestration and mobilization that only in-situ analytical techniques can unlock (Hochella et al., 2019).

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) has emerged as the definitive tool for bridging the gap between microscopic textures and macroscopic chemical signatures. Since its commercialization in the 1980s, the technique has evolved from a tool for simple spot analysis of minerals to a high-speed, high-resolution imaging platform capable of mapping complex geological matrices in two and three dimensions (Van Malderen et al., 2017). The capacity to generate elemental maps visual representations of concentration patterns across a sample surface allows geoscientists to identify the "deportment" of heavy metals, distinguishing whether contaminants are locked in stable crystalline lattices or adsorbed onto reactive, mobile surface coatings. This distinction is critical for predicting the long-term stability of mining legacies and the potential for secondary pollution during environmental shifts such as flooding or acidification (Koschinsky et al., 2020).

2. Technical Foundations of Laser Ablation and Aerosol Generation (

2.1 Laser-Matter Interaction and Wavelength Optimization

The accuracy and spatial resolution of any laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) mapping experiment are fundamentally governed by the physics of the laser-sample interaction. Ablation involves the removal of material from a solid surface via the delivery of a focused, high-energy laser beam. For sedimentary rocks, which often contain diverse mineral assemblages ranging from highly reflective sulfides to transparent carbonates and silicates, the choice of laser wavelength is a primary technical consideration (Woodhead et al., 2007).

Modern mapping protocols predominantly utilize 193 nm ArF excimer lasers. Unlike longer wavelengths such as 266 nm or 213 nm, the 193 nm wavelength operates primarily through a "cold" photo-ablation mechanism, where the high-energy photons break chemical bonds directly rather than relying on thermal melting. This is particularly advantageous for carbonates and other biogenic tissues, which are prone to fracturing and non-stoichiometric sampling under thermal stress (Müller et al., 2009). By producing a finer, more uniform aerosol with particle sizes typically below 100 nm, 193 nm systems significantly reduce the risk of elemental fractionation a process where certain elements are preferentially ablated or transported, leading to analytical bias (Jackson, 2008).

Table 1: Comparison of Laser Wavelength Specifications for Geological Mapping

Laser Specification	193 nm Excimer	213 nm Nd:YAG	266 nm Nd:YAG
Interaction Type	Mostly Photo-ablation	Mixed	Mostly Thermal
Absorption in Carbonates	Excellent	Moderate	Poor
Particle Size Distribution	Mostly Fine (<100 nm	Broad	Coarse
Heat Affected Zone	Minimal	Moderate	Significant
Mapping Suitability	High Resolution	General Use	Qualitative only

2.2 Advanced Aerosol Transport and Cell Dynamics

The transport of the ablated aerosol from the sample chamber to the ICP-MS is a critical link in the imaging chain. Traditional ablation cells were designed for "spot" analysis, where a stable, long-duration signal was preferred. However, for mapping applications, "signal blurring" or "tailing" from these high-dispersion cells causes overlapping signals from adjacent pixels, severely degrading spatial resolution (Gundlach-Graham & Günther, 2016).

The development of low-dispersion or "fast-washout" cells has transformed mapping throughput. These cells utilize optimized internal geometries and dual-volume designs to deliver the aerosol to the mass spectrometer in milliseconds (Wang et al., 2013). For instance, modern aerosol-transport systems can deliver 99% of the total signal intensity from a single laser pulse within approximately 10 ms. This rapid response allows researchers to increase the laser repetition rate (up to 500 Hz) and scanning speed, enabling the mapping of several square millimeters of a thin section in minutes rather than hours (Löhr et al., 2021).

3. Mass Spectrometry and Detection Architectures

3.1 Quadrupole vs. Time-of-Flight Analysis

The choice of mass analyzer determines the scope of the elemental information captured during a mapping run (Huang et al., 2026). Most laboratories currently utilize quadrupole (Q-ICP-MS) systems, which act as mass filters, sequentially scanning through a list of isotopes (Wang et al., 2016). While Q-ICP-MS offers excellent sensitivity and a linear dynamic range spanning up to 10 orders of magnitude, its sequential nature introduces "spectral skew" in mapping (Wälle & Heinrich, 2014). Because the laser is continuously scanning across the sample surface, by the time the quadrupole has finished measuring the last isotope in its list, the laser has moved to a new position, potentially leading to the misinterpretation of elemental associations at the micrometer scale (Gundlach-Graham et al., 2024).

