



HAL
open science

Technological trajectories in iron smelting: slag signatures, recipes, and traditions from Phnom Dek (Cambodia, 7th–20th c. CE)

Stéphanie Leroy, Mitch Hendrickson, Enrique Vega, Quan Hua, Kaseka Phon

► To cite this version:

Stéphanie Leroy, Mitch Hendrickson, Enrique Vega, Quan Hua, Kaseka Phon. Technological trajectories in iron smelting: slag signatures, recipes, and traditions from Phnom Dek (Cambodia, 7th–20th c. CE). *Journal of Archaeological Method and Theory*, 2025, 33 (11), <10.1007/s10816-025-09740-6>. <hal-05226953>

HAL Id: hal-05226953

<https://hal.science/hal-05226953v1>

Submitted on 31 Oct 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

Technological Trajectories in Iron Smelting: Slag Signatures, Recipes, and Traditions from Phnom Dek (Cambodia, 7th–20th c. CE)

Stéphanie Leroy¹ · Mitch Hendrickson² · Enrique Vega¹ · Quan Hua^{3,4} · Kaseka Phon⁵

Manuscript

Abstract

This study investigates the long-term dynamics of bloomery iron smelting practices across the Phnom Dek region of Cambodia, a major metallurgical landscape active from at least the 7th to 20th centuries CE. Based on pXRF analysis of more than 1,700 slag samples, it develops an interpretive framework that integrates multiple scales of evidence, combining chemical composition, spatial distribution, technical features, and chronological context. At the core of this approach is the identification of coherent chemical signatures in slag, which, by using multivariate analyses, function as proxies for metallurgical recipes, and, at a broader level, enduring technological traditions shaped by the social organization of production. These signatures serve as comparative units for tracing production behaviors across sites time periods. Through the categories of practice and recipe, the analysis aims to identify patterns of continuity, adaptation, and transformation in iron-making processes or smelting behavior over time. Results point to significant changes in ore procurement and recipe during the 11th–12th centuries, likely linked to wider transformations within Angkorian state dynamics. The persistence of specific chemical profiles and regionally shared smelting practices beyond this period suggests a bloomery tradition sustained across the landscape. Ultimately, the study argues that the chemistry of slag, as a material trace of smelting activities derived from technical, spatial, and chronological contexts, has unique capabilities to acquire interpretive significance when analyzed across these dimensions. This approach enables the discussion of technological trajectories in iron production and the socio-technical logics that shaped the evolution of the Phnom Dek metallurgical landscape.

Keywords Bloomery ironmaking · Smelting practices · Recipes · Traditions · Slag · pXRF · Chemical variability

Introduction

Recent studies on ferrous metallurgical activities in Cambodia have substantially enriched our understanding of primary iron production and its integration into the distribution networks that supported the Khmer Empire, the dominant political entity in mainland Southeast Asia between the 9th and 13th centuries. One important outcome of this research is the identification of large-scale smelting operations through archaeological surveys, excavations, and spatial and technical analyses of metallurgical remains. In particular, investigations around Phnom Dek (“Iron Mountain”), located approximately 100 km east of Angkor in central Cambodia, have revealed a dense and extensive concentration of iron smelting activities, indicative of long-term bloomery activities that persisted into the mid-20th century (Dupaigne, 2016; Hendrickson *et al.*, 2017, 2018; Pryce *et al.*, 2014). Provenance studies have shown that from the 11th century onward, Phnom Dek deposit emerged as the principal source of iron for Angkor, sustaining the empire’s expansion and increasing demand for metal resources (Hendrickson & Leroy, 2020). Analyses of iron objects, particularly architectural clamps (see examples in Fig. 1), reveal compositional variability that suggests changes in production techniques, raw material inputs, and the operational organization within the chaîne opératoire (Leroy *et al.*, 2017; Leroy & Hendrickson, *in press*).

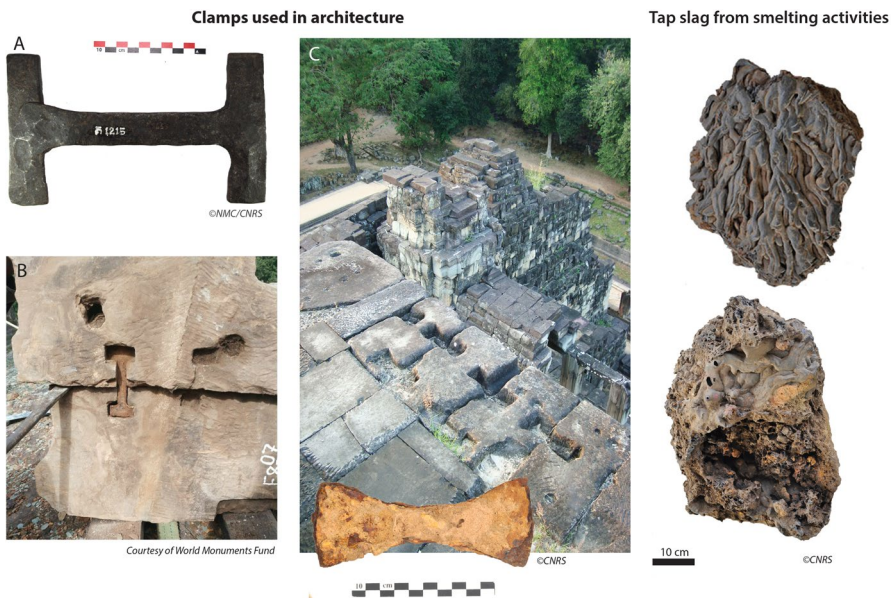


Fig. 1 (Left) Examples of iron clamps used in Angkorian architecture and studied in IRANGKOR project. **A.** Clamp recovered from Angkor Wat (National Museum of Cambodia collection). **B.** Clamp between sandstone blocks of the Phnom Bakheng temple (WMF/APSARA restoration work). **C.** Clamp and corresponding imprints indicating their original placement in the Baphuon temple (EFEO restoration work). (Right) Tap slag from iron smelting activities in the Phnom Dek region

Such transformations, whether technical or organizational, are likely linked to broader dynamics of adaptation to evolving metal needs within the empire, including intensified agricultural production and the changes to sandstone as a construction material after the 11th century (Hendrickson & Leroy, 2020).

Understanding the mechanisms that have shaped metallurgical practices—including the organization of production, resource networks, the transmission of technical knowledge, and the interactions between producers and consumers—is essential for unraveling iron production technologies. While many studies have focused on individual sites or short-term production phases, adopting a broader spatial and temporal perspective is necessary to fully appreciate the complexity and developmental trajectories of bloomery systems. Expanding the scale of analysis allows for a more comprehensive examination of the links between iron-making processes and the social, economic, and political structures in which they were embedded (Iles, 2018; Robion-Brunner *et al.*, 2013, 2022). This regional approach facilitates the study of continuity, change or transformation of practices over space and time, both within and between communities sharing common traditions (Wenger, 1998).

This paper presents an analytical framework for examining the organization and evolution of iron-smelting practices over the long term, through the analysis of chemical variability and slag assemblages variation. Additionally, from a broader interpretive perspective, it aims to investigate the technological relationships, production behaviors, and social dynamics that structured iron-smelting activities within the Phnom Dek landscape. While it does not directly address the social roles or identities of iron producers, it provides a basis for exploring these questions by identifying patterns of continuity and change in production practices, behaviors, and their spatial organization across the region. More broadly, it contributes to understanding how metallurgical knowledge was transmitted, adapted, and embedded within regional communities of practice and production systems (Iles, 2014, 2018). In this perspective, slag is not regarded solely as a by-product of smelting, but as a “material archive” that records the technical choices and transformation processes through which metallic iron was obtained (Fig. 1). Its chemical composition serves as a proxy for reconstructing the combinations of materials and operational conditions that defined specific production behaviors. These configurations are referred as metallurgical ‘recipes’ defined by Charlton *et al.*, (2010, p.234), as the ‘specific resources and methods employed to produce a particular alloy’.

To guide interpretation within this framework, we propose three heuristic categories—*practices*, *recipes*, and *traditions*—which represent distinct but complementary analytical scales. *Practices* refer to localized smelting events, expressed through specific arrangements of materials and technical choices. *Recipes* denote repeatable configurations that produce consistent chemical outcomes. *Traditions* refer to long-term continuities in smelting knowledge and practice, where core technical principles and cultural norms are maintained, adapted, and transmitted across generations and between groups of metallurgists involved in iron production. The chemical dataset underpinning this study derives from pXRF analysis of 1,714 slag samples collected across multiple sites. These data are interpreted through a cross-scalar framework that integrates spatial distribution, chronological sequence, and technical attributes. By identifying coherent chemical groups or “signatures” and situating

them within their archaeological and historical contexts, we reconstruct patterns of smelting activity and investigate the operational logics that structured the regional metallurgical organization.

Ultimately, this study proposes an interpretive model that uses slag chemistry to trace continuities, changes, and shifts in iron-smelting practices. These patterns are understood as expressions of broader technological behaviors shaped by resource availability, technical choices, and historical dynamics. Beyond documenting chemical traits, the aim is to establish a comparative framework for formulating hypotheses about the organization, adaptation, and transmission of iron-making and technical knowledge. Anchoring chemical signatures within their environmental, spatial, and cultural contexts, this approach contributes to a historically grounded narrative of iron technologies in the Phnom Dek region, and lays the groundwork for exploring social organization and interaction patterns. While direct evidence from settlement sites remains limited, and their study is indispensable for a comprehensive understanding of the metallurgical landscape and the identity of the communities involved, the spatial and chronological organization of production, together with indirect links to consumption, provides valuable preliminary insights into the social context of metallurgical activity.

Linking Chemical Variability to Production Behavior

The chemical composition of archaeological artifacts, whether in metal, ceramics, glass, lithics, or pigments, results from a combination of factors, including the properties of the raw materials, the technical elements, and broader functional or cultural constraints (e.g., Amicone *et al.*, 2019; Charlton *et al.*, 2010; Costin, 1991, 2001, p.286-303; Freestone, 2023; Freestone *et al.*, 2015; Lankton *et al.*, 2022; Lebon *et al.*, 2019; Martínón-Torres *et al.*, 2014). In metallurgy, this complexity is particularly evident in slag, whose chemical compositions reflects both the types of resources involved and the transformation conditions under which they were processed, factors that are embedded within broader production systems and specific technological environments. Comparative analysis of slag composition has become a key strategy for identifying recurring patterns in resource use, operational behavior, and metallurgical traditions. Such comparisons are based on the principle that chemical similarities and differences express structured patterns of practice and can serve as proxies for reconstructing aspects of technological organization and production dynamics (Chirikure & Bandama, 2014; Humphris *et al.*, 2009; Martínón-Torres *et al.*, 2014; Morel *et al.*, 2025; Pryce *et al.*, 2010; Rehren *et al.*, 2007; Walmsley *et al.*, 2020). In this framework, chemical patterning is not considered an end in itself but a material expression of technological behavior shaped by historical context, resource availability, and socially embedded technical practices.

To be analytically meaningful, however, compositional data must be interpreted in context. Several studies have emphasized the importance of defining robust interpretative units within the archaeological record—units that not only capture chemical variability but also reflect historically and technically relevant aspects of production behavior (Arnold, 2000; Costin, 1991; Humphris *et al.*,

2009; Pryce *et al.*, 2024; Cadet *et al.*, 2024; see also refs. in Martín-Torres *et al.*, 2014). Most compositional research focuses on assemblages rather than individual samples, allowing for more structured and comparative analyses across diverse production contexts (Costin, 2001; Martín-Torres *et al.*, 2014; Rademakers & Rehren, 2016). At this scale, it becomes possible to identify ‘chemical environments’ associated with particular resource use and operational conditions. To address the complexity of these datasets, characterized by multiple variables and large sample sets, multivariate statistical methods are generally used to explore the relationships among chemical data (*e.g.*, Celauro *et al.*, 2014; Liu & Pollard, 2022; Tomczyk & Żabiński, 2024; see also refs. in Tomczyk & Żabiński, 2024). In this context, descriptive tools such as principal component analysis (PCA) and Agglomerative Hierarchical Clustering (AHC) are most often applied to detect structures within datasets, with particular attention to reading patterns of continuity and discontinuity across data groups. However, assemblages are not explicitly used as analytical units that integrate chemical variation with spatial and historical information, despite their potential to improve interpretations of production behavior.

Production behavior itself is shaped by a range of cultural mechanisms, including the reproduction of technical traits, functional selection, adaptive adjustments, socio-economic transformations, independent experimentation, and even invention. These processes emerge through interaction, exchange, and the transmission of manufacturing knowledge, both within and between communities of practice (Charlton *et al.*, 2010; Chirikure *et al.*, 2023; Iles, 2018; Roux, 2013, 2015). They may also be influenced by external factors such as cultural interactions or the adoption of traits from external sources. In metallurgy, production practices are closely tied to the availability and properties of raw materials. The dynamics of iron production that are conditioned by technical factors, environmental constraints, or cultural interactions directly affect the chemical composition of both metal objects and production residues. Slag is particularly informative, as its chemical composition reflects operational parameters. However, interpretation remains challenging due to the interplay of technical, environmental, and cultural variables. Establishing a direct connection between slag chemistry and the cultural dynamics that shaped it remains a core methodological challenge.

Moreover, production behavior extends beyond individual sites and the spread of specific knowledge systems at regional scales can be influenced and/or modified by diverse social and cultural factors. Archaeological materials preserve these dynamics, but interpreting them effectively requires considering how new stimuli and choices affect chemical composition and complicate the identification of coherent production practices. Addressing this challenge requires attention to analytical scale, from individual workshops to broader regional traditions (Costin, 2001). Smelting processes and practices directly influence the chemical composition of slag, which records the diversity of technical behaviors operating across time and space. This variability can be observed at multiple levels from individual samples to assemblages to broader cultural categories such as recipes or traditions. As data volume increases, analytical complexity also rises, capturing wider underlying variations in technological practice.

From a methodological perspective, two main challenges arise when dealing with large, multi-scalar datasets. The first is to establish an analytical framework grounded in the archaeological record that accounts for the key factors shaping chemical variability: namely cultural mechanisms (*e.g.*, practices, traditions), spatial dynamics (*e.g.*, resource access, distribution) including the mineralogical diversity of available resources, and temporal depth (diachronic evolution). The second challenge is to clarify the relationships between chemical environments, including their connections to production behavior and ore selection. Meeting these challenges requires an observational approach that defines a chemical metric for analyzing assemblages within a statistical framework, while integrating spatial and chronological variables. Defining a consistent analytical unit, at the intersection of chemistry, space, and time, enables systematic exploration of how production behaviors unfolded and evolved. To better understand the dynamics of iron metallurgy, we advocate expanding the scale of sampling and refining interpretive steps. Before addressing chemical variability across the landscape, however, it is essential to review the properties of slag, its chemistry, and the fundamentals of iron smelting practice.

