Computational analysis of lead isotope ratios in artefacts and ores from China: tracing connections, quantifying ambiguity, and rethinking provenance

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Conclusion

6.1 Main outcomes and their implications

6.1.1 Origins and circulation of glass and glazed artifacts

In Chapter 2, four glass disks from the Harvard Arts Museums were examined. The lead in glass disk 1943.50.551 likely originated from provinces Yunnan, Guizhou, Guangdong, or Guangxi and represents a prototypical lead–barium silicate glass of the Warring States Period. Glass disks 1943.50.585 and 1943.50.586 exhibited highly radiogenic isotopes, closely matching lead from Shang Dynasty bronze materials linked to Henan and Sichuan, highlighting the connection to the Sanxingdui and Chu State glass industries. The ring (1943.50.521) differs from Chinese glass and bronze artifacts, with its lead likely originating from deposits in Central China. Evidence supports multiple lead sources for the Warring States glass–making industry, with Southeast Asia sharing common lead reservoirs with regions in southern China.

In Chapter 3, analysis of four lead–glazed objects reveals at least three distinct lead sources. The glaze samples from three artifacts (2006.170.191, 2006.170.197, 2006.170.200) likely originated from provinces Jiangsu, Shaanxi, Fujian, or Shandong, while the glaze from one artifact (2006.170.202) corresponds to lead from Shaanxi, Henan, or South China. Chronological analysis indicates that the bowl (2006.170.191), tripod vessel (2006.170.197), and lamp (2006.170.200) were likely produced in the Western Han Dynasty (202 BCE–8 CE), whereas the incense burner (2006.170.202) aligns with the Eastern Han Dynasty (25–220 CE). A shift in the lead supply network is hypothesized between the Western and Eastern Han Dynasties, where lead glaze and bronze may have shared the same supply network in the Western Han, but lead for glaze production became more independent in the Eastern Han. This study suggests that lead resource movement and transportation capabilities expanded from the Western Han to the Tang Dynasty (618–907 CE), reflecting advancements in long–distance trade.

6.1.2 Methodological contributions of KDE and machine learning

The KDE method was applied in two principal ways. First, it was used to identify correspondences between samples and “lead mining districts” or “lead usage district”, thereby facilitating direct comparisons across spatial and temporal contexts. Second, KDE provided the basis for calculating deposit–level indistinctiveness metrics, which were introduced in Chapter 4. These applications demonstrate the value of KDE not only for interpreting artifacts with unclear provenance but also for explicitly quantifying isotopic overlap and ambiguity.

In addition, clustering techniques such as K–means and hierarchical clustering were explored. In Chapter 4 (Appendix), these methods were applied to group Chinese lead deposits according to their isotopic characteristics, while in Chapter 5 they were used to experiment with artifact groupings. Although these grouping approaches are exploratory, they help visualize structural patterns in the data and illustrate both the potential and the limitations of static classification. Together, KDE, K–means, and hierarchical clustering provide complementary methodological tools that enrich the analysis of lead isotope data and advance the development of more transparent provenance frameworks.

6.1.3 Reevaluating traditional mining source zoning and exploring new lead source groupings

In Chapter 4, analysis of Chinese galena deposits shows that isotopic overlap is pervasive: only about 20% can be considered distinct. This means that the 80% deposits share overlapping isotope signatures with others. Such overlap challenges approaches that rely on simply matching artifacts to deposits within the same region, since deposits in distant regions may exhibit indistinguishable isotopic characteristics.

Moreover, isotopic signatures do not align neatly with ore–forming processes, tectonic settings, or spatial proximity. Geological separation and regional boundaries are therefore not reliable indicators of isotopic distinctiveness. These results highlight the inadequacy of traditional mining source zoning based on geographic or geological categories, and they underscore the need for new frameworks that explicitly address isotopic overlap and ambiguity.

A new zoning approach combines statistical rigor with lead isotopic data distributions, offering a more scientifically grounded and objective method for source classification. While these grouping–based models highlight the complexity of lead resources and demonstrate the potential of statistical approaches, they also suffer from practical limitations: extensive overlaps remain, and the resulting groups are of limited practical use. For this reason, the grouping analysis is presented in the appendix as an exploratory exercise, while the main text emphasizes the Indistinctiveness Index as the more robust framework for provenance research.