Time-of-flight (TOF-ICP-MS) systems have effectively resolved this issue by providing quasi-simultaneous detection of the entire mass spectrum for every laser pulse. In a TOF analyzer, ions are accelerated into a flight tube where their velocity is inversely proportional to their mass-to-charge ratio. This allows for the capture of full elemental "fingerprints" for every pixel, from ^{7}Li to ^{238}U, at kilohertz rates. This "first measure, then determine" paradigm is particularly valuable in mining studies, where the presence of unexpected trace elements (e.g., rare contaminants or critical by-products) might not be known prior to analysis (Muro et al., 2023).

Table 2: Performance Comparison of Quadrupole and Time-of-Flight Mass Analyzers

Analyzer Parameter	Quadrupole (Q-ICP-MS)	Time-of-Flight (TOF-ICP-MS)
Detection Mode	Sequential (Filtering)	Quasi-Simultaneous
Number of Isotopes	Limited (<20-30 for mapping)	Entire Mass Range (>200)

Mapping Speed	Limited by Dwell Times	Limited by Laser Repetition Rate
Spectral Skew	Present	Absent
Sensitivity for Heavy Masses	Very High	High

3.2 Triple Quadrupole and Interference Removal

In the study of heavy metals such as arsenic (As) and selenium (Se), spectral interferences from plasma gases or matrix elements (40Ar^{35}Cl^{+} on 75As^{+}) can lead to significant errors. Triple quadrupole (ICP-QQQ-MS) systems employ a collision/reaction cell between two quadrupoles to selectively remove these interferences using gases such as He, H_2, or O_2. This technology has become essential for mapping trace levels of contaminants in complex sedimentary matrices where background signals would otherwise mask the true concentration of hazardous species (Bohleber et al., 2023)

4. Quantification Strategies and Matrix Matching

4.1 The Challenge of Inhomogeneous Matrices

Quantification in LA-ICP-MS is inherently more complex than in solution-based analysis due to the matrix-dependent nature of laser ablation. In sedimentary rocks, the ablation yield (the amount of mass removed per pulse) can vary significantly between quartz, clay, and carbonate grains, even when using the same laser settings. Standard Reference Materials (SRMs) produced by the National Institute of Standards and Technology (NIST), such as NIST 610 and 612, are the most widely used calibrants due to their homogeneity and high trace element doping. However, these are synthetic glasses that often fail to replicate the ablation behavior of natural minerals (Gundlach-Graham et al., 2024)

