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Hydrological Assessment of Historic Iron-Production Landscapes: A Spatial Analysis of Mining Sites and Reduction Workshops in the Rural Municipality of Nébiélianayou (Sissili, Burkina Faso)

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Abstract: Understanding the relationship between ancient technological systems and their environmental context is a key issue in geoarchaeology and landscape archaeology. In West Africa, ancient iron metallurgy significantly shaped regional landscapes through the exploitation of iron ore deposits and the establishment of smelting workshops, whose remains still structure contemporary territories. However, the environmental factors influencing the spatial organization of these metallurgical activities remain insufficiently documented in several regions of Burkina Faso. This study investigates the influence of hydrographic networks on the spatial distribution of ancient metallurgical sites in the rural commune of Nébiélianayou, located in the Sissili Province in southern Burkina Faso. The dataset derives from geoarchaeological surveys that identified 8 ancient iron ore mining sites and 55 smelting workshops. Spatial analysis was conducted using a Geographic Information System (GIS), applying a proximity-based approach through the creation of buffer zones around river systems to assess the distribution of metallurgical sites relative to watercourses. The results reveal a strong concentration of smelting workshops near rivers, with more than 83% of the sites located within 500 m of watercourses. In contrast, mining sites exhibit a more dispersed distribution largely controlled by the geological availability of iron ore deposits. These findings highlight a spatial differentiation within the metallurgical chaîne opératoire, where extraction activities are constrained by ore availability, whereas smelting activities are preferentially located in valley environments providing favorable resources such as water and woody biomass required for charcoal production. Overall, this study emphasizes the structuring role of valley environments in shaping ancient iron production landscapes and demonstrates the relevance of spatial analytical approaches for understanding the interactions between technological systems and environmental resources in West African archaeological contexts.

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I. INTRODUCTION

Ancient iron metallurgy represents one of the major technological transformations that profoundly reshaped the historical trajectories of pre-colonial African societies. Across sub-Saharan Africa, iron production not only enabled the development of agricultural tools and weapons, but also contributed to the structuring of regional economies, trade networks, and forms of social organization (Hamady Bocoum, 2004; Augustin F. C. Holl, 2009). Archaeological research conducted over several decades has thus revealed the existence of ancient and often highly sophisticated ironworking traditions in many regions of West Africa. The archaeological landscapes of these regions still preserve the physical traces of these metallurgical activities in the form of ancient mines, ironworking remains, reduction furnaces, and large slag heaps. These remains bear witness to production systems that were at times intensive, revealing the existence of distinct metallurgical landscapes structured around the mining and processing of iron ore. From this perspective, the study of the spatial distribution of metallurgical sites is central to understanding the territorial organization of historical iron and steel production and its relationship with the natural environment (Graham Connah, 2001; Roderick J. McIntosh, 1999). Several studies have shown that the location of iron production sites is not simply a matter of ore availability, but

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is shaped by a set of environmental constraints and opportunities. Traditional iron and steel production requires the simultaneous mobilization of several natural resources, notably iron ore, wood for charcoal production, and water essential to various stages of the technical process. Thus, the location of reduction facilities is often closely linked to the ecological characteristics of the landscape and the accessibility of the resources necessary for production (Scott MacEachern, 2005). In this context, river systems play a particularly important role in the spatial organization of ancient metallurgical activities. River valleys provide favorable environments for water supply, the availability of plant resources, and the movement of goods and people. Several archaeological studies conducted in West Africa have thus suggested that ancient ironworking systems frequently developed near watercourses, which play a decisive structuring role in the organization of technical and economic landscapes (Thurstan Shaw, 1993; Roderick J. McIntosh, 2005). Despite the importance of this research, the relationship between hydrography and the spatial organization of metallurgical production remains insufficiently documented in several regions of West Africa, particularly in Burkina Faso. In this country, research on the archaeology of iron has focused primarily on the identification of ironworking remains and the technological study of furnaces, while the spatial and environmental dimensions of production systems remain relatively unexplored.

The municipality of Nébiélianayou, located in the province of Sissili in central-western Burkina Faso, is a particularly relevant case study in this regard. Archaeological surveys conducted in this region have identified several sites associated with ancient iron metallurgy, including old iron ore mines and numerous smelting workshops. The spatial distribution of these sites appears to indicate a frequent proximity to the local river system, suggesting that waterways may have played an important role in the selection of locations for metallurgical activities. However, this relationship has yet to be systematically demonstrated through quantitative spatial analysis. The development of geographic information systems (GIS) now offers particularly effective tools for analyzing the relationships between archaeological sites and elements of the natural landscape.I n particular, buffer zone analysis allows for a precise assessment of the distance between metallurgical sites and watercourses, while spatial density methods (Kernel Density) enable the identification of areas where production activities are concentrated. With this in mind, the present study aims to analyze the spatial relationships between former metallurgical sites (mines and reduction workshops) and the hydrographic network in the municipality of Nébiélianayou. By utilizing GIS spatial analysis tools, the objective is to examine the extent to which proximity to watercourses influenced the spatial organization of former iron and steel activities. More specifically, this research seeks to answer the following question: to what extent have hydrographic networks influenced the spatial distribution of iron ore extraction and reduction sites in the municipality of Nébiélianayou? The main hypothesis is that the majority of reduction workshops and former mines are located at a relatively short distance from waterways, reflecting a functional dependence of metallurgical activities on valley environments.