Interpreting Iron-making Behaviors through Slag Chemistry: Challenges and Insights

Slag as an Archaeological Trace of Bloomery Smelting

Investigations into bloomery ironmaking rely heavily on the interpretation of slags for two primary reasons (Bachmann, 1982; Humphris *et al.*, 2009; Miller & Killick, 2004; Morel *et al.*, 2025; Rehren *et al.*, 2007; Serneels, 1993). First, slag is the primary by-product and the most frequently encountered trace of ore processing. Slags are therefore essential for investigating metallurgical production. Second, because of its composite formation, slag preserves valuable clues about the components and conditions of the smelting system—many of which are no longer visible in the archaeological record. The mineralogical and chemical characteristics of slag are determined by the nature of the input materials involved (*e.g.*, clay, ore, charcoal) and the operational parameters (*e.g.*, furnace construction, air supply), all embedded within broader technological frameworks. As such, these characteristics can serve as ‘identity markers’ of metallurgical practice. Compared to mineralogical analysis, chemical composition offers a particularly effective means for inter-site and inter-object comparisons (particularly when investigating slag, ore, or slag inclusions) within a shared analytical framework. While mineralogical data are crucial for reconstructing local operating conditions, chemical analysis is more appropriate for large-scale comparisons and exploring patterns of technical variability across sites. For these reasons, chemical composition was prioritized in this study.

Chemical markers in slag reflect multiple factors: the nature of the resources, the contribution of non-refractory materials from technical elements (*e.g.*, furnace walls, tuyères), and technical actions of the smelters, such as the addition of fluxes (see Buchwald & Wivel, 1998; Coustures *et al.*, 2003; Desaulty *et*

al., 2009; Hørst-Madsen & Buchwald, 1999; Leroy *et al.*, 2012; Miller & Killick, 2004; Paynter, 2006). Slag composition is also influenced by furnace temperature and redox conditions, which are determined by furnace design, air supply mechanisms and fuel-to-ore ratios (*e.g.*, Charlton, 2009; Charlton *et al.*, 2010; Rehren *et al.*, 2007; Rostoker & Bronson, 1990; Veldhuijzen & Rehren., 2007). These factors leave measurable traces in the thermochemical profile of the furnace, some of which can be approached through the Reducible Iron Index (RII) calculated as: $RII = (2.39 * \text{wt}\% \text{ SiO}_2) / (\text{wt}\% \text{ FeO} + \text{wt}\% \text{ MnO})$ (Charlton *et al.*, 2010). This empirical index expresses the proportion of gangue minerals (primarily silica) relative to reducible iron oxides in the slag, providing an indirect proxy for both ore quality and the degree of metal-slag separation. Through the combined analysis of elemental concentrations and RII values, it becomes possible to reconstruct the chemical fingerprint of bloomery ironmaking. These chemical traits offer a framework for identifying specificities in metallurgical configurations, whether at the scale of a recipe (Charlton, 2009; Charlton *et al.*, 2010) or as part of broader metallurgical traditions. The comparison of these profiles makes it possible to explore variations in smelting behavior, from short-term operational adjustments to long-term transformations shaped by environmental, technical, or cultural factors at the regional scale.

The selection of analytical techniques used to study slag chemistry is critical for determining the level of detail and the specific chemical properties measured, ranging from major to trace elements (Mikulec *et al.*, 2022; Miller & Killick, 2004; Piatak & Seal, 2012). While laboratory-based methods (*e.g.*, SEM–EDS, ICP–MS) provide highly precise data, they often require lengthy sample preparation, are costly, and offer limited accessibility, factors that restrict their use in large-scale metallurgical studies. In this context, portable X-ray fluorescence (pXRF), despite inherent limitations in precision and cross-comparability with other analytical techniques, offers a promising alternative for generating extensive datasets directly in the field (Scott *et al.*, 2016; Speakman & Steven Shackley, 2013; Vega *et al.*, 2019).

Defining Chemical Signatures as Units of Analysis

Metallurgical slag produced during smelting events is commonly categorized into two categories: furnace (or internal) slag and tap (or external) slag. In smelting traditions that involve tapping technology, tap slag is often preferred for chemical analyses because of its relatively homogeneous composition, which allows for clearer identification of chemical variation related to smelting practices (Charlton, 2009; Humphris *et al.*, 2009; Paynter, 2006; Vega *et al.*, 2019; Young *et al.*, 2012). This compositional consistency supports the aggregation of slag data across various archaeological contexts, whether individual tappings, stratified successive tappings, or broader site-level accumulations, enabling the construction of chemical profiles that are associated with production configurations. These profiles, which we refer to as “signatures”, are defined by statistical descriptors such as central tendencies and dispersion. When interpreted within their archaeological context, they can serve as analytical proxies for ironmaking processes at different levels of metallurgical production, such as smelting episodes, practices, recipes, or traditions. The

link between slag chemistry and smelting recipes was first formalized by Charlton *et al.* (2010), who emphasized that chemical patterns observed at the site level could reflect coherent operational choices. However, slag from a single site cannot be assumed to represent a “single unchanging technological endeavor” (Charlton *et al.*, 2010; Heimann *et al.*, 2001; Humphris *et al.*, 2009; Morton *et al.*, 1972; Vega *et al.*, 2019). It is therefore essential to define meaningful archaeological units that account for both compositional coherence and historical or operational significance. Ideally, this involves slag from a single stratigraphic layer, since entire slag mounds often result from multiple, unrelated smelting events. Previous studies have shown the potential of comparing stratified chemical data within slag mounds using descriptive statistical tools such as PCA, treating the archaeological layer as the structuring unit of interpretation. While this approach is effective for tracking diachronic variability at the workshop scale, it remains limited to local and short-term dynamics and is not readily extendable to inter-site or regional comparisons.

To extend this framework, our study proposes a more integrative approach to addressing broader spatial and temporal dynamics. Establishing meaningful links between chemical ‘signatures’, smelting ‘recipes,’ and metallurgical ‘traditions’ requires interpreting chemical variability through the lens of operational, cultural, and environmental contexts. Rather than viewing recipes as static entities, we consider them as dynamic configurations shaped by evolving conditions and decisions. Chemical variability thus gains analytical relevance only when interpreted in conjunction with archaeological context, resource use, technical agency, and processes of cultural transmission. This practical fluidity calls for a nuanced reading of variability, ranging from workshop-level operational logics to broader trajectories of regional metallurgical production. To support this perspective, we developed a model that enables exploration of both the spatial distribution and temporal dynamics of smelting practices. From the fieldwork stage onward, our approach seeks to ground chemical patterns within their archaeological contexts, ensuring that each unit of analysis reflects not only compositional coherence, but also operational and cultural significance.

Comparing Assemblages: A Relational Approach to Chemical Variation

Addressing chemical variability requires treating data sets as inherently heterogeneous. This involves defining a statistical unit explicitly anchored in historical contexts, namely the chemical signature at the scale of the smelting mound. Such a signature, based on the chemical composition of an archaeological assemblage, represents an *a priori* structuring hypothesis integrated into the statistical analysis. Comparing these signatures supports the construction of a general chemical network, which is crucial for identifying relationships between archaeological assemblages and accounting for the underlying dynamics of production. In this context, the chemical network must be interpreted in its spatial and temporal dimensions, in connection with ironmaking variables, such as raw material selection, technical choices, and the nature of the metal produced (*e.g.*, quality, intended type). Building on a broader theoretical framework of production systems (Costin, 2001), which

has been echoed in the context of iron metallurgy (e.g., Charlton, 2009; Chirikure & Bandama, 2014; Mathoho *et al.*, 2016; Rehren *et al.*, 2007), recurrent patterns and trends can be used to refine our understanding of metallurgical variability. This involves relating the chemical clusters or trends to other archaeological evidence, such as technical attributes or chronological data, to better grasp inter-sites relationships and cultural dynamics. Doing so requires a multidimensional analytical strategy. The effectiveness of such analysis depends heavily on data quality: issues such as uncertainty, missing values, and measurement inconsistencies must be carefully addressed (Batton-Hubert *et al.*, 2019), alongside questions of statistical homogeneity and representativeness (Benzécri, 1973a, b).

By integrating time, space, and human agency, this multiscalar approach examines how ironmaking practices emerge at the site level and connect with broader patterns across the metallurgical landscape. Rather than isolating production events, it places them within technological trajectories and regional dynamics. It also provides a structured framework for reading chemical variability not merely as a technical process, but as a potential reflection of broader patterns of similarity and difference across smelting communities. While chemical analysis alone cannot fully account for social or cultural processes, the patterns it reveals—when interpreted in their archaeological context—can serve as entry points for exploring hypotheses related to technological transmission, external interaction, or the organization of production (Charlton, 2009; Charlton *et al.*, 2010; Chirikure & Bandama, 2014; Iles, 2018; Martínón-Torres, 2023).

A Multiscale Framework for Comparative Analysis

Analytical Framework: Practices, Recipes, and Traditions

We adopt the categories of *process*, *practice*, *recipe*, and *tradition* as complementary analytical scales of metallurgical activities. In this framework, the *process* refers to the general method of bloomery iron smelting, encompassing the techniques involved. A *practice* denotes the context-specific enactment of this process, shaped by specific resources conditions and operational choices. *Recipes* are recurring patterns of inputs and parameters yielding consistent metallurgical results, identifiable in slag composition and metallic outcomes. These likely arise from learning, transmission, or standardization. A *tradition* represents a historically sustained configuration where practices and recipes are stabilized, transmitted, and adapted over time. It is defined by enduring consistencies in technical behavior despite variations in materials or furnace design. Tradition is thus a historically contingent form of technical knowledge shaped by transmission, adaptation, and collective experience and anchored in recognizable material outcomes. Innovation may arise within localized practices and, when repeated and proven effective, become integrated into recipes. Over time, these recipes can be absorbed into traditions, which serve as dynamic frameworks where technical knowledge is continuously reinterpreted and sustained.

These categories serve as heuristic tools rather than fixed classifications. The degree of chemical variability linked to each category is inferred from data.

Chemical signatures here are empirical groupings based on compositional coherence among slag samples, while their association with entities like ‘recipe’ or ‘tradition’ remains conceptual, organizing observations into historical hypotheses discernible through patterns of continuity and coherence over time and space. Tradition reflects a historical trajectory embedded in broader socio-technical contexts rather than technical uniformity. Although centered on archaeometallurgical data, this framework acknowledges that social context, including relational, organizational, and cultural dimensions, both shapes and is shaped by metallurgical practices in a dynamic, reciprocal process. Spatial distribution, chronological sequences, and material patterns offer indirect insight into these social dynamics, enabling hypotheses about community interactions, knowledge transmission, and economic roles. This approach places the metallurgical evidence within the broader dynamics of past social organization, even without direct evidence from settlement sites. By integrating chemical composition, technical traits, spatial distribution, and chronology dimensions, which reflect both technological and social factors, this framework identifies patterns from gradual change to rupture. It links chemical variability to hypotheses on the organization, transmission, and transformation of metallurgical practices without imposing fixed cultural identities. This approach is operationalized as follows (Fig. 2):

- *Defining a Metallurgical Practice:* Slags from a defined archaeological unit (e.g., a stratigraphic layer or synchronous slag mound) provide a chemical signature reflecting a coherent smelting process interpreted here as a metallurgical practice at the site level. While this signature may relate to a broader recipe or tradition, it forms the primary unit of inter-site comparison.
- *Comparing Assemblages Across the Landscape:* Once defined, these chemical signatures are used as statistical units for comparison. Their internal variability and expected ranges guide multivariate analyses. Techniques such as Bayesian analysis and Linear Discriminant Analysis (LDA) allow for the comparison of different units (prior groups) across the landscape. In the absence of a fully defined probabilistic model for chemical dispersion that would support Bayesian

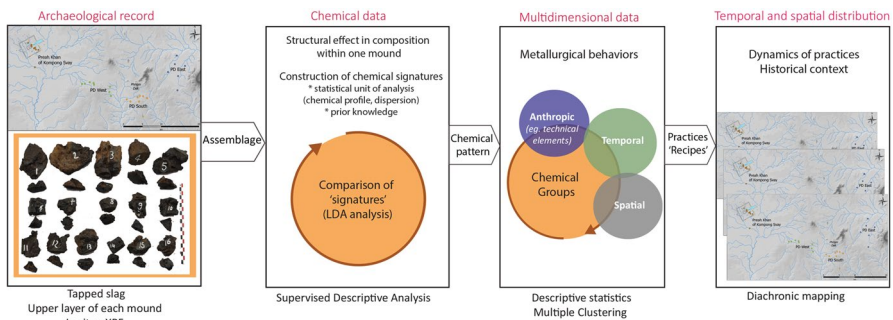


Fig. 2 A methodological approach comparing the chemistry of archaeological assemblages and multidimensional data analysis to identify metallurgical groups, evolution of smelting practices across multiple sites, and explore dynamics over time

inference, LDA is employed here as a descriptive method to explore variation across sites.

- *Identifying Groups*: Patterns in chemical relationships help delineate distinct groups, which may correspond to different practices, recipes, or traditions. Principal Component Analysis (PCA) and other exploratory methods help visualize these relationships. Recurring signatures across sites suggest the repeated application of similar recipes, understood as inferred operational logics rather than predetermined typologies.
- *Contextualizing Metallurgical Behaviors*: Chemically defined groups are then interpreted in relation to spatial, chronological, and cultural factors. By integrating chemical and non-chemical variables via multimodal clustering or correspondence analysis, we relate compositional traits to operational choices, smelting conditions, or cultural norms. This cross-analysis links technical behaviors embedded in the metallurgical process to broader archaeological and historical frameworks.
- *Exploring Spatial and Temporal Dynamics*: The distribution of these groups over time and space reveals trajectories of continuity, adaptation, or rupture. in technical behavior over time, which may reflect responses to evolving resource landscapes, social structures, or transmission networks

A key strength of this framework is its ability to address broad spatial and temporal scales, enabling the integration of diverse metallurgical trajectories. Rooted in anthropological perspectives, it situates chemical analysis as a means to explore the relationship between technological variability and social dynamics in past iron production systems (Chirikure & Bandama, 2014).

Data Collection and Analytical Procedures

For this study, the archaeological assemblage consists of slag collected from the uppermost layer of each slag mound, interpreted as the final phase of production. Particular care was taken to exclude slag likely displaced post-depositionally, such as those found at mound edges or resulting from collapsed slopes. While excavating every slag mound stratigraphically would of course be ideal, practical field constraints and site conditions make this impossible. In this context, systematic surface sampling remains the most realistic and effective approach. Surface cleaning and contextual assessment guided the selection of slag representative of the uppermost coherent layer of each mound. In accordance with our methodological requirements, a sufficient number of samples was collected to ensure representativity and account for internal compositional variability for each assemblage. This approach is validated by subsequent chemical analyses, which reveal intra-assemblage heterogeneity consistent with stratigraphic coherence. Chemical signatures are defined using oxide ratios and empirical indices of smelting conditions (e.g., RII). Although such compositional analyses are traditionally performed in laboratories, pXRF was chosen as a practical tool to facilitate broad comparative studies and enable scalable investigations of production dynamics across large spatial and temporal ranges (Scott *et al.*, 2016; Vega *et al.*, 2019).

We argue that acquiring data from a large number of samples, which is a central premise of our approach, helps mitigate resolution issues noted in previous studies and highlights relevant compositional variations between distinct activity phases (Scott *et al.*, 2016).