6.1.4 Indistinctiveness and a risk–aware framework for provenance

A key methodological outcome in Chapter 4 is the construction of the Indistinctiveness Index, which directly quantifies the degree of isotopic overlap among Chinese lead ore deposits. This framework allows deposits to be compared and ranked in terms of their isotopic ambiguity, enabling more transparent and risk–aware provenance assessments. The demonstrative four–tier risk classification shows how such metrics can be embedded into lead isotope databases to guide archaeological interpretation.

By making ambiguity explicit, measurable, and manageable, the Indistinctiveness Index advances provenance research in two ways. Methodologically, it shifts the focus from rigid groupings to probabilistic assessments of overlap. Archaeologically, it offers a more nuanced and transparent basis for interpreting the sourcing of artifacts, ensuring that uncertainty is recognized rather than obscured. Beyond the Chinese case, this framework has broader applicability to other materials and regions where isotopic overlaps complicate provenance studies.

6.1.5 Rethinking lead isotopes and resource acquisition in ancient societies

In Chapter 5, the role of lead isotopes in Chinese artifacts' provenance research has been redefined, suggesting that they are better understood as "mtDNA" rather than "fingerprints". While the fingerprint metaphor emphasizes uniqueness and exclusivity, the findings of this study reveal the limitations of this analogy. Due to overlapping geological backgrounds and the historical mixing of ores from various sources, many lead isotopic signatures in Chinese deposits and artifacts are not distinct enough for precise, one–to–one identification. Instead, lead isotopes behave more like "mtDNA", indicating broader familial or lineage–based connections among deposits and artifacts.

This study also attempted to generalize artefact groupings based on lead isotopes and showed that although artefacts could be classified into distinct groups, these groupings lacked clear geographical or historical distinctions. Furthermore, they did not directly correspond to natural lead groupings derived from ore deposits. This finding highlights the complexity of lead sourcing in antiquity, where overlapping isotopic characteristics and mixed resource use challenge simple correlations between artefacts and natural deposits. This research challenges the long–standing "Proximity–based Procurement Principle", which assumes that ancient societies primarily acquired resources from the nearest available sources to minimize transportation efforts and costs. Factors such as trade networks, economic or political control, and technological or cultural preferences likely played a more significant role than geographic proximity. The comparison of cultural and natural lead underscores the scale and sophistication of these ancient systems.

6.2 Limitations

6.2.1 Insufficiency of datasets

Lead isotope research heavily relies on the completeness and comprehensiveness of datasets. While this study integrates data from multiple sources, the following deficiencies remain:

1. Limited artifact data and missing archaeological context

   The analyzed artifacts, including glass and glazed ceramics, are museum collections originating from donations and acquisitions. These artifacts lack detailed archaeological background information, such as specific excavation sites, cultural contexts, and precise dating. This absence of contextual data constrains the linkage between isotopic results and the broader archaeological narrative. For example, while certain glass artifacts demonstrate isotopic connections to mineral deposits in central or southern China, the lack of information on their production sites or use contexts hinders further exploration of their technological characteristics or distribution networks.

Additionally, Chapter 3 represents the first lead isotope analysis of Han dynasty glazed ceramics. The scarcity of other Han Dynasty glazed samples with well–documented archaeological contexts limits the understanding of how lead circulation evolved in the glazing industry during this period.

2. Uneven distribution of mineral deposit data

   Although this study compiles lead isotope data from various regions of China, the coverage is uneven. Regions such as Yunnan, Guizhou, and Guangxi have relatively complete datasets, whereas areas like Northwest China and Shandong are underrepresented. This uneven distribution may result in conclusions skewed towards regions with better data coverage, leaving gaps in the broader understanding of lead resource utilization across China.

3. Lack of cross–regional data

   This study focuses on lead resources within China, but the absence of comparative isotopic data from East Asia, Central Asia, and other parts of Eurasia limits its scope. For instance, some glass artifacts exhibit isotopic signatures that potentially correspond to Southeast Asian deposits, but the lack of sufficient data from these regions prevents verification of this hypothesis. The absence of cross–regional datasets constrains the study's ability to contextualize lead circulation within broader interregional trade and cultural exchange networks.