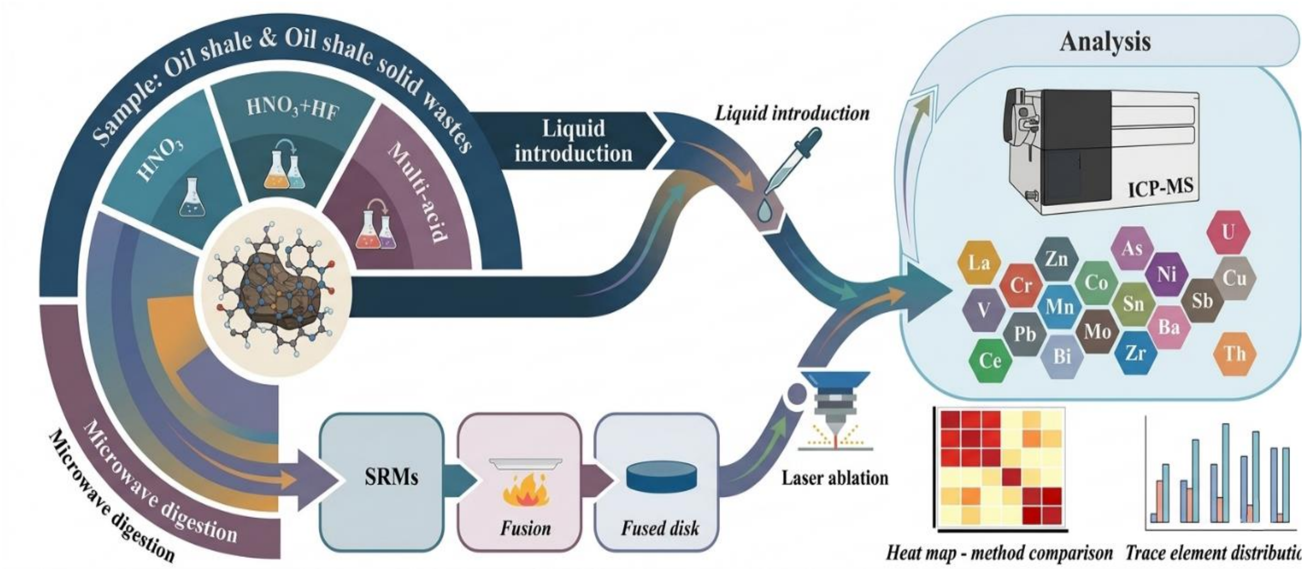

Figure:1 Analytical workflow comparing liquid introduction and laser ablation ICP-MS for trace element determination in oil shale and solid wastes.

4.2 Nano-Pellets and Matrix-Matched Standards

To improve accuracy, the development of "nano-pellets" has emerged as a significant methodological advancement. These standards are created by milling natural minerals (e.g., carbonates, apatite, or magnetite) to a particle size below 100 nm and pressing them into tablets without the use of binders (Bussweiler et al., 2017). This process re-homogenizes natural materials, making them suitable as microanalytical reference materials that closely mimic the sample matrix. Quantitative studies have shown that using matrix-matched nano-pellets can improve the accuracy of trace element determination in carbonates by up to 30% compared to glass-based calibration (Van Malderen et al., 2015).

Table 3: Characteristics and Applications of Common LA-ICP-MS Reference Materials

Standard Category	Example	Best Use Case	Limitations
Synthetic Glass	NIST 612	General trace elements	High matrix mismatch
Fused Rock Powder	USGS BCR-2G	Igneous/Silicate rocks	Limited trace element range
Biogenic Analog	Doped Hydroxyapatite	Teeth and Bone mapping	Specific to phosphates
Mineral Nano-Pellet	Apatite-NP	Matrix-matched mineralogy	High production cost

4.3 Internal Standardization and 100% Mass Normalization

The conventional approach to correcting for ablation yield variations involves using an "internal standard" an element of known concentration (e.g., ^{43}Ca for carbonates or ^{29}Si for silicates) determined independently via electron probe microanalysis (EPMA) or scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS). In multi-phase sedimentary rocks, however, the target element may vary between minerals, making a single internal standard impossible to apply across the whole map (Bussweiler et al., 2017).

A transformative solution implemented in time-of-flight (TOF)-based mapping is the 100 wt% mass normalization approach. This mathematical procedure assumes that the sum of all measured elements (calculated as their common oxide or carbonate forms) must equal 100% of the mass. Because TOF systems capture the entire mass range, including major rock-forming elements such as Ca, Mg, Fe, and Si, this method can correct for ablation rate fluctuations on a pixel-by-pixel basis without prior knowledge of the local concentration of a single internal standard (Bussweiler et al., 2017).

5. Geochemical Mechanisms of Heavy Metal Sequestration

5.1 Adsorption and Surface Complexation

In mining-impacted sediments, the distribution of heavy metals is rarely random; it is dictated by the chemical affinity of specific metals for mineral surfaces. Adsorption onto fine-grained particles, particularly Fe–Al–Mn oxides and clay minerals, is the primary mechanism for removing metals such as Pb, Cd, and Zn from the water column. These minerals offer high specific surface areas and reactive sites for electrostatic attraction and surface complexation reactions. LA-ICP-MS mapping often reveals these metals concentrated in thin coatings on larger detrital grains or within the fine-grained silty matrix of the rock (Wang et al., 2020).