By providing a detailed spatial analysis of the relationships between ironworking sites and the river network, this study contributes to a better understanding of the organizational dynamics of ancient metallurgical landscapes in Nébiélianayou, West Africa, and, more broadly, of the interactions between pre-colonial societies and the environment.

II. METHODOLOGY

➢ *Study Area*

This study was conducted in the rural commune of Nébiélianayou, located in the province of Sissili, in the central-western region of Burkina Faso. This commune lies within the Sudano-Sahelian climate zone (Figure 1), characterized by alternating wet and dry seasons. The local hydrographic network consists of several seasonal watercourses belonging to the Volta River basin, which strongly shape the landscape and human activities.

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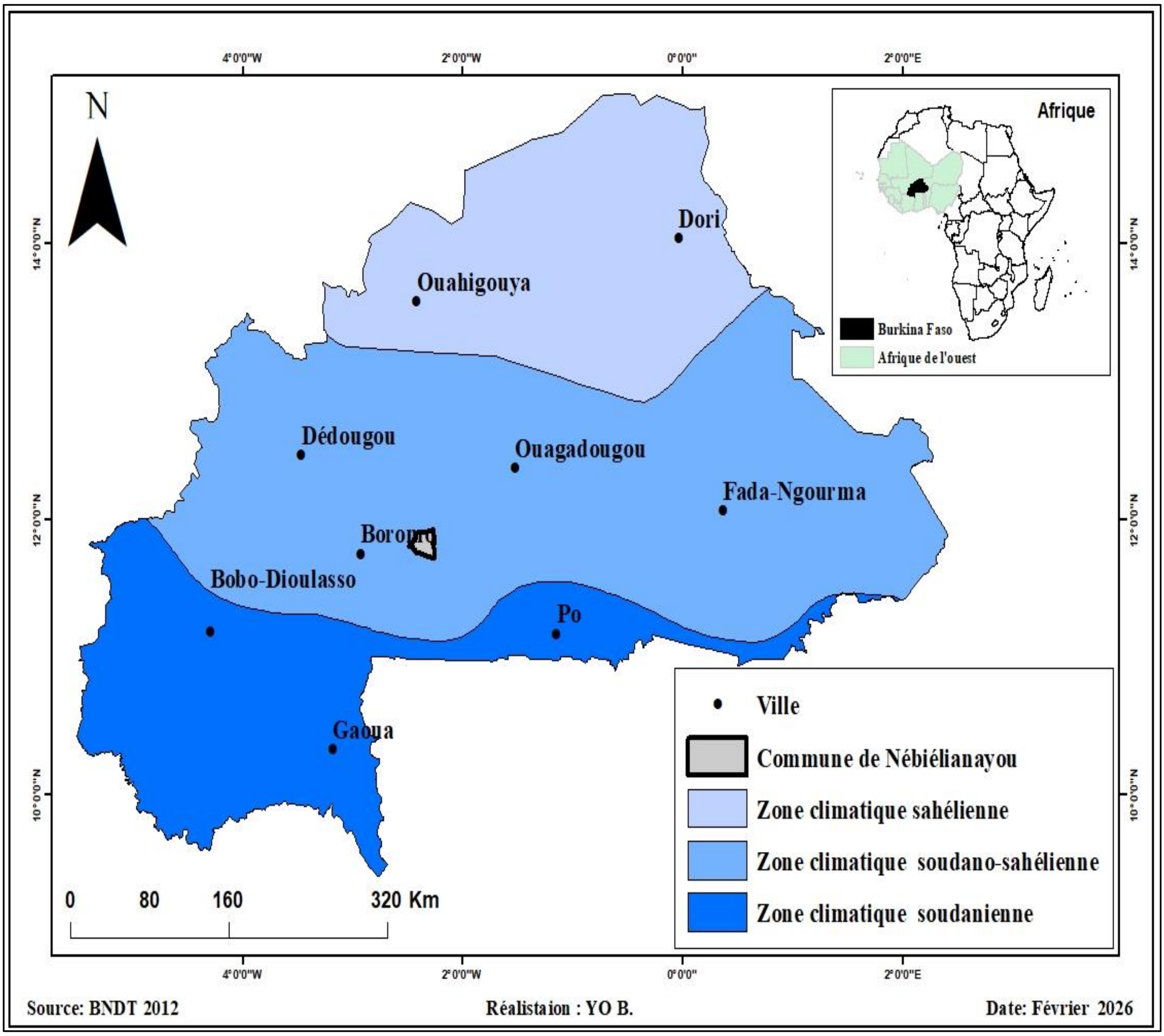

Fig 1 Location of the Study Area

Archaeological surveys conducted in this municipality have identified several remains associated with ancient iron metallurgy, notably old ore mines and smelting workshops characterized by the presence of slag and furnace remains. The spatial distribution of these remains suggests a potential relationship with the local river system, which justifies conducting an in-depth spatial analysis.