Our study is based on 1,714 samples from 165 slag concentrations—defined as spatially delimited accumulations or mounds of slag identified in the field. The focus is on key oxide combinations: Al_2O_3 , SiO_2 , P_2O_5 , K_2O , CaO , TiO_2 , MnO , FeO , SrO , and BaO . Contextual variables such as tuyère types, ore categories and furnaces structure, help frame the chemical data within broader metallurgical behaviors. Temporal attributes can include relative chronology derived from dating markers such as pottery or tuyère typologies. However, these markers may often lack the resolution necessary for regional-scale analysis. Therefore, tuyères were excluded from the primary chronological framework, as existing typologies are too broad to provide meaningful resolution. Radiocarbon dating of entrapped charcoal in slag was prioritized as a more reliable chronological anchor. This approach also allows for a critical reassessment of the correlation between tuyère types and dated assemblages, giving typological markers chronological value once empirical associations are established. Spatial attributes were recorded using GPS coordinates and displayed through maps generated in a Geographic Information System (GIS).

Our approach presents both distinct limitations and advantages. While it may not fully capture diachronic variation in metallurgical practices within individual slag concentrations, and despite the dataset's inherent fragmentary nature due to reliance on field discoveries, the broad scope of the investigation and the use of recognized statistical categories enable us to identify significant trends in metallurgical behavior. Diachronic reconstruction of smelting practices allows us to hypothesize which traits remained stable over time—indicating transmission of metallurgical knowledge—and which evolved through transformation or innovation in response to changing social, economic, or environmental conditions. Synchronic variation, on the other hand, may reveal the coexistence of distinct metallurgical communities at a given time, reflecting either cultural divergence or interaction. At the regional scale, spatial divergences in metallurgical traits may indicate distinct groups of metallurgists associated with specific villages or production sites, reflecting socially embedded networks and localized traditions. When such divergences cannot be explained by functional requirements (*i.e.*, the intended use of objects requiring a specific type of metal), they may instead reflect different cultural or social logics. Conversely, spatial convergence may suggest the existence of broader exchange networks, coordinated production strategies, or the persistence of shared metallurgical traditions across different communities.

Interpreting these temporal and spatial patterns requires situating the evolution of smelting practices within broader economic, political, and social contexts (*e.g.*, phases of political expansion or decline). Only by integrating these frameworks can we infer the organization of ironmaking behaviors and the nature of interactions between ironmaking metallurgists and other communities, such as consumers or social groups connected to metal production. This approach enhances our understanding of how metallurgical behaviors were shaped by, and in turn contributed to, broader historical processes. To examine the dynamics

of iron production within the Phnom Dek metallurgical landscape, we focus on analyzing the evolution and interaction of these processes using the analytical framework outlined above.

Investigating the Metallurgical Landscape of Phnom Dek

Context

Iron-rich mineral resources in central and northern Cambodia have been documented since the late 19th century, particularly in the context of geological surveys conducted under the administration of French Indochina (Alabouvette, 1969; Contri, 1972; Dottin, 1971). Among these, Phnom Dek, located 135 km east of Angkor, stands out as a localized iron ore deposit composed of magnetite, hematite and limonite primarily formed by goethite. Hydrothermal alteration processes partially transformed magnetite into hematite, making hematite a widespread iron-rich mineral within the broader geological formation (Caillère, 1972; Leroy *et al.*, 2020; Saladin & Fuchs, 1882; Uchida *et al.*, 2019). The region is also historically the homeland of the Kuay, an ethnic minority known to have practiced bloomery smelting from at least the 16th century until the cessation of production activities in the early 20th century (Choulean, 2006; Dufossé, 1934; Dupaigne, 2002, 2016). The area around Phnom Dek stands out for its lack of archaeological evidence of Angkorian Khmer occupation (*e.g.*, temples, water infrastructure, *etc.*). However, the landscape between Phnom Dek and the Angkorian complex of Preah Khan of Kompong Svay (PKKS) (Fig. 3) is characterized by dozens of sites comprising hundreds of individual slag mounds spread over 200 km² (Hendrickson *et al.*, 2017; Pryce *et al.*, 2014; Thuy, 2014; this paper). In this study, ‘sites’ refer to broader archaeological entities encompassing multiple slag concentrations and related features. Recent sourcing analysis of metal clamps from temples in Angkor demonstrate that iron from Phnom Dek was incorporated into Khmer construction by the 11th century and had become dominant by the 13th century (see provenance analysis in Hendrickson & Leroy, 2020). Radiocarbon dating confirms smelting from the Pre-Angkor to the Modern periods (7th to 20th c. CE), with a significant increase in production during the mid to late phases of Angkor (11th to 15th c. CE) (*ibid.*). Overall, these findings highlight that Phnom Dek became a geographic and titular center of a vast iron production landscape sometime during the Angkor Period.

PKKS is the largest Angkorian settlement complex built outside the capital. Developed through successive state-led building campaigns between the 11th and 13th centuries, PKKS served as an important Buddhist religious center and an intermediary site linking Angkor to the iron resources of the Phnom Dek region (Hendrickson & Evans, 2015; Hendrickson & Leroy, 2020; Jacques & Lafond, 2004). PKKS is currently the only known Angkorian temple with evidence of smelting activity within its enclosure—36 slag concentrations distributed across 9 sites indicate on-site primary production. Most of these smelting activities are dated to the late and post-Angkor periods (13th-16th c. CE) (Hendrickson *et al.*, 2013, 2018), suggesting that PKKS was not an active iron

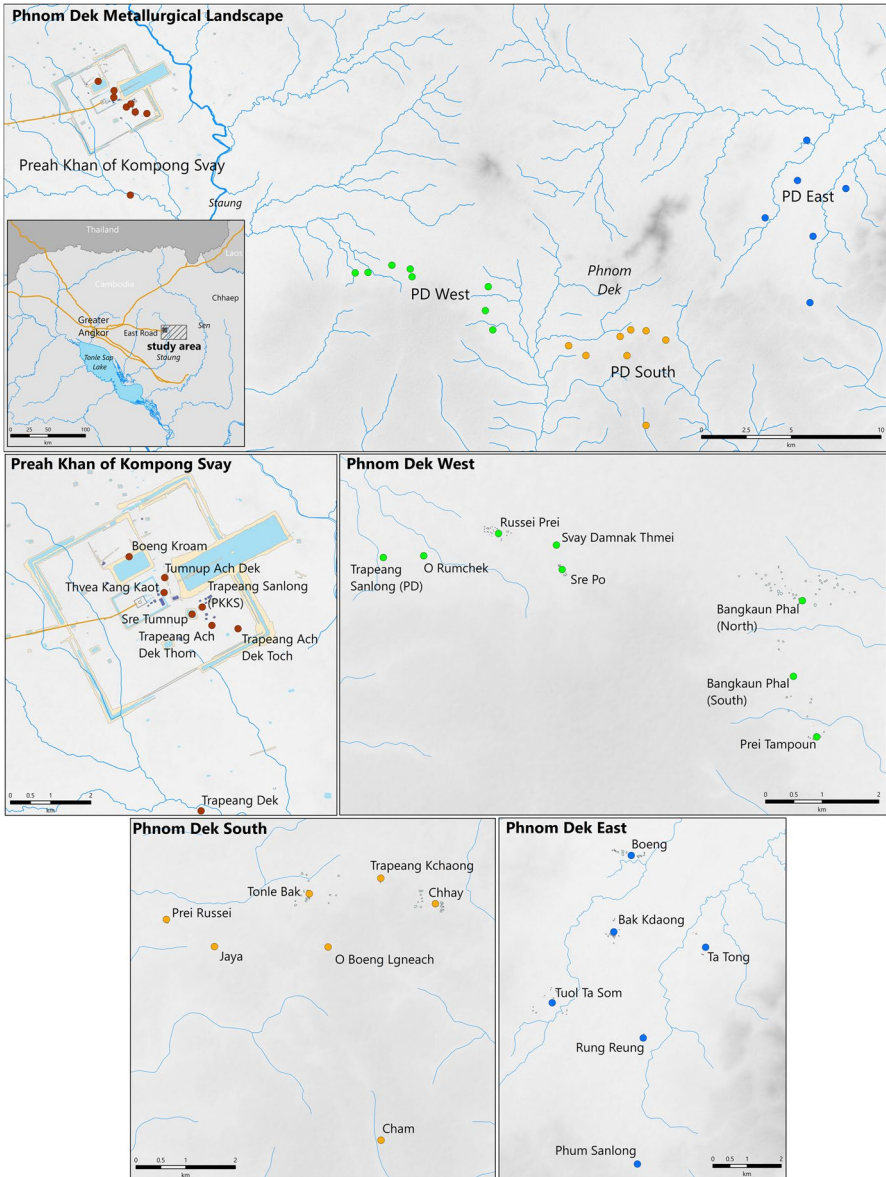


Fig. 3 Location of the iron metallurgy sites (colored circles) and the 165 slag concentrations (detailed small grey dots) across the Phnom Dek region and within the PKKS enclosure. The four regional areas (Preah Khan of Kompong Svay, Phnom Dek West, Phnom Dek South, Phnom Dek East) surrounding Phnom Dek are also identified

producer directly meeting the resource needs of Angkor’s elites (Hendrickson & Leroy, 2020). However, the observed similarities in metallurgical features (*e.g.*, tuyère typology, mound form), its proximity to Phnom Dek, and temporal links

with other sites suggest that PKKS played a role in the development and transmission of regional iron-smelting practices.

Extensive fieldwork conducted around Phnom Dek and inside PKKS between 2016 and 2017 identified 16 sites comprising 156 slag mounds. Radiocarbon dates derived from in-slag charcoals (see Supplementary Table S1) indicate phases of activities dating back to the 7th–8th centuries CE in the northeastern sector of the Phnom Dek region. The forms of waste disposal and associated technical features indicate three phases of operational smelting. The first type corresponds to the Pre-Angkor (6th to 9th c. CE) and early Angkor Periods (9th to 10th c. CE) and is characterized by small, highly fragmented tap slags, infrequent discovery of large gauge tuyères (71–80 mm bore diameter) often found in pairs, and no clearly visible furnace remains. The second phase is linked to the expansion and collapse of Angkor (11th to 16th c. CE) and is marked by multiple types of slags, including large tap slag masses (up to 80 kg), high frequencies of medium-gauge tuyères (45–55 mm bore diameter), and the presence of furnace fragments. The third phase is associated with the historic Kuay smelting (~ 17th to 20th c. CE) identified by more fragmented tap slag and narrow-gauge tuyères (32–40 mm bore diameter). Initial chemical analysis of slag from five slag mounds at Phnom Dek and PKKS (Pryce *et al.*, 2014) suggested a degree of continuity in smelting behavior over time. Later excavations at Tonle Bak uncovered three Angkorian furnaces (Hendrickson *et al.*, 2019) that are formally similar to ethnographic examples of Kuay smelting (Boulangier, 1888; Dufossé, 1934), reinforcing the hypothesis of a technological lineage. Together, the abundant archaeological and technical evidence from Phnom Dek and PKKS offers a robust foundation for investigating iron-smelting practices across the Phnom Dek region, identifying patterns of continuity and change through the lens of metallurgical recipes and the traditions they reflect.

Archaeological Evidence, Data and Variables

Surface surveys targeted the upper layers or terminal phases of slag mounds, recovering tap slag fragments, technical components (tuyères pieces), and, when possible, charcoal embedded in large slag pieces. AMS radiocarbon dating of in-slag charcoal provided chronological markers for final production phases. Spatial coordinates were recorded with handheld GPS units and integrated into GIS maps. Although area and height of mounds were documented, they were not used in this study due to their greater relevance to labor organization than smelting process analysis. In-field pXRF analysis was conducted on 10 to 20 slag fragments per mound (see chemical results in Supplementary Table S2). Larger mounds were sampled more extensively to capture potential temporal variability. Details on sample preparation, analytical conditions, and calibration protocols are provided in Supplementary Information 1 (SI1). Chemical signatures are based on measured oxide concentrations. For direct comparison, data were transformed using a log-ratio transformation (labelled X_{ij} below, see SI2). While this method is not essential in our context, it minimizes variations, aligns all concentrations on a common scale, and allows for the comparison of elemental ratios (Aitchison, 1982). The Geometric Enrichment Index (Gei) calculated as the geometric mean of lithophile elements (Al, Ba,

K, Mg, Sr, Si), reflects their enrichment relative to residual FeO content. In bloomery processes, lithophile elements are systematically incorporated into slag, and a high Gei indicates greater presence of these elements relative to unreduced iron oxides. While Gei does not directly quantify metallic yield or reduction efficiency, it captures the internal chemical balance of the slag, influenced by ore composition and smelting conditions. Together with the RII, these indices provide complementary insights into charge composition, smelting conditions, and the overall metallurgical process, allowing the detection of consistent technical patterns across sites.

Comparison of Signatures and Identification of Chemical Groups

To assess internal compositional consistency, slag samples from the terminal phases of production were first analyzed for the homogeneity of their chemical signatures. Some assemblages—particularly from the largest mounds—may be composite, reflecting multiple smelting episodes or operational processes over time, as well as possible post-depositional modifications. To verify internal consistency, a preliminary intra-mound partitioning was conducted using HCA with Euclidean distances and the Ward method (see example in Fig. 4). This step serves to test and validate the initial classification of analytical units, which are considered *a priori* as data classes. Once intra-mound clusters were defined, chemical signatures were compared using LDA, as explained in the methodological framework section. This approach emphasizes the observed differences between signatures while incorporating the *a priori* class information. To help visualize and interpret the overall structure of the dataset, given its size, we applied HCA to the coordinates of the LDA-derived cluster centroids ($n = 161$) derived from the LDA results. This helped reveal broader patterns and relationships within the multivariate space, enhancing our understanding of group-level dynamics (see example for iron clamps signatures in Leroy *et al.*, 2017).

Multimodal Data Analysis to Identify Ironmaking Practices

To investigate variation in iron-smelting across the Phnom Dek landscape, we combined chemical groupings with technical, spatial, and chronological attributes using Multiple Correspondence Analysis (MCA). This integrative approach enables the identification of distinct operational patterns, and helps related these patterns to processes such as knowledge transmission, processes of continuity, or localized changes in ironmaking behaviours.

Results of Multivariate Analyses

The following section presents the main outcomes of the chemical and statistical analyses. It focuses on the identification of chemical signatures from slag mounds and their grouping into coherent sets associated with distinct iron-smelting practices or operational recipes (see Supplementary Table S2).