5.2 Substitution and Mineral Inclusion

Over geological timescales, heavy metals may move from surface adsorption sites into more stable mineralogical positions through isomorphous substitution. For instance, arsenic (As) can substitute for sulfur (S) in the lattice of pyrite (FeS_2), while cadmium (Cd) and manganese (Mn) are frequently incorporated into secondary carbonates. LA-ICP-MS mapping allows researchers to visualize these patterns as concentric growth zones or crystallographically controlled enrichments, which are invisible under standard optical microscopy (Burger et al., 2015). In the case of the Sullivan mine, the identification of metals such as bismuth (Bi) and indium (In) within sphalerite and galena lattices has provided crucial data for "deportment" modeling, helping mines manage the recovery of valuable by-products versus toxic "penalty" elements (Liu et al., 2010)

5.3 Redox Sensitivity and Secondary Migration

Sedimentary "sinks" for heavy metals are not permanent reservoirs; they are sensitive to environmental shifts. Heavy metals associated with Fe–Mn oxides can be released back into the environment if reducing conditions develop (e.g., during seasonal flooding or burial), causing the dissolution of the oxide host (Zhu et al., 2024). Conversely, the oxidation of sulfide-bearing mining waste releases H^+ ions and dissolved metals, creating acid mine drainage (AMD). LA-

ICP-MS depth profiling and mapping can track these "weathering fronts" in sedimentary rocks, showing the depletion of primary metals and the subsequent re-precipitation of secondary phases at the boundary layers (Di Fusco, 2026).

6. Computational Geochemistry: From Raw Signals to Insight

6.1 The Software Ecosystem: iolite and XMapTools

The production of quantitative elemental maps involves complex data reduction workflows. Raw LA-ICP-MS data are typically recorded as a continuous time-series of signal intensities (counts per second). Software packages such as iolite utilize "data reduction schemes" (DRS) to synchronize the laser's position log with the mass spectrometer's data stream, correcting for instrumental drift and calculating concentrations based on bracketing standards (Ngerem, 2026).

Advanced tools such as XMapTools have introduced the concept of multi-standard calibration, allowing users to apply different reference materials and internal standards to different parts of an image based on the local mineralogy. This approach is critical for sedimentary rocks, where a single map may contain both silicate and carbonate phases (Fisher et al., 2023).

6.2 Dimensionality Reduction and Unsupervised Learning

As LA-ICP-TOF-MS generates "high-dimensional" data (where each pixel contains hundreds of elemental channels), manual interpretation becomes impractical. Researchers are increasingly turning to Machine Learning (ML) techniques to segment and interpret these datasets (Montes-Atenas, 2022).

- **Uniform Manifold Approximation and Projection (UMAP):** This non-linear dimensionality reduction technique can compress a 100-element TOF dataset into a 2D or 3D embedding. In this embedding, pixels with similar chemical spectra are clustered together, allowing for the automated identification of mineral phases or subtle alteration zones that would be missed by bivariate plots.
- **k-means Clustering:** Often used in conjunction with UMAP, k-means can segment an image into distinct mineralogical "facies" based on trace element signatures. This approach has been used to correct systematic quantification errors of up to 60\% by ensuring that phase-specific calibration is applied to each pixel.
- **Random Forest (RF) Classifiers:** These supervised algorithms have been successfully applied to determine the provenance of minerals or to classify deposit types (e.g., MVT vs. SEDEX) based on the trace element "fingerprints" of minerals like sphalerite (Yang et al., 2016).

7. Case Study Analysis in Mining Environments

7.1 Athabasca Basin: Uranium and Rare Earth Element Mobility

The Athabasca Basin provides a premier example of how LA-ICP-MS mapping can resolve controversies in mineralization models. By mapping "barren" sandstones distal to known high-grade uranium (U) deposits, researchers identified that elevated U and rare earth elements (REE) were hosted within aluminum phosphate sulfate (APS) minerals rather than detrital heavy minerals. The strong correlation among U, REE, Th, and P observed in the maps suggested that these elements were mobilized by basin-wide diagenetic fluids. This mapping provided the first direct evidence that the U and REE in the deposits were leached from the overlying sandstone basin rather than sourced from the basement, significantly altering exploration strategies in the region (Gwimbi et al., 2020).