6.2.2 Limitations in analytical techniques

This study employs advanced analytical techniques, including Kernel Density Estimates (KDE), K–means clustering, and hierarchical clustering, to interpret complex isotopic data. However, these methods have inherent limitations:

1. Overlapping lead isotope signatures

   Approximately 80% of lead deposits in China exhibit overlapping isotopic characteristics, which poses a fundamental limitation to isotopic provenancing. While probabilistic classifications (e.g., KDE) can provide tentative groupings, they cannot fully resolve sources with highly similar isotope ratios. Importantly, this issue reflects an inherent overlap in geological signatures, meaning that even the addition of further data cannot necessarily overcome this limitation.

2. Complexity of mixed resources

The historical mixing of ores presents additional challenges. Some artifacts may have been produced using multiple ore sources, resulting in isotopic signatures that reflect combined contributions. This complexity increases the difficulty of analysis, as current techniques cannot accurately quantify the proportions of mixed resources or fully attribute their origins.

6.2.3 Constraints in research scope

This study is geographically focused on China, without fully incorporating cross–regional perspectives that could link Chinese lead networks to Southeast Asia, Central Asia, or Eurasia. The range of artifact types is also limited, as the analysis concentrates on glazed ceramics, glass, and some bronzes, while other materials such as pigments remain unexplored. In addition, although the study maps lead circulation networks, it pays less attention to the social, economic, and political factors, such as state control of mining or the integration of peripheral regions.

6.2.4 Challenges in conceptual frameworks

This study redefines the role of lead isotopes in provenance research by proposing the metaphor of "mtDNA" rather than "fingerprints". The new framework highlights relational and networked aspects of resource use, but it also faces several challenges. The "fingerprin" metaphor remains more familiar and widely accepted in both geochemistry and archaeology, while the "mtDN" analogy may require more explanation, especially in international contexts. Moreover, the framework currently lacks standardized quantitative metrics and remains at a conceptual stage. Its broader applicability will need to be demonstrated through future case studies and systematic testing.

6.3 Future Research

6.3.1 Expansion of the lead isotope database

The expansion of the lead isotope database is essential for advancing research on East Asian archaeology. A key priority is to significantly increase the volume and diversity of data, particularly for glazed materials. Current glaze data especially from the Han dynasty (202 BCE–220 CE) and later periods is notably scarce. This lack of data limits our ability to conduct comprehensive analyses of resource utilization and technological exchange.

It is equally important to diversify the temporal and spatial coverage of the data. While certain well–studied periods and regions have yielded substantial information, many areas remain underrepresented, and chronological gaps persist in the existing records. For example, collecting samples from later periods, such as the Tang (618–907 CE) and Liao dynasties (907–1125 CE). Similarly, expanding sampling efforts to include marginal or less-studied regions will provide critical insights into interregional trade and resource flow.

In addition to artefact data, a critical component of future database expansion lies in incorporating lead isotope information from ore deposits, particularly those associated with ancient mining activities. Although many ore bodies in China exhibit overlapping isotopic signatures, the systematic collection of ore data remains essential. A more comprehensive ore dataset would not only reduce current geographic and chronological gaps but also allow for the probabilistic assessment of provenance through advanced statistical models. Moreover, isotopic data from historically exploited deposits are especially valuable, as they can establish closer links between archaeological artefacts and the geological sources that were actually available in antiquity. Such efforts should therefore combine targeted archaeological surveys with geological prospection, followed by systematic sampling of ores, slags, and related remains, within an interdisciplinary framework involving archaeologists, geologists, and geochemists.

Finally, another important direction for future research is the identification of production sites and the study of the raw materials they employed. Current research lacks sufficient information on the locations and operational details of production centres, such as those for glass and glazed ceramics. To address this, future work should combine archaeological field surveys to identify furnaces, kilns, and associated debris with laboratory analyses of slags, crucibles, and production waste. Isotopic and compositional studies of these materials can then be directly compared with finished artefacts, providing insights into technological choices, raw material procurement, and the organization of ancient manufacturing industries.