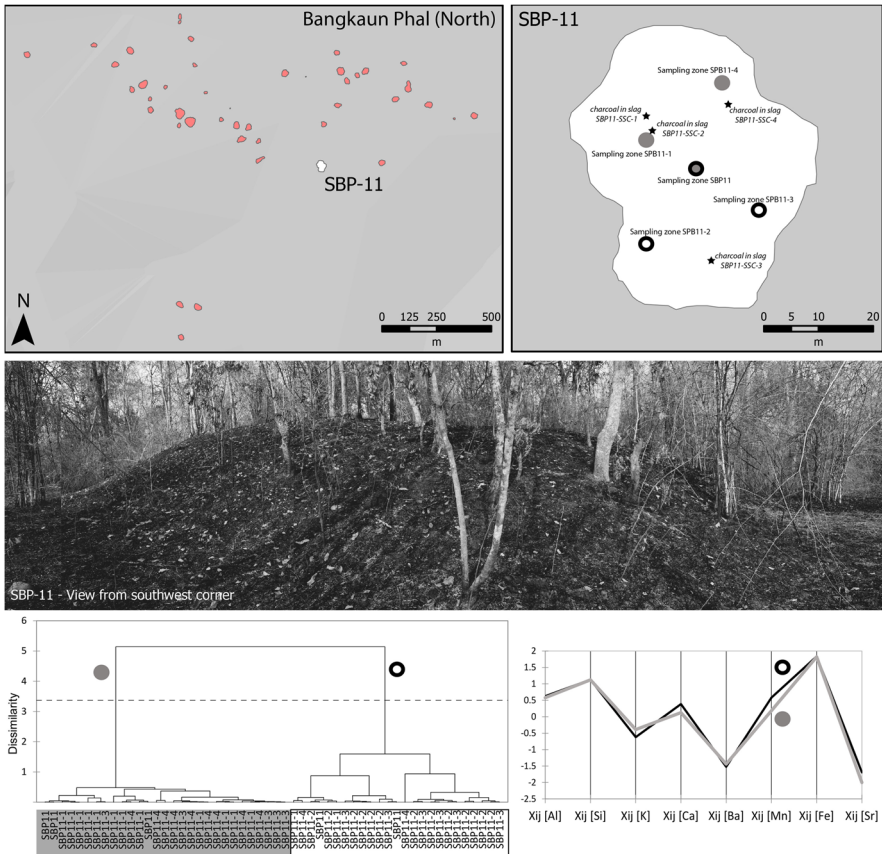


Fig. 4 Example of the treatment of sub-compositional data from slag samples of the large mound SBP-11, with the locations of the different sampling zones indicated (SBP11=top of the mound, SBP11-1, SBP11-2, SBP11-3, SBP11-4). HCA was performed on the slag sample scores, revealing two distinct chemical profiles

Slag Chemistry and Concentrations

Initial chemical groupings were defined using HCA, particularly for large slag mounds likely to reflect multiple smelting episodes over time (*e.g.*, SKD11, SKD05, SBO03, and SCH04). For instance, the large mound of Bangkaun Phal 11 (SBP-11), with activity dated between the 9th and 12th centuries, was sampled in five distinct surface areas across its 4-m-high profile. Two chemically distinct profiles, corresponding to the northern and southern parts of the mound, are revealed (Fig. 4). These internal differences indicate changes in ironmaking processes at the same place over time and were used to define discrete chemical signatures, which were then incorporated into the supervised phase of analysis.

Defining and Characterizing Chemical Groups

To compare chemical signatures across the entire dataset, LDA was performed on the 161 initial classes (corresponding to 156 mounds) defined through HCA (Fig. 5). This approach highlights both overlapping and distinct chemical clusters across the Phnom Dek landscape. A subsequent HCA, applied to the centroid coordinates derived from the LDA, identified seven distinct chemical groups (Fig. 6), interpreted as reflecting different smelting systems shaped by variations in raw materials and operational strategies.

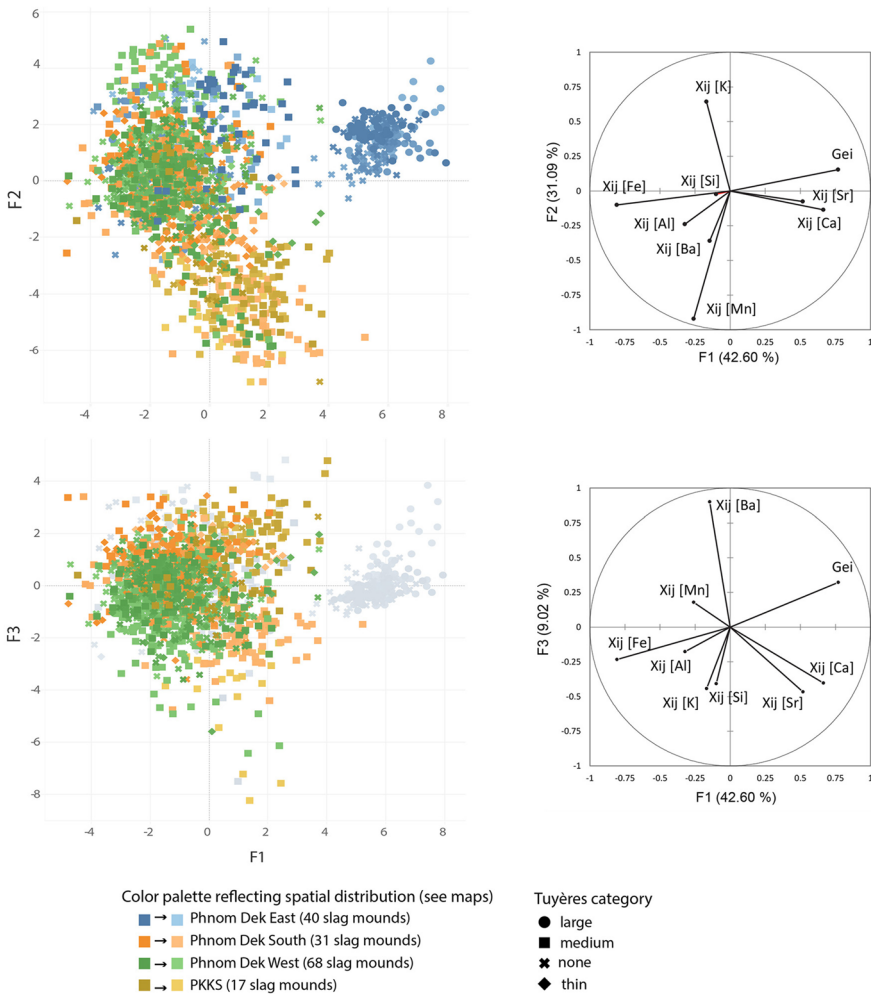


Fig. 5 LDA applied to the sub-compositional data of slag samples. Scores for samples from the same "region location" are color-coded as shown in Fig. 3

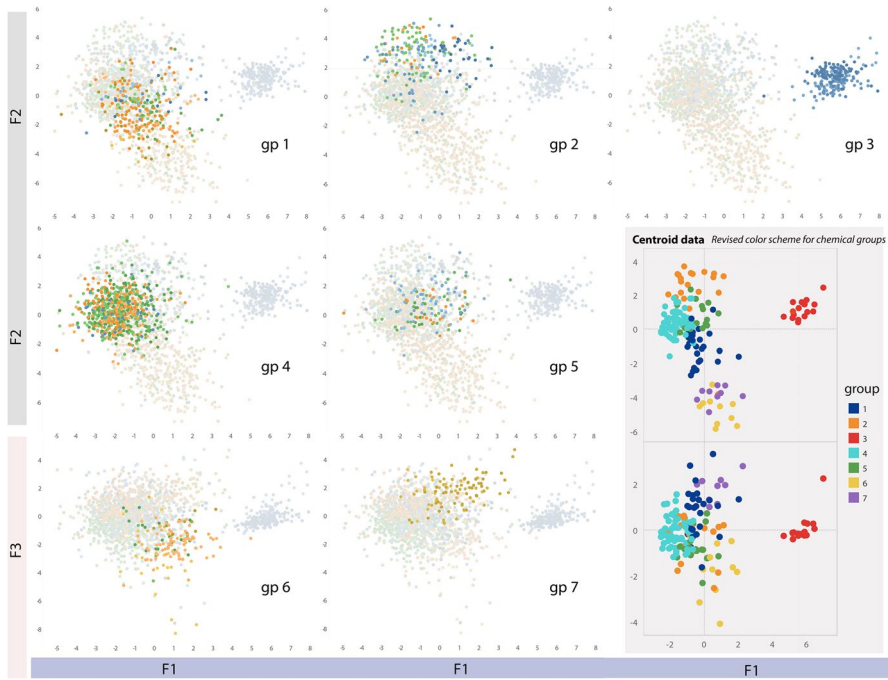


Fig. 6 Identification of the seven chemical groups: Groups 1 to 5 are represented in the (F1/F2) plot, while Groups 6 and 7 are represented in the (F1/F3) plot

The projection planes F1/F2 and F1/F3 reveal the structure of the dataset: while some groups show overlapping distributions, others form clearly distinct clusters. Group 3 (see Fig. 6) stands out particularly in the F1/F2 projection. Composed mainly of slags from the eastern Phnom Dek area (shown in blue), it is characterized by relatively small, greenish slag pieces unlike the larger slags observed elsewhere in the region. Chemically, Group 3 is marked by comparatively higher proportions of calcium (Ca) and strontium (Sr), lower manganese ($\text{Mn} < 3_{\text{wt}}\%$) and occasional traces of copper (Cu) (Figs. 6 and 7). It also presents relatively higher silicon (Si) and lower iron (Fe) contents compared to other groups. These characteristics, combined with elevated Gei and RII values suggest a distinct smelting configuration. This may reflect the processing of more gangue-rich ore or specific furnace environment for effective iron extraction. Although the exact source of the iron ore remains unidentified, the chemical signature of Group 3 and its geographic context point to the possible use of iron-rich weathering formations. Among the geological formations commonly found in northern Cambodia are laterites, iron-rich soils formed through intense tropical weathering; ferricrusts, hardened surface layers resulting from the cementation of iron oxides; and more localized iron oxide enrichments such as hematite blocks, frequently reported in the Chhaep and Stung Treng regions (locations in geological map from Carbonnel, 1972; Dottin, 1971; Harada, 2010; ongoing material characterization). All of these represent plausible ore sources in this context. Further

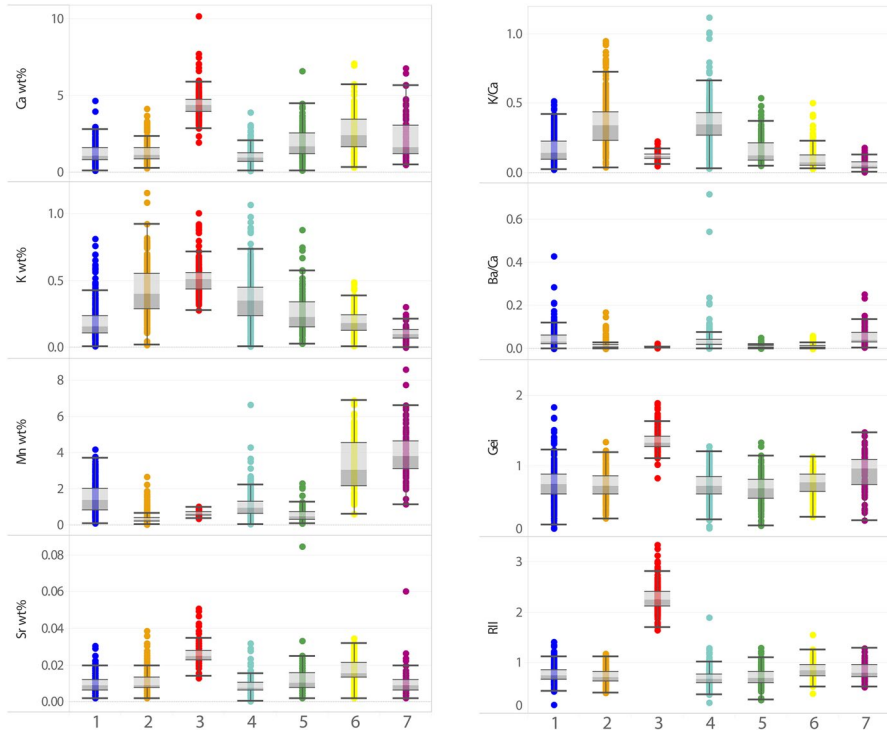


Fig. 7 Boxplot showing the distribution of measured chemical values within each group of signatures. Group 3 shows a broader RII range (1.71 to 2.82; median=2.26), suggesting greater variability in smelting inputs or parameters. Other groups display lower, more consistent RII values (0.68–0.85)

geological, chemical, and mineralogical investigations are required to identify the most likely sources exploited for local iron production.

Groups 6 and 7 also diverge from the main cluster (Groups 1, 2, 4, and 5). Found primarily within the PKKS complex, these groups exhibit distinct K/Ca ratios, lower potassium (K), and higher manganese (Mn) (Fig. 5), suggesting the use of a different, likely more manganese-rich ore source. Their separation in the F1/F3 projection, especially in Ba/Ca and Sr ratios, may also reflect variation in furnace clay composition or fuel inputs. This interpretation aligns with 19th- and 20th-century geological surveys that identified and localized ferrous formations northwest of PKKS (Alabouvette, 1969; Contri, 1972; Dottin, 1971; Saladin & Fuchs, 1882), as well as with recent provenance studies showing that slags from PKKS display trace element patterns inconsistent with geology of Phnom Dek deposit (Hendrickson & Leroy, 2020). It is likely that metallurgists at PKKS either had access to or selected an alternative primary ore source, possibly more locally available (see also Uchida *et al.*, 2019). The presence of manganese may indicate that this formation originates from a primary limonite source, which has also been documented and characterized in the aforementioned geological

studies. As we were unable to conduct field surveys in this area, comparative materials are not currently available. However, this remains a promising avenue for future research.

By contrast, Groups 1, 2, 4, and 5 form a more homogeneous compositional core, with only subtle internal differences. Group 1, found primarily in South Phnom Dek, exhibits lower K values, rather linked to differences in fuel ash input. Groups 4 and 5 differ slightly in Ca and Sr levels and share overlapping spatial distributions, which may suggest technical, spatial, or chronological continuities. Group 2, mostly found in East and West Phnom Dek, is characterized by slightly lower Mn content, likely reflecting natural variability in ore mineralization. Although iron-rich weathering formations such as laterites are often referenced as ore sources for iron-making in tropical regions, this model does not fit the geological context of the Phnom Dek deposit. Geological surveys, field observations, and compositional analyses indicate that the massif mainly consists of a skarn-type ferriferous formation developed over a volcanic substratum (Carbannel, 1972; Dottin, 1971; Fromaget, 1941). Dominated by magnetite and hematite, and locally altered to limonite, this formation features high iron content alongside relatively low silica and manganese levels (Dupouy, 1913, p.216–220; Léger, 1925; Saladin & Fuchs, 1882; Carbannel, 1972; Leroy *et al.*, 2020). While laterite compositions can be variable, the specific chemical components observed, along with the geographic proximity of many sites in these groups to the massif and the compatibility of trace element compositions in slag from selected sites with ores from the deposit (see provenance in Hendrickson & Leroy, 2020), support the hypothesis that metallurgists working in these zones have exploited resources linked to the deposit. While further analyses are needed to expand the geochemical dataset, the patterns identified here already offer a solid framework for interpreting technological variability across the Phnom Dek landscape.