7.2 Sullivan Mine: Critical Metal Deportment and Geometallurgy

In the past-producing Sullivan Pb-Zn-Ag mine, LA-ICP-MS mapping was used as part of a multi-analytical study to identify the "deportment" of critical companion metals. Mapping revealed that elements like Bismuth (Bi), Germanium (Ge), and Antimony (Sb) were not evenly distributed but were hosted in specific sulfide phases or as micro-inclusions. In was found concentrated in sphalerite, while Sn occurred in both cassiterite and as a trace component in other sulfides. This spatial data is essential for modern "circular economy" mining, where legacy tailings are re-evaluated for critical minerals that were not the primary target during the mine's original operation (Guillong et al., 2003).

7.3 Qaidam Basin: Source Apportionment via Mapping and PMF

Research in the alluvial fans of the Qaidam Basin utilized a massive dataset (over 8,000 samples) and LA-ICP-MS characterization to differentiate between natural and mining-driven heavy metal inputs. By combining mapping with positive matrix factorization (PMF), it was determined that while 39.1% of the metal load was attributable to natural mineralization, industrial and mining activities contributed a further 19.1% and 41.28% in specific river systems. The mapping clearly showed that metals such as Hg and Pb were often associated with atmospheric deposition from smelting activities, appearing as surface enrichments in sediment cores (Leach & Hieftje, 2001).

7.4 Environmental Forensics and Bio-Imaging

The impact of mining-impacted sediments is perhaps most clearly seen in the biological uptake of metals. LA-ICP-MS mapping of deciduous teeth has been used to reconstruct the exposure history of children living near mining sites. Because teeth grow incrementally, they preserve a "chemical calendar" of exposure to metals like Pb and Mn. Similarly, the mapping of fish otoliths (calcium carbonate ear stones) allows for the tracking of fish migration through contaminated water bodies, as the otolith chemistry reflects the water chemistry at the time of growth (Günther & Hattendorf, 2005).

8. The Three-Dimensional Frontier: Depth Profiling and Voxel Mapping

The transition from 2D maps to 3D volumes represents the current "cutting edge" of LA-ICP-MS research. Three-dimensional imaging is achieved by repetitive laser scanning over the same area, with each pass "peeling" away a layer of material (Koch & Günther, 2011).