6.3.2 Integrating lead isotope analysis into site–based multi–isotope research

Future research could achieve significant advances by integrating multiple isotopic systems within the study of large, well–documented archaeological sites. A single site can serve as a testing ground for cross–material and cross–disciplinary isotope analysis, linking artefacts, environmental samples, and human remains into one comparative framework. Lead isotopes from artefacts such as bronzes, glass, glazes, and pigments can be used to investigate the provenance of raw materials and the circulation of technological resources. At the same site, strontium and oxygen isotopes from human skeletal remains, animal bones, or plant remains may be analysed to reconstruct individual mobility, geographic origins, and dietary patterns. Carbon and nitrogen isotopes further contribute to understanding subsistence strategies and environmental contexts. Bringing these datasets together would allow researchers to examine the degree of correspondence between material supply and human movement. For example, if isotopic analysis reveals that a portion of the population was non–local, while artefact data indicate the use of imported ores or glass recipes, this convergence would provide strong evidence for long–distance trade or migration. Conversely, a mismatch between local human signatures and non–local raw materials could indicate the arrival of goods through exchange networks rather than the movement of people. Multi–isotope integration at the site level has the potential to move research beyond isolated artefact provenancing. Instead, it offers a holistic reconstruction of how technological, social, and economic systems interacted. By situating artefacts, people, and environmental resources in a shared isotopic framework, researchers can map out the extent of activity areas, the scale of resource exploitation, and the breadth of interaction zones.

In this way, comprehensive isotopic studies at major archaeological sites could significantly enhance our understanding of ancient technological organisation, patterns of human mobility, and the reach of cultural and economic exchange.

6.3.3 Increase the use of computer science in isotope archaeology

Future research in isotope archaeology could benefit from a closer integration with computer science.

Machine learning may help identify patterns in isotopic data. It can also be used to explore possible links between provenance, circulation, and migration. For example, clustering algorithms such as K–means might group isotopic signatures into broad regions. Supervised methods like random forests or gradient boosting could be tried to predict the provenance of new samples using reference datasets. These models might also be combined with GIS to show possible transport routes or migration pathways. In addition, time–series data could be used to trace changes in resource use over time.

Deep learning may be used to analyze complex or multimodal datasets. For example, it could combine isotopic evidence with stratigraphic images or textual records. However, this would require large and standardized datasets, as well as substantial computational resources.

At the same time, big data technologies may help manage increasingly diverse archaeological datasets. These include isotopes, ancient DNA, geospatial information, and artefact imagery. Such tools can support comparative studies at both micro and macro scales.

These approaches face challenges, such as data quality, interpretability, and accessibility. Even so, with interdisciplinary collaboration and investment in data infrastructure, they could become powerful tools for advancing our understanding of resource use and human interaction in the past.

6.3.4 Advancing archaeological theory for lead isotope studies

Future research could also focus on developing stronger theoretical frameworks to interpret the patterns revealed by isotopic analysis. In this dissertation, concepts such as lead connections, the mtDNA metaphor, lead families, and object biographies have been used to interpret the findings. These perspectives move beyond a simple question of “where does it come from?” and begin to frame isotopic data as evidence for social interaction, technological traditions, and cultural choices.

Yet important questions remain: if isotopic similarities suggest that artefacts are related, what kinds of relationships do they represent? Do they point to shared knowledge about technology, being part of the same exchange network, the same political control of resources, or is it just a coincidence that the isotopic characteristics of lead sources are indistinguishable? Answering such questions requires theoretical approaches that can bridge the gap between scientific signals and historical meaning.

Future work could therefore draw more explicitly on frameworks such as network theory, which models artefacts and deposits as nodes within dynamic systems of exchange; biography approaches, which situate materials within long–lived social trajectories. Comparative studies could test these frameworks across different materials, such as bronze, glass, glaze, and pigments. They could also extend across regions and time periods. Such work would trace how isotopic connections relate to technological and cultural histories. In this way, the study of isotopic data will not only identify potential sources and artefact connections but also explain how these connections reflect broader systems of economy, politics, and culture.