Exploring Patterns: Temporal, Spatial, Technical Dimensions of Ironmaking Practices

Archaeological remains, such as furnace fragments and tuyères, serve as technical indicators of the smelting conditions of the reduction process. In particular, tuyères—used to channel air into the furnace—offer indirect insights into the diversity of redox conditions that can influence slag composition. While furnace structures are rarely preserved on the surface of slag concentrations, tuyères are more frequently encountered and can be classified based on the diameter of their bore, forming three main typological groups. Previous observations from an earlier corpus have linked these types to different chronological phases (Hendrickson *et al.*, 2017). Typological characteristics of the tuyères, radiocarbon dates (^{14}C) obtained from in-slag charcoal, and spatial data have all been integrated into a MCA. For this, the variables were standardized as nominal categories. Tuyère diameters were grouped into four categories: ‘large’, ‘medium’, ‘narrow’, and ‘unknown’. The chronological variable, labeled as ‘period’ and based primarily on ^{14}C data was subdivided into five categories: ‘Pre-Angkorian’ (7th–8th

c.), ‘Angkorian’ (9th–13th c.), ‘Angkorian Decline’ (14th–15th c.), ‘Post-Angkorian’ (post 16th c. CE), and ‘Unknown’. The combination of typological, chronological, spatial, and chemical group data provides a multifactorial framework for exploring ironmaking behaviors across the landscape. An overview of the categorical variables and the spatial distribution of chemical group assignments by geographical zone is shown in Fig. 8 (see also Supplementary Information 3 for more detailed spatial resolution).

By cross-referencing chemical clustering results with qualitative data, the MCA enables the identification of distinct technological groupings across the study area. The analysis incorporates four key categorical variables—chemical group, chronological period, tuyère bore diameter, and site location—to explore correlations that may reflect either discontinuities (technological change) or continuities (transmission) in ironworking practices (Fig. 9). It is important to note that the absence of chronological or technical data for certain slag mounds introduces a degree of differential inertia in the analysis. This limitation should be considered when interpreting the relative positioning of mounds and the attribution of patterns. Considering this variability is essential for a balanced interpretation that reflects both the potential and constraints of the dataset.

The MCA shows that the first four axes capture enough explained variances, allowing us to focus on the two main factorial planes (Fig. 9A and B). Within these projections, seven subdivisions can be distinguished and organized into five major groupings, each corresponding to a distinct set of ironmaking practices over time (labeled A to G in Fig. 9C). Cluster A (upper left, F1/F2) corresponds to Group 3 (Recipe A), linked to sites from East Phnom Dek (Boeng, Bak Kdaong, Tuol Ta Som). It is associated with the pre-Angkor period and the use of large tuyères (first group in Fig. 9C). Cluster B, also in East Phnom Dek, includes Group 2 (Recipe B) and shows partial extension into West Phnom Dek (e.g., Russei Prei), indicating some spatial continuity over time. A second compositional pole (bottom of F1/F2) includes Groups 7 and 6 (Recipes E and F), associated with the Angkorian and Angkorian decline periods, medium gauge tuyères, and sites within the PKKS complex and Tonle Bak (South Phnom Dek). Group 6 is more closely aligned with the Angkorian Decline phase, while Group 7 is linked to the Angkorian period, particularly at Tumnup Ach Dek. A third configuration (right of F1/F2) corresponds to Group 1 (Recipe G) associated with narrow tuyères, the Post-Angkor period, and sites in South Phnom Dek (Jaya, Chhay), West Phnom Dek (Sre Po), and again PKKS. Finally, in the F1/F3 projection (Fig. 9B), Groups 4 and 5 (Recipes C and D), is linked to smelting at sites in West Phnom Dek (e.g., Russei Prei and Bangkaun Phal) and South Phnom Dek (e.g., Chhay), and span the Angkorian and undated categories. Together, these patterns highlight strong correlations between medium-sized tuyères and the Angkorian to Angkorian decline phases. Groups 2, 4, and 5 (Recipes B, C, and D), while chemically distinct, share overlapping characteristics suggesting a technologically related metallurgical history.

Ironmaking Recipes and Their Evolution around Phnom Dek

The diachronic and spatial analysis of iron production evidence around Phnom Dek (see Fig. 10) provides key insights into the dynamics of change, development, and the possible transmission of metallurgical practices. Between the Pre-Angkor and early Angkor periods (~6th–11th c. CE), smelting activities associated with Recipe A are primarily concentrated in the northeastern part of the Phnom Dek landscape. During this phase, metalworkers relied on an ore of presently unidentified origin, likely sourced from one of the mineral deposits recorded near the Stung Sen River (see location possibilities in Geological map of Cambodia in Harada, 2010; also ESCAP, 1993). Traces of malachite reported in schist-sandstone formations from this region (Dottin, 1971) could account for the copper detected in some slag compositions. Further investigation is needed to clarify the origins of this ore supply and the broader history of early ironmaking practices in this area.

The chemical characteristics of the slags, along with the use of broad-gauge tuyères at sites associated with Recipe A, point to a distinctive smelting practice likely involving a specific furnace configuration, and air delivery system. The relatively high and variable RII values observed in these assemblages may reflect redox conditions potentially consistent with airflow variations. If this is consistent with the smelting of siliceous, gangue-rich ores (or blends of ores and possibly flux), then sustained high temperatures and reducing atmospheres would have been required to achieve effective iron extraction.

The presence of broad-gauge tuyères is particularly noteworthy, as tuyère diameter directly influences airflow, furnace temperature, and redox dynamics (Rehder, 2000). Such large-diameter tuyères may be associated with natural draft systems as documented in African and some European contexts (Killick, 1991; Pelet *et al.*, 1993, p.18–28; Rehder, 2000; Pleiner, 2000). Combined with suitable furnace structures, such as height-to-diameter ratios that promote natural convection, these tuyères can enable substantial air intake without bellows, as demonstrated experimentally (Rehder, 2000). Although no furnace structures are documented at Recipe A sites, natural draft operation remains plausible. These systems can sustain high temperatures and reducing atmospheres, depending on factors like smelting duration, ore quality, charcoal type, and furnace design (Killick, 1991; Rehder, 2000). Such conditions may also favor carburization, especially when the bloom remains in prolonged contact with charcoal under reducing conditions. In this context, the occurrence of carburized iron, rather than soft iron, during this period, documented in architectural clamps and other Angkorian types of artifacts (Leroy *et al.*, 2017; Morel, 2017), is particularly significant. While slag chemistry, tuyère dimensions, and production features are documented, interpreting them as evidence of natural draft operation remains speculative. Alternatives, including the use of bellows, cannot be excluded (Avery & Schmidt, 1979). Still, the hypothesis of a natural draft system presents a valuable research avenue. If confirmed, it would raise important questions about labor organization and fuel management, particularly regarding the quantities of charcoal required and the logistical effort needed to sustain smelting process. In this context, the observed variations in elements associated with fuel ash

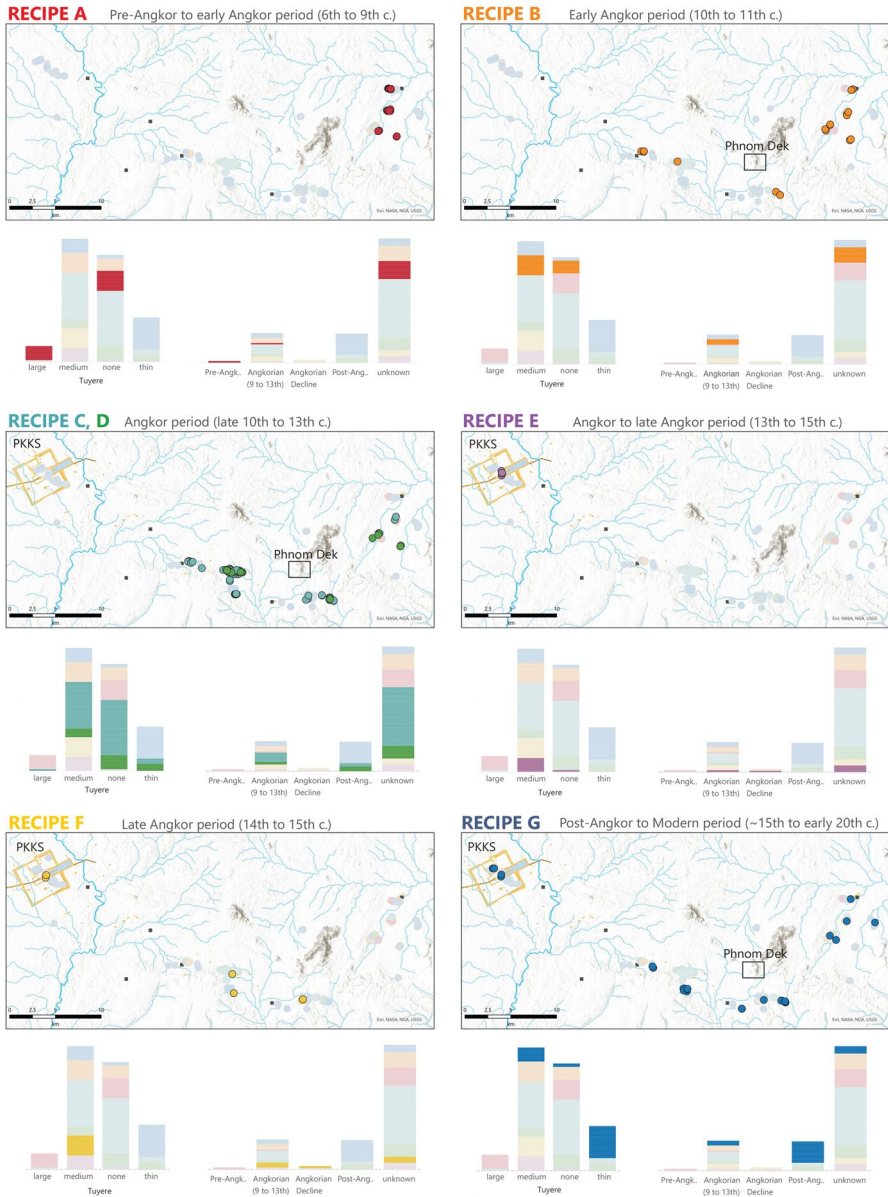


Fig. 10 The evolution of the metallurgical phases in a spatial and diachronic perspective

(such as K, Ca, and Sr) could reflect differences in the amount of charcoal consumed rather than differences in the species of wood used. Further excavations combined with detailed technological and sourcing analyses are essential. In particular, linking high-carbon iron artifacts to Recipe A production sites will help better understand local metallurgical practices and their relationship with available geological

resources and cultural choices. At the very least, our results suggest a distinct local trajectory shaped by both geological resources and embedded cultural practices.

Fieldwork in the Chhaep district, approximately 55 km to the northeast, has revealed slags with similar morphological characteristics (see Thuy, 2014), suggesting a potential historical connection to the technical traits studied here, though not necessarily the same recipe. More broadly, similar slags reported from northeastern Cambodia and southern Laos (*e.g.*, Heng, 2018, pp.131–155; Leroy, 2018) may indicate broader technological affinities or shared traditions across these regions. Additional compositional and chronological data would help clarify these relationships. The spatial distribution of Recipe A, combined with the absence of contemporary smelting evidence nearer to Phnom Dek, suggests that these early workshops may have served supply zones in the northeastern Phnom Dek landscape, and/or oriented toward the Sen River catchment as suggested by the proximity to eastward-flowing tributaries. By extension, these routes could have connected producing communities with regional centers like Sambor Prei Kuk (Shimoda & Shimamoto, 2012). In metal used at Angkor ultimately derived from this production, it would imply that iron may have reached the Tonle Sap basin through these networks. Provenance studies on metal artifacts from sites along the Sen River corridor may help confirm such connections.

Recipe B emerges in the early Angkor period (~10th–11th c. CE) and marks a clear shift in technical configuration. It is characterized by the use of medium-gauge tuyères, modified smelting parameters, and a distinct ore source, likely associated with the Phnom Dek deposit and rather associated with hematite-type ore (Leroy *et al.*, 2020). Many of the sites previously linked to Recipe A are now associated with this new recipe. The adoption of different operational practices at the same production locations indicates a significant transformation in technical choices possibly reflecting the introduction of new metallurgical inputs or traditions, while suggesting, through spatial continuity, a probable persistence of the same smelting communities. This juxtaposition of technical rupture and spatial continuity defines a pivotal stage in the region's metallurgical trajectory.

For the first time, Recipe B is also attested west of Phnom Dek, particularly at Russei Prei and Bangkaun Phal, and, to a lesser extent, at Chhay. The transition from broad- to medium-gauge tuyères suggests a reconfiguration of air delivery dynamics and internal redox dynamics, consistent with slag chemistries that show significantly higher iron content compared to Recipe A. This reflects both a shift in ore supply and changes in how the smelting process was managed. This technical transformation parallels a documented change in the metal used for architectural clamps around the 11th century, shifting from high-carbon to lower-carbon iron (Leroy *et al.*, 2017). Whether this shift was intentionally implemented by metallurgists or emerged in response to evolving needs or expectations among social groups of users, such as Angkorian elites, it signals a convergence between new technical configurations and the structural requirements of contemporary architecture (Hendrickson & Leroy, 2020). Beyond the properties of the metal produced, Recipe B appears to embody a shift in smelting logic. These changes in smelting parameters may have contributed to a more stable management of furnace atmospheres (Charlton *et al.*, 2010) or to more efficient use of fuel resources potentially reducing the

risk of smelting failure and lowering the consumption of charcoal, one of the most resource-intensive inputs in ironmaking (Rostoker & Bronson, 1990). Nevertheless, such changes should not be reduced to technical optimization alone, as if driven purely by utilitarian concerns. They should not be seen only as attempts to improve technical performance, but rather as developments potentially shaped by a range of practical, environmental, and cultural factors. In iron making, transformative production are not merely functional sequences, they often encode ritual, symbolic, and social dimensions (*e.g.*, Childs & Killick, 1993; Chirikure, 2007; Dupaigne, 2002). Adjustments to furnace atmospheres or raw materials may thus signal evolving conceptions of transformation, not only technical, but also cosmological and political. In this sense, the transition from Recipe A to Recipe B might represent not just a shift in technology, but a redefinition of how iron production was situated within broader frameworks of meaning and practice.

Later in the Angkor period (late 10th to 13th c. CE), iron production expanded significantly across the Phnom Dek region, with more than 130 new smelting concentrations relying specifically on ores from Phnom Dek. During this phase, Recipes C and D became dominant. These recipes are technically similar and use the same general ore type, yet they show notable differences in calcium and minor variations in manganese content. These discrepancies likely reflect variations in the proportions of gangue within the ores or differences in the composition of the clays used for furnace linings and tuyères. In a few cases (seven slag mounds in total), narrow-gauge tuyères clearly linked to Post-Angkorian production were mistakenly grouped with this phase. This underlines the difficulty of classifying slag chemistry in isolation and the importance of combining multiple lines of evidence when interpreting large compositional datasets.