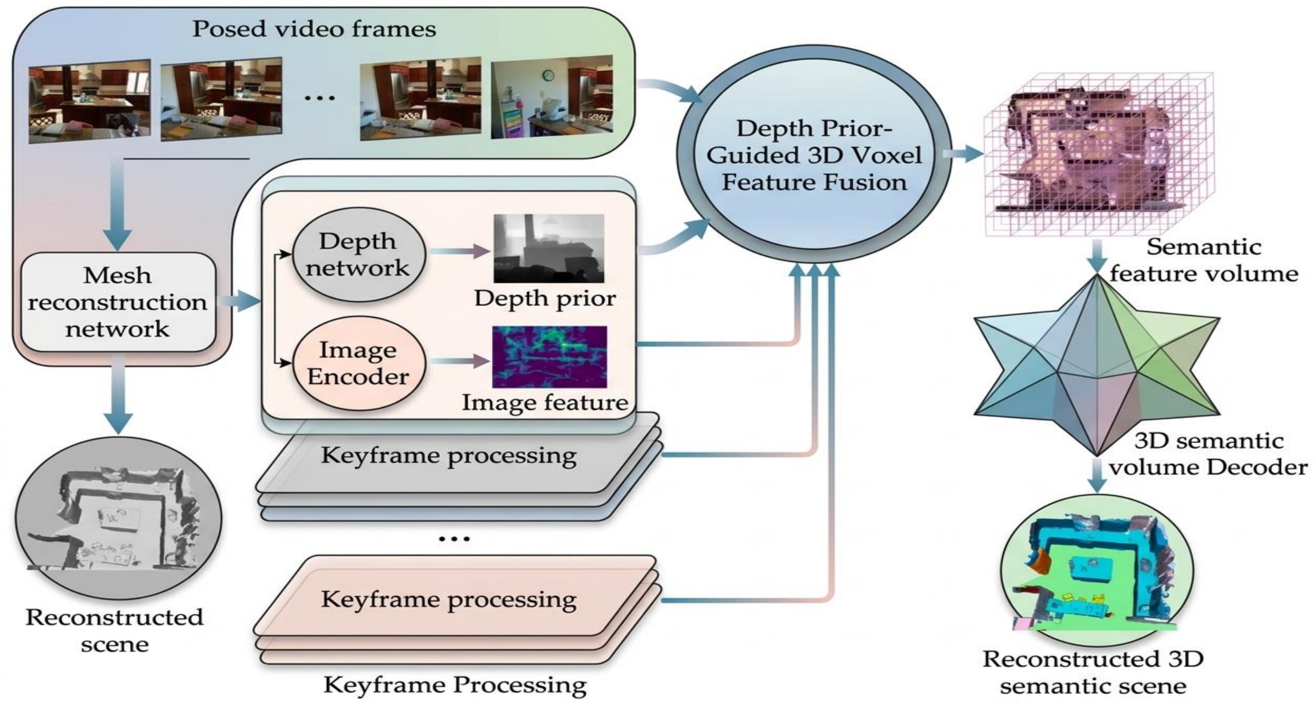

Figure: 2 A Joint Architecture for Depth-Prior-Guided Voxel Fusion and Mesh Reconstruction"

8.1 Voxel Resolution and Depth Assignment

A "voxel" in LA-ICP-MS is defined by the laser spot size (lateral resolution) and the ablation depth per pulse or pass (vertical resolution). Lateral resolutions down to 1–5 µm are achievable with modern lasers, while vertical resolution can be as fine as 300 nm to 3 µm per layer. The primary challenge in three-dimensional mapping of sedimentary rocks is the non-uniform ablation depth; a laser drilling into a soft clay matrix will penetrate deeper than one hitting a hard quartz grain. Advanced numerical inversion methods are now being developed to correct these depth profiles based on the mineralogy identified in the mass spectrum (Reich & Vasconcelos, 2015).

8.2 Applications in Transport and Weathering

3D mapping has been successfully used to study the infiltration of cesium (Cs) into Opalinus clay, a geological material being investigated for nuclear waste storage. The 3D images revealed how the Cs moved through micro-fractures and along specific mineral boundaries, providing a much more accurate model of transport than 2D slices. In mining contexts, 3D mapping of sulfide grains allows for the visualization of "oxidation rinds," showing the volume and depth of metal release during the weathering of mining waste (Hudson-Edwards, 2024).

9. Correlative Microscopy and Integrated Workflows

9.1 SEM-EDS and Mineral Identification

While LA-ICP-MS provides exquisite trace element data, it lacks the crystallographic and morphological information provided by electron microscopy. Correlative imaging workflows involve mapping the same sample area with both Scanning Electron Microscopy (SEM) and LA-ICP-MS. SEM-EDS is used to generate a quantitative mineral map, which is then used as a "template" for the LA-ICP-MS data. This allows for the "phase-resolved" analysis of trace elements, ensuring that as concentrations in pyrite are not mixed with background signals from the surrounding clay matrix (Large et al., 2018).

9.2 The Role of "Mixels" and Deconvolution

In fine-grained sedimentary rocks, the laser spot often overlaps multiple mineral phases, creating "mixels" (mixed pixels). Recent software developments allow for the "quantitative deconvolution" of these mixels, calculating the percentage contribution of each mineral phase to the pixel's total mass spectrum. This enables a deeper understanding of how heavy metals are partitioned between the different constituents of a sedimentary rock, even at the sub-micrometer scale (Balaram et al., 2023).

10. Emerging Trends and the 2026 Outlook

As the field of LA-ICP-MS mapping enters 2026, several key trends are defining the next generation of analytical excellence.

