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Geochemical Predictive Modeling of Metal Abundance in Seafloor Massive Sulfide Deposits

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Seafloor massive sulfide (SMS) deposits host base, precious, and critical minerals, yet their geochemical variability, including metal abundance, remains poorly understood. This variability is likely influenced by the interplay of tectonic, magmatic, and hydrothermal processes. SMS deposits typically form along mid-ocean ridges, back-arc basins, and volcanic arcs, where hydrothermal activity leads to metal precipitation. Understanding the factors controlling metal enrichment in these environments is essential for advancing deep-sea resource assessment and predictive modeling efforts.

To unravel this complexity, we compiled a global geochemical dataset containing over 2,000 sample analyses from SMS deposits and developed a multi-stage ensemble machine learning (ML) framework to predict the abundance of Co, Au, and Zn in SMS deposits across diverse tectonic settings. Our framework integrates: (1) KMeans++ clustering to identify geochemical groupings driven by key enrichment controls, (2) Random Forest classification to assign geochemical labels for vent fields with incomplete data, and (3) XGBoost regression to produce high-fidelity predictions of metal concentrations.

Our results reveal controlling factors influencing metal enrichment, including spreading rate, vent depth, and host rock composition, while highlighting distinct spatial patterns for Co, Au, and Zn across the sampled SMS systems. For example, our findings suggest Co enrichment is associated with deeper, slow-spreading environments, whereas Au enrichment appears to be linked to host rock compositions and depositional settings.

By integrating a comprehensive geochemical dataset with ensembled ML techniques, this study provides a scalable approach for characterizing the geochemical variability of SMS deposits. The developed ML model enhances the ability to assess and understand the distribution and enrichment processes of critical minerals in marine environments. These findings have direct applications in prospectivity mapping and resource assessments, offering a data-driven approach to predicting metal enrichment in underexplored marine regions.