Recipes C and D are the most widespread in the dataset, reflecting both an intensification and a geographic expansion of iron production. This expansion is particularly visible in the western and southern parts of the Phnom Dek region—Bangkaun Phal, Russei Prei, Tonle Bak, and Chhay—marking a shift away from the earlier eastern focus of Recipe A. This spatial reorganization appears to align with broader political and infrastructural developments, including the establishment of PKKS and the construction of new routes connecting Phnom Dek to the Angkor heartland. These transformations may signal a reconfiguration of production and supply systems in response to the evolving needs of the Khmer state during its expansionist phase in the 11th century (de Mestier du Bourg, 1971; Vickery, 1985). In this context, Recipe B—and later Recipes C and D—may not only reflect changes in smelting logic, but also a tighter integration of iron production into centralized distribution frameworks. The increase in both the number and density of production sites during this phase suggests a broader mobilization of labor and resources. This intensification aligns with evidence from the organization of clamp production, which, by the end of the 12th century, involved multiple workshops likely responding to a standardized production framework and the increasing demand for iron driven by the major temple-building programs of the period (Leroy *et al.*, 2017).

Recipe E appears within the enclosure of PKKS and coincides with, or slightly postdates, the major expansion of iron production around Phnom Dek. The establishment and expansion of PKKS, combined with the intensification of primary

iron production and lack of typical evidence of Angkorian settlement (*e.g.*, temples, water reservoirs) around Phnom Dek, suggests a reorganization of socio-economic relationships between the capital and established smelting groups during this expansionary phase (Hendrickson & Evans, 2015). This technical system, marked by the use of medium-gauge tuyères, also incorporates a new ore source, richer in manganese and not originating from Phnom Dek. A second production type, Recipe F, also documented at PKKS, draws on the same manganiferous ore but is distinguished by the use of different fuel sources or fuel consumption. It corresponds to the peak of Angkor's zenith (late 13th century), its decline, and the early Post-Angkor period (~14th-15th c. CE). A few additional sites using the same Mn-rich ore are documented outside PKKS, notably at Tonle Bak, located 2 km south of Phnom Dek. Production there spans the 12th to 14th centuries and provides some of the most direct evidence for Khmer-period occupation in the area, including a large rectangular reservoir, the remains of a wooden shrine, and a range of local and imported ceramics (Hendrickson *et al.*, 2019). While the identity of the Tonle Bak smelting community remains uncertain, the technical parallels with PKKS and the cultural material recovered suggest interaction between Kuay and non-Kuay peoples within the broader Angkorian economic sphere.

Recipes E and F show slightly higher RII values compared to Recipes C and D. These differences are particularly notable given that Recipes E and F also exhibit higher manganese content, with average levels above 3 wt%. Among the chemical variables distinguishing these phases, manganese clearly emerges as a key parameter. The metallurgical literature has repeatedly pointed to the potential role of manganese in bloomery smelting, particularly in relation to carburization processes (Redher, 2000; Crew *et al.*, 2011; Iles, 2014; as well as references in Leroy *et al.*, 2012; Verna, 2001). Although the mechanisms involved remain debated, the consistent association between elevated manganese levels and carburized iron suggests that these compositional patterns may carry technological significance. These differences may reflect changes in furnace environments that were not fully aligned with prevailing production objectives. As a result, it is likely that smelters ceased using this ore source and resumed exploiting Phnom Dek's mineral resources. Ethnographic description emphasize that Kuay smelters made deliberate choices in ore selection (Boulangier, 1888; Harmand, 1876; Moura, 1874). Ongoing research is needed to assess how the mineral diversity of the region may have structured the development of technical systems and influenced the properties of the resulting iron. In this perspective, ore characteristics should not be viewed merely as passive geological constraints, but as active components structuring the organization and outcomes of iron production.

The final technical tradition, Recipe G, emerges after the early 16th century and remains in use until the early 20th century, corresponding to the historic Kuay smelting practices documented ethnographically. It is widely attested across the Phnom Dek region, including PKKS, and frequently co-occurs at sites previously associated with earlier recipes, while continuing to exploit ore sources consistent with Phnom Dek deposit primary source. The main variation lies in the incorporation of narrower-diameter tuyères, likely reflecting modified or adapted air delivery dynamics. Despite these adjustments, the recipe demonstrates strong continuity with

earlier processes, indicating a stable operational framework that persisted for several centuries, likely shaped by resource availability, production needs, and the transmission of technical knowledge within local communities. Changes in slag chemistry likely reflect variations in fuel characteristics. These variations may be linked to gradual changes in the types of trees available locally indicating evolving resource availability and corresponding technical adaptations over time.

Iron Production and Technological Trajectories around Phnom Dek

The multi-scalar analysis of chemical and technological data from iron production sites around Phnom Dek reveals patterns of both continuity and change in smelting practices over time. These transformations involve shifts not only in technical parameters but also in knowledge transmission, adaptation to environmental conditions, and the spatial distribution of production activities.

The most significant transformation occurs between Recipe A and Recipe B, within a relatively narrow chronological window around the early Angkorian period. We interpret this change as a rupture rather than a gradual transition. This rupture includes notable modifications in furnace operation, tuyère category (from large to medium diameter), and ore supply. These shifts are evident in both slag chemistry and metallic outcomes, indicating a significant change in smelting practices. However, this rupture in iron-making process coexists with continuities: the spatial overlap of production sites and ongoing activity suggest an adaptive transformation within a persistent community of practice rather than a complete replacement of actors or locations. This dual dynamic highlights the complex interplay between innovation and continuity. Recognizing this interplay allows for a nuanced understanding of metallurgical change and calls for further investigation into its social and organizational aspects. While these observations indicate a marked shift, broader implications for metallurgical traditions and material culture remain to be explored.

These changes coincide with the relocation of production towards the Phnom Dek massif and parallel broader political-economic developments within the Angkorian state, such as the formalization of infrastructural networks linking production centers to the capital. The establishment of the PKKS complex and the formalization of the east road connecting it to Angkor indicate a deliberate integration of this production zone within centralized economic and infrastructural networks. In this context, Recipe B may reflect internal innovation, through localized experimentation and technical reformulation, or it may result from external influences, including indirect contacts and the adoption of new operational elements that transformed smelting practices.

While the precise origins of these transformations remains open to interpretation, it is important to consider that Cambodia was long connected to regional networks of cultural and technological interaction with polities from South and East Asia. By the first millennium CE, the Khmers had adopted key aspects of South Asian socio-political and religious systems, although direct evidence of economic integration remains limited (Coedès, 1968; Pelliot, 1903). Recent archaeological, including early glass artifacts, and bioarchaeological findings highlight longstanding

South Asian connections predating this period (Carter *et al.*, 2020; Changmai *et al.*, 2022). Conversely, Khmer ties with China were more continuous and economically oriented, beginning in the Han period and intensifying through the Tang and Song dynasties (Stark & Cremin, 2023; Wade, 2009; Zhou & Harris, 2007). However, evidence from Phnom Dek does not support direct Chinese metallurgical influence. The metallurgical tradition associated with Recipe B differs markedly from the smelting processes characteristic of medieval China (Chen & Han, 2013; Liu *et al.*, 2014; Qian & Huang, 2021; Zou *et al.*, 2019). In contrast, slags from Recipe A, predating the 10th century, shows affinities with evidences documented further north in mainland Southeast Asia (as noted above), inviting further comparative research.

A key avenue to further apprehend this significant technological shift lies in exploring the specific features of the furnaces linked to Recipe B. Based on archaeological remains dated to the 12th–13th centuries and 20th-century ethnographic observations, these furnaces are hypothesized to feature a linear design with multiple tuyères (Dupaigne, 2016; Hendrickson *et al.*, 2019). This configuration invites comparison with broader Asian traditions, particularly the linear-configured furnaces and single-use wall with multiple tuyères documented in Sri Lanka during the first millennium CE (Juleff, 2009). A hypothesis of wider diffusion has been proposed based on archaeological data from Sri Lanka, ethnographic descriptions of 19th-century Kuay furnaces in Cambodia (Boulangier, 1888), and knowledge of the Japanese tataru tradition (Keiji & Yamamura, 1988; Rostoker & Bronson, 1990). While this comparison is not based on direct historical connections, it offers a productive framework for interpreting certain aspects of the Phnom Dek sequence. Recent discoveries of similar furnace configurations in southern Siberia (3rd–6th centuries) and early historic Japan (6th–8th centuries) further demonstrate the presence of this smelting technology across diverse regions of Asia over a wide chronological span (Vodyasov *et al.*, 2023).

Comparative analysis reveals both parallels and divergences. In Sri Lanka, natural ventilation, enhanced by topography and monsoon winds, produced stable airflow and thermal regimes (Juleff, 1996). Cambodian ethnographic sources indicate bellows-driven air circulation (Dupaigne, 2016), but recent research suggests airflow intensity was likely more moderate than previously assumed. Rather than high-pressure injection, air delivery may have functioned through a balanced regime, combining aspects of induced and natural convection (Leroy *et al.*, 2020). This opens the possibility of convergent thermal management strategies, despite differences in design and implementation. Rehder's (2000) concept of the "wind furnace", typically associated with rectangular designs, may thus be relevant to both contexts. While the two traditions appear to differ in the types of metals produced, this remains hypothetical. In Sri Lanka, production may have yielded a heterogeneous alloy combining high-carbon steel and soft iron (Juleff, 1996), whereas in Cambodia, the output may have been a more homogeneous, low-carbon iron (Leroy *et al.*, 2017). Although the production of a more heterogeneous bloom involving sorting processes cannot be entirely ruled out, no indications of such sorting have been identified so far in the study of crampton irons. Data on other artifact types, necessary to confirm this hypothesis, remain limited and insufficient. The iron-rich minerals

exploited in both regions (Jayawardana *et al.*, 2014; Solangaarachchi, 2011) for Sri Lanka might have been similar in type, possibly influencing comparable technical choices.

While certain aspects of ventilation in 19th-century Cambodian furnaces show parallels with the Japanese tataru, caution is warranted in drawing comparisons. Japanese metallurgy, which relied on iron sand from the 9th–10th centuries onward, developed specific techniques to produce cast iron and later steel (Kozuka, 1968; Michel-Tanaka, 2023; Tate, 2005; Tawara, 2007), diverging significantly from the practices documented in Cambodia after the 11th century. These comparisons underscore the value of a broad analytical lens attentive to local mineralogical specificity while acknowledging the potential for indirect or analogical connections across regions.

From the 11th century onwards, iron production around Phnom Dek reflects strong elements of continuity, particularly in the consistent use of ores from the Phnom Dek deposit. The compositional proximity among Recipes B, C, D, and G indicates a more continuous and regionally connected pattern of smelting. Minor technical changes and variations in labor organization likely occurred, but overall pattern points to gradual adaptation shaped by environmental conditions, spatial organization, and knowledge transmission. These recurring consistencies in slag chemistry, ore selection, and operational choices reflect shared logics of transformation, which we interpret as material expressions of a metallurgical tradition. Here, “recipe” has been used as a heuristic tool to interpret the observed chemical and technical variations. It also refers to a set of practical procedures embedded in local knowledge systems which, through repetition, give rise to traditions. Beyond embodied know-how, a recipe can represent a conceptual framework shaped by historical modes of transmission, guiding the evolution of metallurgical practices. This approach highlights the interdependence between recipe and tradition: traditions stabilize groups of recipes, while new recipes may emerge within or between these traditions, reflecting innovation and adaptation. Combining these concepts allows for a more comprehensive understanding of both continuity and change observed in the archaeological record.

Localized deviations such as Recipes E and F at PKKS during a discrete period (13th–15th centuries) suggest a moment where external influences, resource constraints, or experimentation may have temporarily modified patterns. These cases invite reflection on circulation, contact, and transformation, echoing broader anthropological discussions about how local knowledge systems engage with supra-local or global trajectories.

While slag and their chemical composition form the foundation of this interpretive framework, future integration of targeted geological and mineralogical analyses will further refine these insights. Ultimately, these transformations raise important questions about the cultural and symbolic dimensions of technological change and the value attributed to iron in its material forms in Khmer society. Our study delivers detailed insights into the technological, spatial, and chronological dynamics of iron-making processes, offering coherent interpretive model for the Phnom Dek metallurgical landscape. Although direct archaeological evidence from settlement contexts and a clearer identification of producing communities remain areas for further research, the analysis of groups of production sites, their spatial distribution, chronological

sequences, and indirect links to consumption provides valuable perspectives for situating technological practices within their broader social contexts and communities of metallurgical practices. As we propose an archaeometallurgical approach, future research integrating settlement archaeology, strengthens geological investigations, and expands archaeometallurgical analysis will further consolidate these insights and advance understanding of the socio-economic and cultural systems underpinning iron-making and production.

Conclusion

This study proposes a cross-scalar analytical framework to examine the historical trajectories of smelting and, in turn, iron-making in the Phnom Dek region, based on an integrated archaeological, chemical, spatial, and technical evidence. By distinguishing between practices, recipes, and traditions, iron production is approached both as a series of localized operational choices and as part of broader technological and cultural dynamics. The concept of statistically coherent chemical signatures serves as a comparative tool to characterize metallurgical behaviors and trace how technical systems were maintained, adapted, or transformed over time in response to shifts in resource availability, cultural logics, and sociopolitical conditions. Using pXRF, a large-scale compositional dataset was compiled, revealing both enduring continuities and phases of technological change. These include variations in ore supply and iron-making processes that seems to be related to evolving economic, environmental, and social contexts. At PKKS, shifts in chemical patterns and operational parameters suggest episodes of experimentation or organizational restructuring. In contrast, the continued use of Phnom Dek ores, connecting the most recent Kuay-related production with earlier periods, suggests the existence of a regional tradition that has likely been preserved through local knowledge transmission. Whether this continuity reflects the legacy of a single community or multiple interacting groups remains an open question, calling for further interdisciplinary investigation.

Beyond its empirical contributions, this study advances a structured interpretive model that connects chemical variability to broader anthropological questions. By embedding slag chemistry within its archaeological and historical context, metallurgical recipes emerge not as fixed procedures but as dynamic knowledge systems shaped by social practices and historical contingencies. Periods of technical stability contributed to the structuring of metallurgical traditions through the sustained transmission of technical knowledge. In contrast, shifts in practices may reflect moments of adaptation or transformation, illustrating how technical choices were reshaped in response to moving conditions. This approach invites wider comparative inquiry into how communities relate to metals, not merely as technical materials, but as mediums for social knowledge, cultural identity, and historical transformation.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10816-025-09740-6>.

Acknowledgements We thank the Ministry of Culture and Fine Arts of Cambodia for their collaboration and for granting permission to undertake prospection and sampling around Phnom Dek. This work was supported by the French National Research Agency (ANR-14-CE31-0007) (IRANGKOR project), the National Science Foundation (NSF EAR1550850) (INDAP project), the French National Centre for Scientific Research, the University of Illinois at Chicago, and the Wenner-Gren Foundation. We are grateful to the teams from the 2016 and 2017 field seasons, as well as to the community members in and around Phnom Dek for their collaboration. We also extend our thanks to Philippe Dillmann and Sylvain Bauvais, for their support in the field and acquisition of slag data. Finally, we thank the three anonymous reviewers for their insightful comments, which greatly contributed to the final version of this paper.

Author Contribution S.L., M.H., and E.V. wrote the main manuscript text; S.L. conceptualized the proposed work; All authors carried out the fieldwork and provided the data; S.L. and E.V. provided the data on slag, signatures and iron-making behavior; M.H. provided the data on tuyères, GIS and charcoal-¹⁴C; O.H. performed the ¹⁴C data analysis; All authors reviewed the manuscript.

