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Integrating Machine Learning and Lead Isotope Analysis for Archaeometallurgical Provenance

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Provenance analysis of ancient metal artefacts is vital for reconstructing past economic behaviours and long-distance exchange, yet traditional lead isotope analysis (LIA) approaches face challenges when discriminating among multiple overlapping ore fields. This study presents a novel archaeometric framework that integrates machine learning techniques with high-precision lead isotope data to enhance the identification of geological sources for Phoenician silver artefacts. Building on an extensive isotopic database of potential metal sources relevant to Phoenician exchange networks, we employed a hybrid analytical strategy combining unsupervised and supervised learning models to improve source discrimination and classification reliability.

Initially, **DBSCAN** clustering was used to detect natural groupings and remove noise within lead isotope ratio space, revealing statistically coherent ore clusters that mitigate ambiguity inherent in visual biplot interpretation. Addressing class imbalance in the reference dataset—where some ore sources are underrepresented—was achieved using **SMOTE** (Synthetic Minority Over-Sampling Technique), enabling the development of more balanced training sets. For formal source assignment, we utilised **XGBoost** (Extreme Gradient Boosting), a gradient-boosted decision tree classifier adept at capturing non-linear relationships among isotope ratios. Cross-validation results indicate robust predictive performance, with high confidence in assigning archaeological silver samples to specific ore clusters.

Applying this machine learning framework to lead isotope data from Phoenician silver hoards demonstrates concordance with established source hypotheses—such as connections to the Iberian Peninsula, Sardinia, and Anatolia—while suggesting nuanced contributions from additional Mediterranean ore provinces. Our results underscore the potential of combining statistical learning with traditional isotope geochemistry to resolve complex provenance questions, advancing the interpretive power of archaeometallurgy. This transparent and scalable methodology thus offers a promising pathway for future studies of ancient exchange systems where multiple source fields and isotopic overlaps complicate conventional analysis.