1. **Miniaturization and field deployment:** There is a growing trend toward "handheld" or "mobile" spectroscopy for real-time, on-site analysis of mining sites. While high-resolution LA-ICP-MS remains a laboratory technique, more compact ICP-MS units and portable lasers are narrowing the gap between field screening and lab characterization (Sylvester & Egins, 2022).
2. **Hybrid techniques (LA-ICP-MS + LIBS):** Modern instruments are increasingly being designed as hybrid systems, combining the trace element sensitivity of ICP-MS with the major-element and light-element (e.g., Li, Be, B, C) capabilities of laser-induced breakdown spectroscopy (LIBS). This allows for complete chemical characterization of a rock in a single analytical pass.
3. **AI-driven automated imaging:** Artificial intelligence is transitioning from post-processing to real-time control. Future mapping systems will likely use real-time image analysis to identify rare minerals or phase boundaries during the ablation process, automatically adjusting the scanning resolution to capture more detail in critical areas.
4. **Sustainability in the laboratory:** Environmental awareness is driving the development of "Eco-mode" ICP-MS systems that significantly reduce argon consumption, making high-throughput mapping more sustainable and cost-effective.

5. **Single-cell and nano-mapping:** In environmental studies, the focus is shifting toward how metals interact with individual cells in the rhizosphere (the soil–root interface). Fast time-of-flight (TOF) systems and low-dispersion cells are now capable of mapping metal distributions at the sub-cellular level, clarifying how plants or bacteria sequester metals from mining-impacted sediments (Wang et al., 2013).

11. Technical Synthesis and Strategic Implications

The mapping of heavy metal distribution in mining-impacted sedimentary rocks via LA-ICP-MS has reached a level of maturity that allows for both scientific discovery and practical environmental management. The ability to visualize the spatial deportment of metals provides a definitive advantage over bulk chemical analysis, enabling the identification of stable versus mobile phases. This is the cornerstone of modern environmental forensics, where the source of a pollutant (e.g., geogenic weathering versus anthropogenic discharge) can be identified by the unique trace element and isotopic "fingerprint" of the mineral hosts (Koschinsky et al., 2020).

Furthermore, the integration of Machine Learning and correlative microscopy has transformed the "data deluge" of full-spectrum mapping into actionable insights. By segmenting mineral phases and applying phase-specific quantification, geochemists can now achieve levels of accuracy that were previously impossible in heterogeneous rocks. This has direct implications for the mining industry, particularly in the recovery of critical metals and the management of long-term environmental liabilities (Bussweiler et al., 2017).

Table 4: Strategic Selection of Analytical Techniques for Mining Environmental Assessment

Analytical Goal	Recommended Technique	Key Advantage
Initial Screening	Bulk ICP-MS/XRF	Speed and cost
Phase Identification	SEM-EDS / EPMA	Spatial Resolution
Trace Element Deportment	LA-ICP-TOF-MS	Multi-elemental Spatial Context
Interference Removal	LA-ICP-QQQ-MS	Accuracy for As, Se, Hg
Source Fingerprinting	LA-MC-ICP-MS	Isotopic Precision
Transport Mechanism	3D Voxel Mapping	Depth and Volume Data

12. Conclusion

Laser Ablation ICP-MS mapping has revolutionized the study of heavy metal distribution in mining-impacted sedimentary rocks by providing spatially resolved chemical information that cannot be achieved through conventional bulk analytical methods. The integration of advanced laser systems, rapid aerosol transport technologies, and high-performance mass analyzers has significantly enhanced analytical precision, mapping speed, and multi-element detection capability. In particular, TOF-ICP-MS and triple quadrupole systems have improved the identification of trace contaminants and minimized spectral interferences in complex geological matrices. The review demonstrates that heavy metal sequestration is controlled by complex mineralogical and geochemical interactions, including adsorption onto Fe–Mn oxides, incorporation into sulfide lattices, and remobilization under changing redox conditions. LA-ICP-MS mapping enables direct visualization of these processes, making it an essential tool for environmental forensics, contamination source tracking, and long-term monitoring of mining legacies. Furthermore, the integration of machine learning, correlative microscopy, and three-dimensional voxel imaging has transformed large geochemical datasets into meaningful interpretations of mineral behavior and transport pathways. Emerging developments such as hybrid LA-ICP-MS/LIBS systems, AI-assisted imaging, eco-efficient instrumentation, and nano-scale mapping are expected to further expand the applicability of the technique in both environmental and industrial geoscience. Overall, LA-ICP-MS mapping provides a robust platform for understanding heavy metal mobility, improving environmental risk assessment, supporting sustainable mining practices, and advancing the recovery of critical metals from complex geological materials.

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