References

- Aitchison, J. (1982). The statistical analysis of compositional data. *Journal of the Royal Statistical Society*, 44, 139–177.
- Alabouvette, B. (1969). *Rapport de la Mission Carte Géologique du Cambodge, Campagne 1968–1969*. BRGM.
- Amicone, S., Quinn, P. S., Marić, M., Mirković-Marić, N., & Radivojević, M. (Eds.) (2019). Tracing pottery-making recipes in the Prehistoric Balkans 6th–4th Millennia BC. *Archaeopress*. <https://doi.org/10.2307/j.ctvndv954>
- Arnold, D. E. (2000). Does the standardization of ceramic pastes really mean specialization? *Journal of Archaeological Method and Theory*, 7, 333–375. <https://doi.org/10.1023/A:1026570906712>
- Avery, D. H., & Schmidt, P. (1979). A metallurgical study of the iron bloomery, particularly as practiced in Buhaya. *JOM Journal of the Minerals Metals and Materials Society*, 31, 14–20. <https://doi.org/10.1007/BF03354507>
- Bachmann, H. G. (1982). *The identification of slags from archaeological sites*. Institute of Archaeology.
- Batton-Hubert, M., Desjardin, E., & Pinet, F. (2019). L'imperfection des données géographiques 1: Bases théoriques. ISTE Group.
- Benzécri, J. -P. (1973a). L'analyse des données. 1: La taxinomie. Dunod, Paris.
- Benzécri, J. -P. (1973b). L'analyse des données. 2: L'Analyse des Correspondances. Dunod, Paris.
- Boulangier, E. (1888). Un Hiver au Cambodge. Chasses au tigre, à l'éléphant et au buffle sauvage, souvenirs d'une mission officielle remplie en 1880–1881, Alfred Mame et Fils. ed, 2e édition. Tours.
- Buchwald, V. F., & Wivel, H. (1998). Slag analysis as a method for the characterization and provenancing of ancient iron objects. *Materials Characterization*, 40, 73–96.
- Cadet, M., Pryce, T. O., Ciarla, R., Rispoli, F., Venunan, P., Lertcharnrit, T., & Iizuka, Y. (2024). Beyond 'community craft specialisation' in prehistoric Mainland Southeast Asian metallurgy: Copper smelting behaviours at Khao Sai On, Nil Kham Haeng, Non Pa Wai, Phromthin Tai, and Tha Kae in Central Thailand. *Asian Perspectives*, 63, 189–223.
- Caillière, S. (1972). Examen microscopique de trois échantillons du minerai de fer (Cambodge). Laboratoire de Minéralogie du Muséum National d'Histoire Naturelle.
- Carbonnel, J. -P. (1972). Le Quaternaire cambodgien : structure et stratigraphie.

- Carter, A. K., Dussubieux, L., Stark, M. T., & Gilg, H. A. (2020). Angkor Borei and protohistoric trade networks: A view from the glass and stone bead assemblage. *Asian Perspectives*, 60, 32–70. <https://doi.org/10.1353/asi.2020.0036>
- Celauro, A., Schiavon, N., Brunetti, A., Manfredi, L.-I., Susanna, F., Dekayir, A., Graziani, V., Pargny, D., & Ferro, D. (2014). Combining chemical data with GIS and PCA to investigate Phoenician-Punic Cu-metallurgy. *Applied Physics A*, 114, 711–722. <https://doi.org/10.1007/s00339-013-8179-0>
- Changmai, P., Pinhasi, R., Pietrusewsky, M., Stark, M. T., Ikehara-Quebral, R. M., Reich, D., & Fleogontov, P. (2022). Ancient DNA from protohistoric period Cambodia indicates that South Asians admixed with local populations as early as 1st–3rd centuries CE. *Scientific Reports*, 12, Article 22507. <https://doi.org/10.1038/s41598-022-26799-3>
- Charlton, M. (2009). Identifying iron production lineages. In S. Shennan (Ed.), *Pattern and Process in Cultural Evolution* (pp. 133–144).
- Charlton, M. F., Crew, P., Rehren, T., & Shennan, S. J. (2010). Explaining the evolution of ironmaking recipes - An example from northwest Wales. *Journal of Anthropological Archaeology*, 29, 352–367.
- Chen, J., & Han, R. (2013). The manufacture techniques and dates of iron objects found at several Chinese archaeological sites in recent years. In *The World of Iron*. Archetype Publications.
- Childs, S. T., & Killick, D. (1993). Indigenous African metallurgy: Nature and culture. *Annual Review of Anthropology*, 22, 317–337.
- Chirikure, S. (2007). Metals in society: Iron production and its position in Iron Age communities of southern Africa. *Journal of Social Archaeology*, 7, 72–100. <https://doi.org/10.1177/1469605307073164>
- Chirikure, S., & Bandama, F. (2014). Indigenous African furnace types and slag composition—Is there a correlation? *Archaeometry*. <https://doi.org/10.1111/arc.12013>
- Chirikure, S., Killick, D. J., & Stephens, J. (2023). Global commodities in precolonial Southern Africa: Local concepts and global conversations. *World Archaeology*, 55, 461–475. <https://doi.org/10.1080/00438243.2024.2425286>
- Choulean, A. (2006). The Kuy, their possible contribution to the Angkor power, cultural heritage: Thais and their neighbours. Presented at the Silpakorn University, Thai Fine Arts Department, SPAFA, Silpakorn University Alumni Association, Silpakorn University.
- Coedès, G. (1968). *The Indianized states of Southeast Asia*, University of Hawaii Press. ed, fulcrum.org. East-West Center Press.
- Contri, J. -P. (1972). Carte géologique de reconnaissance à 1:200 000, Tbeng Meanchey.
- Costin, C. L. (1991). Craft specialization: Issues in defining, documenting, and explaining the organization of production. *Archaeological Method and Theory*, 3, 1–56.
- Costin, C. L. (2001). Craft production systems. In G. M. Feinman, & T. D. Price (Eds.), (pp. 273–327). Springer US. https://doi.org/10.1007/978-0-387-72611-3_8
- Coustures, M. P., Béziat, D., Tollon, F., Domergue, C., Long, L., & Rebiscol, A. (2003). The use of trace element analysis of entrapped slag inclusions to establish ore - bar iron links: Examples from two Gallo-Roman iron-making sites in France (Les Martyrs, Montagne Noire, and les Ferrys, Loiret). *Archaeometry*, 45, 599–613.
- Crew, P., Charlton, M., Dillmann, P., Fluzin, P., Salter, C., & Truffaut, E. (2011). Cast iron from a bloomery furnace. In J. Hosek, H. Cleere, & L. Mihok (Eds.), *The Archaeometallurgy of Iron – Recent Developments in Archaeological and Scientific Research* (pp. 239–262). Prague.
- de Mestier du Bourg, H. (1971). La première moitié du XIe siècle au Cambodge: Suryavarman 1er, sa vie et quelques aspects des institutions à son époque. Impr. nationale, Paris.
- Desauty, A.-M., Dillmann, P., L'Héritier, M., Mariet, C., Gratuze, B., Joron, J.-L., & Fluzin, P. (2009). Does it come from the Pays de Bray? Examination of an origin hypothesis for the ferrous reinforcements used in French medieval churches using major and trace element analyses. *Journal of Archaeological Science*, 36, 2445–2462. <https://doi.org/10.1016/j.jas.2009.07.002>
- Dottin, O. (1971). *Géologie et mines du Cambodge*. Service National des Mines, de la Géologie et du Pétrole.
- Dufossé, M. (1934). *Monographie des peuplades Kouys du Cambodge*. Les Editions d'Extreme-Asie, Saigon, pp. 553–568.
- Dupaigne, B. (2002). Obtention du fer et rituels chez les métallurgistes du Cambodge. In *La Forge et Le Forgeron. I. Pratiques et Croyances*, Revue Eurasie. Paris, pp. 11–30.
- Dupaigne, B. (2016). *Les maîtres du fer et du feu dans le royaume d'Angkor*.
- Dupouy, G. (1913). *Etudes minéralogiques sur l'Indochine française. Minéraux, minerais, gisements. Eaux et limons. Industrie minérale indigène statistique*. Emile Larose.

- ESCAP, (1993). Atlas of mineral resources of the ESCAP region : Geological map of Cambodia ; Mineral resources map of Cambodia.
- Freestone, I. C. (2023). The archaeometry of glass. In *Handbook of Archaeological Sciences* (pp. 885–910). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781119592112.ch44>
- Freestone, I. C., Jackson-Tal, R. E., Taxel, I., & Tal, O. (2015). Glass production at an early Islamic workshop in Tel Aviv. *Journal of Archaeological Science*, 62, 45–54. <https://doi.org/10.1016/j.jas.2015.07.003>
- Fromaget, J. (1941). L'Indochine française, sa structure géologique, ses roches, ses mines et leurs relations possibles avec la tectonique. Impr. d'Extrême-Orient.
- Harada, H. (2010). Geological map of Cambodia. General Department of Mineral Resources (GDMR).
- Harmand, J. (1876). Voyage au Cambodge. Bull. Soc. Géographie Paris, Bulletin de la Société de géographie XII, 337–367.
- Heimann, R. B., Kreher, U., Spazier, I., & Wetzel, G. (2001). Mineralogical and chemical investigations of bloomery slags from prehistoric (8th century BC to 4th century AD) iron production sites in upper and lower Lusatia, Germany. *Archaeometry*, 43, 227–252. <https://doi.org/10.1111/1475-4754.00016>
- Hendrickson, M., & Evans, D. (2015). Reimagining the city of fire and iron: A landscape archaeology of the Angkor-period industrial complex of Preah Khan of Kompong Svay, Cambodia (ca. 9th to 13th centuries A.D.). *Journal of Field Archaeology*, 40, 644–664. <https://doi.org/10.1080/00934690.2015.1105034>
- Hendrickson, M., & Leroy, S. (2020). Sparks and needles: Seeking catalysts of state expansions, a case study of technological interaction at Angkor, Cambodia (9th to 13th centuries CE). *Journal of Anthropological Archaeology*, 57, 101141.
- Hendrickson, M., Hua, Q., & Pryce, T. O. (2013). Using in-slag charcoal as an indicator of “Terminal” iron production within the Angkorian period (10th–13th centuries AD) Center of Preah Khan of Kompong Svay, Cambodia. *Radiocarbon*, 55(1), 31–47.
- Hendrickson, M., Leroy, S., Quan, H., Phon, K., & Vooun, V. (2017). Smelting in the shadow of the Iron Mountain: Preliminary field investigation of the industrial landscape around Phnom Dek, Cambodia (9th to 20th centuries CE). *Asian Perspectives*, 56, 55–91.
- Hendrickson, M., Pryce, T., Sonnemann, T., Phon, K., Hua, Q., & Chan, S. (2018). Industries of Angkor project: Preliminary investigation of iron production at Boeng Kroam, Preah Khan of Kompong Svay. *Journal of Indo-Pacific Archaeology*. <https://doi.org/10.7152/jipa.v42i0.15257>
- Hendrickson, M., Leroy, S., Castillo, C., Hua, Q., Vega, E., & Phon, K. (2019). Forging empire: Angkorian iron smelting, community and ritual practice at Tonle Bak. *Antiquity*, 93, 1586–1606. <https://doi.org/10.15184/aqy.2019.174>
- Heng, P. (2018). Organizational change in political economy and ideology: Transition from the Early Historic to Pre-Angkorian Period Cambodia, ed from Thala Borivat. Dissertation. University of Hawai'i at Mānoa.
- Hørst-Madsen, L., & Buchwald, V. F. (1999). The characterisation and provenancing of ore, slag and iron from the Iron Age settlement in Snorup. *Journal of the Historical Metallurgy Society*, 33, 57–67.
- Humphris, J., Martínón-Torres, M., Rehren, T., & Reid, A. (2009). Variability in single smelting episodes – A pilot study using iron slag from Uganda. *Journal of Archaeological Science*, 36, 359–369. <https://doi.org/10.1016/j.jas.2008.09.020>
- Iles, L. (2014). The exploitation of manganese-rich ‘ore’ to smelt iron in Mwenge, western Uganda, from the mid second millennium AD. *Journal of Archaeological Science*, 49, 423–441. <https://doi.org/10.1016/j.jas.2014.05.029>
- Iles, L. (2018). Forging networks and mixing ores: Rethinking the social landscapes of iron metallurgy. *Journal of Anthropological Archaeology*, 49, 88–99. <https://doi.org/10.1016/j.jaa.2017.10.001>
- Jacques, C., & Lafond, P. (2004). L'Empire khmer: cités et sanctuaires, Ve–XIIIe siècles. Fayard.
- Jayawardana, D. T., Balasooriya, N. W. B., & Weerakoon, W. A. P. (2014). Geochemical characteristics of hydrated iron-ore deposit in Dela, Sri Lanka. *Journal of the Geological Society of Sri Lanka*, 16, 43–52.
- Juleff, G. (1996). An ancient wind-powered iron smelting technology in Sri Lanka. *Nature*, 379, 60–63. <https://doi.org/10.1038/379060a0>
- Juleff, G. (2009). Technology and evolution: A root and branch view of Asian iron from first-millennium bc Sri Lanka to Japanese steel. *World Archaeology*, 41, 557–577. <https://doi.org/10.1080/00438240903345688>
- Keiji, N., & Yamamura, K. (1988). Shaping the process of unification: Technological progress in Sixteenth- and Seventeenth-Century Japan. *Journal of Japanese Studies*, 14, 77–109. <https://doi.org/10.2307/132532>

