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Predicting Metal Distributions in Seafloor Massive Sulfides

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Seafloor massive sulfide (SMS) deposits host variable concentrations of base, precious, and critical metals, reflecting complex and non-linear interactions among hydrothermal fluid evolution, host rock composition, tectonic setting, and physical conditions like spreading rate and water depth. This multiscale complexity, combined with uneven sampling of the seafloor, limits conventional statistical approaches and complicates early-stage assessments of SMS resource potential.

We present a scalable, metal-specific, multi-stage ensemble machine learning (ML) framework that integrates a global SMS geochemical dataset. We use a combination of K-Means clustering, Random Forest classification, and XGBoost regression to predict metal concentrations in both measured and unmeasured hydrothermal systems. The framework is designed to capture element-specific enrichment processes by performing clustering independently for each target metal, allowing geological and geochemical controls to vary by element rather than enforcing a single global classification.

The approach is demonstrated for three metals with contrasting geochemical behavior—Zn, Au, and Co. Model results show that Zn displays substantial variability and weaker correlation with first-order geological parameters, consistent with its sensitivity to localized paragenetic processes and temperature-controlled precipitation within hydrothermal chimneys. Gold exhibits the strongest dependence on tectonic setting and host rock composition, with distinct enrichment in arc volcano systems and ultramafic-hosted ridges. In contrast, Co enrichment is primarily governed by depth and spreading rate, with the highest predicted concentrations occurring at deep (≥2,500 m water depth), ultraslow-, slow-, and ultrafast-spreading mid-ocean ridges, consistent with high-temperature conditions that favor Co mobility and incorporation into Fe-sulfides.

Applications of the trained models to hundreds of SMS-relevant vent fields lacking geochemical measurements demonstrate the predictive power and practical utility of this framework for generating first-order estimates of metal abundance. This approach is transferable to additional metals of interest and has direct applications in resource assessments, offering a data-driven approach to predicting metal distribution in underexplored marine regions.