- Killick, D. (1991). A little-known extractive process: Iron smelting in natural-draft furnaces. *JOM Journal of the Minerals Metals and Materials Society*, 43, 62–64. <https://doi.org/10.1007/bf03220550>
- Kozuka, J. (1968). “Tatara” process - a pig iron- and steel-making process, transmitted from ancient times in Japan-. *Transactions of the Iron and Steel Institute of Japan*, 8, 36–47. <https://doi.org/10.2355/isijinternational1966.8.36>
- Lankton, J. W., Pulak, C., & Gratuze, B. (2022). Glass ingots from the Uluburun shipwreck: Glass by the batch in the Late Bronze Age. *Journal of Archaeological Science: Reports*, 42, 103354. <https://doi.org/10.1016/j.jasrep.2022.103354>
- Lebon, M., Gallet, X., Bondetti, M., Pont, S., Mauran, G., Walter, P., Bellot-Gurlet, L., Puaud, S., Zazzo, A., Forestier, H., Auetrakulvit, P., & Zeitoun, V. (2019). Characterization of painting pigments and ochres associated with the Hoabinhian archaeological context at the rock-shelter site of Doi Pha Kan (Thailand). *Journal of Archaeological Science: Reports*, 26, 101855. <https://doi.org/10.1016/j.jasrep.2019.05.020>
- Léger, A. (1925). Societe des mines de fer du Cambodge. Entrep. Colon., L’Éveil économique de l’Indochine.
- Leroy, S. (2018). *Preliminary scientific report on the investigation of the slag samples from Phu Lek, report for the Vat Phu - Champasak World Heritage Office*. CNRS, Université Paris-Saclay.
- Leroy, S., Cohen, S. X., Verna, C., Gratuze, B., Téreygeol, F., Fluzin, P., Bertrand, L., & Dillmann, P. (2012). The medieval iron market in Ariège (France). Multidisciplinary analytical approach and multivariate analyses. *Journal of Archaeological Science*, 39, 1080–1093. <https://doi.org/10.1016/j.jas.2011.11.025>
- Leroy, S., Hendrickson, M., Bauvais, S., Vega, E., Blanchet, T., Disser, A., & Delque-Kolic, E. (2017). The ties that bind: Archaeometallurgical typology of architectural crampons as a method for reconstructing the iron economy of Angkor, Cambodia (tenth to thirteenth c.). *Archaeological and Anthropological Sciences*. <https://doi.org/10.1007/s12520-017-0524-3>
- Leroy, S., Bauvais, S., Delqué-Količ, E., Hendrickson, M., Josso, N., Dumoulin, J.-P., & Soutif, D. (2020). First experimental reconstruction of an Angkorian iron furnace (13th–14th centuries CE): Archaeological and archaeometric implications. *Journal of Archaeological Science: Reports*, 34, 102592. <https://doi.org/10.1016/j.jasrep.2020.102592>
- Leroy, S., & Hendrickson, M. (In press). La production et la circulation du fer dans le royaume angkorien éclairées par les crampons architecturaux des temples d’Angkor. In P. Charlier, F. -X. Fauvelle, D. Garcia (Eds.), *Anthropologie et archéologie du fer*. 978–2–87772–973–4. [ffhal04367427f](https://doi.org/10.1007/978-2-87772-973-4)
- Liu, R., & Pollard, A. M. (2022). Squeezing mind out of metal: Combining textual evidence with scientific data for metallurgy in early dynastic China. *Archaeological and Anthropological Sciences*, 14, 117. <https://doi.org/10.1007/s12520-022-01578-3>
- Liu, H., Qian, W., Chen, J., Li, Y., Guo, J., & Liu, N. (2014). A preliminary study of furnace materials from Shuiquangou Iron Smelting Site of Liao and Jin Period in Beijing. *ISIJ International*, 54, 1159–1166. <https://doi.org/10.2355/isijinternational.54.1159>
- Martinón-Torres, M. (2023). Making and using metals. In *Handbook of Archaeological Sciences* (pp. 935–952). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781119592112.ch46>
- Martinón-Torres, M., Li, X. J., Bevan, A., Xia, Y., Zhao, K., & Rehren, T. (2014). Forty thousand arms for a single emperor: From chemical data to the labor organization behind the bronze arrows of the Terracotta Army. *Journal of Archaeological Method and Theory*, 21, 534–562. <https://doi.org/10.1007/s10816-012-9158-z>
- Mathoho, E. N., Bandama, F., Moffett, A. J., & Chirikure, S. (2016). A technological and anthropological study of iron production in Venda, Limpopo Province, South Africa. *Azania: Archaeological Research in Africa*, 51, 234–256. <https://doi.org/10.1080/0067270X.2016.1177937>
- Michel (Michel-Tanaka), X. (2023). Le fonctionnement d’une opération du tatara d’après le « Tetsuzan Hitsujo Kiji ». 東京理科大学教養教育研究紀要.
- Mikulec, R., Hlavica, M., & Kmošek, M. (2022). Archaeological evidence of independent iron production from the 9th-century rural settlement of Bořitov (Blansko District, Czechia). *Archeology & History*, 47, 763–794.
- Miller, D., & Killick, D. (2004). Slag identification at Southern African archaeological sites. *Journal of African Archaeology*, 2, 23–47. <https://doi.org/10.3213/1612-1651-10017>
- Morel, M. (2017). Etude de provenance pour la compréhension des réseaux de production et de distribution du fer dans l’Empire khmer Application d’une approche intégrée sur des objets du quotidien (VIe -XIVe siècles) (Master 1 Matériaux du patrimoine Culturel et Archéométrie, Bordeaux).

- Morel, M., Serneels, V., Robion-Brunner, C., & Kiénon Kabore, H. T. (2025). Efficiency of ancient iron production: A case study from the Kaniasso district, Ivory Coast (11th–19th century). *Journal of Archaeological Science: Reports*, 63, 105089. <https://doi.org/10.1016/j.jasrep.2025.105089>
- Morton, G. R., Wingrove, J., & Experimental Archaeology Collection Manager, E. X. A. R. C. (1972). Constitution of bloomery slags: Part II: Medieval. *J. Iron Steel Inst.*, 210, 478–488.
- Moura, J. (1874). Notes sur le minerai de fer de Compong Soai au Cambodge. *Bull. Com. Agric. Ind. Cochinchine*, Bulletin du Comité agricole et industriel de Cochinchine I, 147–151.
- Paynter, S. (2006). Regional variations in bloomery smelting slag of the Iron Age and Romano-British periods. *Archaeometry*, 48, 271–292.
- Pelet, P. -L., de Carvalho-Zwahlen, B., & Decollogny, P. (1993). Une industrie reconnue : fer, charbon, acier dans le Pays de Vaud. <https://doi.org/10.5169/SEALS-835406>
- Pelliot, P. (1903). Le Fou-nan. *Bull. L'École Fr. Extrême-orient* 3, 248–303. <https://doi.org/10.3406/befeo.1903.1216>
- Piatak, N. M., & Seal, R. R. (2012). Mineralogy and environmental geochemistry of historical iron slag, Hopewell Furnace National Historic Site, Pennsylvania, USA. *Applied Geochemistry*, 27, 623–643. <https://doi.org/10.1016/j.apgeochem.2011.12.011>
- Pleiner, R. (2000). Iron in archaeology. The European bloomery smelters. Archeologický ústav AVČR, Praha.
- Pryce, T. O., Pigott, V. C., Martínón-Torres, M., & Rehren, T. (2010). Prehistoric copper production and technological reproduction in the Khao Wong Prachan Valley of Central Thailand. *Archaeological and Anthropological Sciences*, 2, 237–264. <https://doi.org/10.1007/s12520-010-0043-y>
- Pryce, T. O., Hendrickson, M., Phon, K., Chan, S., Charlton, M. F., Leroy, S., Dillmann, P., & Hua, Q. (2014). The iron kuay of Cambodia: Tracing the role of peripheral populations in Angkorian to colonial Cambodia via a 1200 year old industrial landscape. *Journal of Archaeological Science*, 47, 142–163. <https://doi.org/10.1016/j.jas.2014.04.009>
- Pryce, T. O., Cadet, M., Tomczyk, C., Venunan, P., Lertcharnrit, T., Ciarla, R., & Rispoli, F. (2024). Ricardo's law of comparative advantage in bronze age, iron age, and early historic mainland Southeast Asian metallurgy: Copper-base metal production, exchange, and consumption behaviours at Khao Sai On, Nil Kham Haeng, Non Pa Wai, Phromthin Tai, Sab Champa, and Tha Kae in Central Thailand. *Asian Perspectives*, 63, 151–188. <https://doi.org/10.1353/asi.2024.a948116>
- Qian, W., & Huang, X. (2021). Invention of cast iron smelting in early China: Archaeological survey and numerical simulation. *Advanced Archaeomaterials*, 2, 4–14. <https://doi.org/10.1016/j.aia.2021.04.001>
- Rademakers, F. W., & Rehren, T. (2016). Seeing the forest for the trees: Assessing technological variability in ancient metallurgical crucible assemblages. *Journal of Archaeological Science: Reports*, 7, 588–596. <https://doi.org/10.1016/j.jasrep.2015.08.013>
- Rehder, J. E. (2000). *The mastery and uses of fire in antiquity*. McGill-Queen's University Press.
- Rehren, T., Charlton, M., Chirikure, S., Humphris, J., Ige, A., & Veldhuijzen, H. A. (2007). Decisions set in slag: the human factor in African iron smelting, in: *Metal and Mines*. pp. 211–218.
- Robion-Brunner, C., Serneels, V., & Perret, S. (2013). Variability in iron smelting practices : Assessment of technical, cultural and economic criteria to explain the metallurgical diversity in the Dogon area (Mali). In J. Humphris & T. Rehren (Eds.), *The World of Iron* (pp. 257–265). Archetype Publication.
- Robion-Brunner, C., Coustures, M. -P., Dugast, S., Tchetre-Gbandi, A., & Béziat, D. (2022). Origines et étapes de la diversité des techniques sidérurgiques en Afrique de l'Ouest : le cas de la production du fer en pays bassar (nord du Togo) du XIIIe au XXe siècles. *Afr. Débats Méthodes Terrains D'histoire*. <https://doi.org/10.4000/afriques.3408>
- Rostoker, W., & Bronson, B. (1990). Pre-industrial Iron: Its Technology and Ethnology, *Archeomaterials monograph*. Archeomaterials.
- Roux, V. (2013). Spreading of innovative technical traits and cumulative technical evolution: Continuity or discontinuity? *Journal of Archaeological Method and Theory*, 20, 312–330. <https://doi.org/10.1007/s10816-012-9153-4>
- Roux, V. (2015). Standardization of ceramic assemblages: Transmission mechanisms and diffusion of morpho-functional traits across social boundaries. *Journal of Anthropological Archaeology*, 40, 1–9. <https://doi.org/10.1016/j.jaa.2015.04.004>
- Saladin, E., & Fuchs, E. (1882). Mémoire sur l'exploration des gîtes de combustibles et de quelques-uns des gîtes métallifères de l'Indo-Chine, extrait du Rapport adressé aux ministres de la Marine et des Travaux publics et au gouverneur de la Cochinchine. *Annales des Mines* 185–298.

- Scott, R. B., Eekelers, K., & Degryse, P. (2016). Quantitative chemical analysis of archaeological slag material using handheld X-ray fluorescence spectrometry. *Applied Spectroscopy*, *70*, 94–109.
- Serneels, V. (1993). Archéométrie des scories de fer. Recherches sur la sidérurgie ancienne en Suisse occidentale, Cahiers d'Archéologie Romande, 61. Cahiers d'Archéologie Romande, Lausanne.
- Shimoda, I., & Shimamoto, S. (2012). Spatial and chronological sketch of the ancient city of Sambor Prei Kuk. *Aséanie*, *30*, 11–74. <https://doi.org/10.3406/asean.2012.2251>
- Solangaarachchi, R. (2011). Ancient iron smelting technology and the settlement pattern in the kiri oya basin in the dry zone of Sri Lanka.
- Speakman, R. J., & Steven Shackley, M. (2013). Silo science and portable XRF in archaeology: A response to Frahm. *Journal of Archaeological Science*, *40*, 1435–1443. <https://doi.org/10.1016/j.jas.2012.09.033>
- Stark, M. T., & Cremin, A. (2023). Angkor and China: 9th–15th Centuries, in: The Angkorian World. Routledge.
- Tate, M. (2005). History of iron and steel making technology in Japan - Mainly on the smelting of iron sand by Tatara. Tetsu-to-Hagane 91.
- Tawara, K. (2007). 古来の砂鉄製錬法 [Traditional Iron Sand Smelting Techniques].
- Thuy, C., 2014. Iron and Stone. Ancient Khmer. Result of Research into the Ancient Khmer Iron Smelters. Cambodia Research. Phnom Penh.
- Tomczyk, C., & Żabiński, G. (2024). A PCA-AHC approach to provenance studies of non-ferrous metals with combined Pb isotope and chemistry data. *Journal of Archaeological Method and Theory*, *31*, 93–143. <https://doi.org/10.1007/s10816-022-09598-y>
- Uchida, E., Murasugi, M., Kuroda, A., & Lu, Y. (2019). Chemical compositional signatures of constituent minerals of iron slags and ores from the Khmer monuments. *Heritage*, *2*, 1724–1738. <https://doi.org/10.3390/heritage2020105>
- Vega, E., Leroy, S., Dillmann, P., Gaspard, P., Hendrickson, M., & Téreygeol, F. (2019). L'analyse chimique des déchets sidérurgiques sur le terrain par pXRF Un jeu d'échelle sous contraintes. <https://doi.org/10.17184/eac.2465>
- Veldhuijzen, H. A., & Rehren, T. (2007). Slags and the city: early iron production at Tell Hammeh, Jordan and Tel Beth-Shemesh, Israel. In S. LaNiece, D. R. Hook, & P. T. Craddock (Eds.), *Metals and Mines : Studies in Archaeometallurgy* (pp. 189–201). Archetype/British Museum.
- Verna, C. (2001). Le temps des Moulines. Fer, technique et société dans les Pyrénées centrales (XIIIe - XVIe siècles). Publications de la Sorbonne.
- Vickery, M. (1985). The reign of Sūryavarman I and royal factionalism at Angkor. *Journal of Southeast Asian Studies*, *16*, 226–244. <https://doi.org/10.1017/S0022463400008420>
- Vodyasov, E. V., Amzarakov, P. B., Sadykov, T. R., Shirin, Y. V., Zaitceva, O. V., Leipe, C., & Tarasov, P. E. (2023). Nine types of iron smelting furnaces in southern Siberia in the first millennium AD: A review of archaeological and chronological data. *Archaeological Research in Asia*, *36*, 100479. <https://doi.org/10.1016/j.ara.2023.100479>
- Wade, G. (2009). An early age of commerce in Southeast Asia, 900–1300 CE. *Journal of Southeast Asian Studies*, *40*, 221–265. <https://doi.org/10.1017/S0022463409000149>
- Walmsley, A., Serneels, V., Hajdas, I., & Mayor, A. (2020). Variability of early iron production in the Falémé Valley region, eastern Senegal. *African Archaeological Review*, *37*, 225–250. <https://doi.org/10.1007/s10437-020-09381-y>
- Wenger, E. (1998). Communities of practice: Learning, meaning, and identity, Communities of practice: Learning, meaning, and identity. Cambridge University Press. <https://doi.org/10.1017/CBO9780511803932>
- Young, T., Poyner, D., Bryant, V., & Clapham, A. (2012). Two medieval bloomery sites in Shropshire: The adoption of water power for iron smelting. *J. Hist. Metall. Soc.*, *46*, 78–97.
- Zhou, D., & Harris, P. (2007). *A record of Cambodia: The land and its people*. Silkworm Books.
- Zou, G., Min, R., Cui, J., Ma, R., Zhou, X., & Yang, C. (2019). The special iron making in Southwest China around the 10th CE: Scientific evidence from an iron smelting site in Erhai lake area, Yunnan province. *Journal of Cultural Heritage*, *37*, 266–272. <https://doi.org/10.1016/j.culher.2018.10.015>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted

manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Stéphanie Leroy¹ · Mitch Hendrickson² · Enrique Vega¹ · Quan Hua^{3,4} · Kaseka Phon⁵

✉ Stéphanie Leroy
stephanie.leroy@cnrs.fr

¹ LAPA–IRAMAT, NIMBE, CEA, CNRS, CEA Saclay, Université Paris-Saclay, 91191 Gif-Sur-Yvette, France

² Department of Anthropology, University of Illinois at Chicago, Chicago, IL 60607, USA

³ Australian Nuclear Science and Technology Organisation, Kirrawee DC, NSW 2232, Australia

⁴ School of Social Science, University of Queensland, St Lucia, QLD 4072, Australia

⁵ Institute of Humanities and Social Sciences, Royal Academy of Cambodia, Phnom Penh 12000, Cambodia