➢ *Collection and Processing of Spatial Data*

The data used in this study come from two main sources: field surveys and cartographic data. Geoarchaeological surveys made it possible to locate and record the geographic coordinates of the various metallurgical remains identified in the municipality, notably the former ore mines and smelting workshops. The geographic locations of these sites were recorded using a portable GPS device and then converted into digital format to create a spatial database. Hydrographic data and administrative boundaries were obtained from the National Topographic Database (BNDT) and other available cartographic sources for Burkina Faso. This data was integrated into a geographic information system to enable spatial analysis of the relationships between metallurgical sites and the hydrographic network. All data was projected into the WGS 84 / UTM Zone 30N coordinate system, which is commonly used for spatial analyses in West Africa.

➢ *Creation of the Geoarchaeological Database*

The collected data were organized into a geographic database comprising several layers of information:

- The layer of former iron ore mines
- The layer of smelting workshops
- The layer of the hydrographic network
- The layer of current villages
- The administrative boundary of the municipality of Nébiélianayou

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Each archaeological site was characterized by several attributes, such as site type (mine or reduction workshop), geographic coordinates, the nearest village, and field archaeological observations. This database enabled various spatial analyses aimed at understanding the logic behind the location of metallurgical sites.

➢ *Spatial Analysis of the Relationship between Metallurgical Sites and Watercourses Buffer Analysis*

To assess the influence of waterways on the location of metallurgical sites, a proximity analysis was conducted using the buffer zone method within a GIS environment. This method involves creating concentric zones around waterways to measure the distance between them and archaeological sites. Several distances (100 m, 200 m, 300 m, 400 m, 500 m, 600 m, 700 m, 800 m, 1000 m, and 1500 m) were selected for creating the buffers. These distances allow for a progressive analysis of the distance of metallurgical sites from watercourses. A spatial intersection operation was then performed between the buffers and the archaeological site layers to identify the number of mines and workshops located within each distance zone.

➢ *Spatial Density Analysis (Kernel Density)*

Kernel Density Estimation (KDE) was used to identify areas of concentration of metallurgical sites in the study region. This spatial method allows point data (the locations of archaeological sites) to be transformed into a continuous surface representing the intensity of their spatial distribution. For this study, the geographic coordinates of the inventoried archaeological sites were entered into a geographic information system (GIS) and analyzed using the Kernel Density tool available in ArcGIS software. For each raster cell, the algorithm calculates the density of points located within a defined search radius by applying a weighting function that assigns decreasing influence to points as distance increases. This approach makes it possible to:

- Identify spatial clusters of metallurgical production;
- To highlight areas with high concentrations of steel industry activity;
- To explore the spatial relationships between metallurgical sites and environmental factors, particularly the hydrological network and resource availability.

The results are presented as a raster density map, where higher values indicate areas with a high concentration of sites. This representation thus allows us to visualize ancient metallurgical landscapes and interpret the spatial organization of ironworking activities in the studied region. Density analysis is an effective tool for detecting spatial patterns that are not visible in the raw distribution of archaeological points, thereby enabling the interpretation of the logic behind the location of ancient metallurgical activities.

➢ *Statistical Analysis of Site Distribution*

The results obtained from the buffer analysis were summarized in statistical tables to measure the distribution of sites based on their distance from watercourses. This analysis aims to:

- Identify the most common distances between metallurgical sites and waterways
- Determine whether there is a particular concentration of sites near the river network
- Assess the relative importance of water in the selection of locations for metallurgical activities.

Comparing former mines with smelting facilities also allows for the identification of potential differences in the spatial logic of site selection between extraction sites and ore processing sites.

➢ *Mapping and Visualization of Results*

The results of the spatial analysis were represented using thematic maps created in a GIS environment. These maps allow for the visualization of the spatial distribution of former mines and smelting facilities, their relationship with the river network, and the areas where metallurgical activities were concentrated. Mapping is therefore an essential tool for the geoarchaeological interpretation of the ancient metallurgical landscape of the municipality of Nébiélianayou.

III. RESULTS

➢ *Spatial Distribution of Former Mines Relative to the River Network*

The proximity analysis conducted using buffer zones (Figure 3) established around the hydrographic network reveals a variable relationship between former iron ore mines and watercourses. Of the eight mining sites identified in the rural commune of Nébiélianayou, the spatial distribution shows a relative concentration in areas of intermediate proximity to watercourses.

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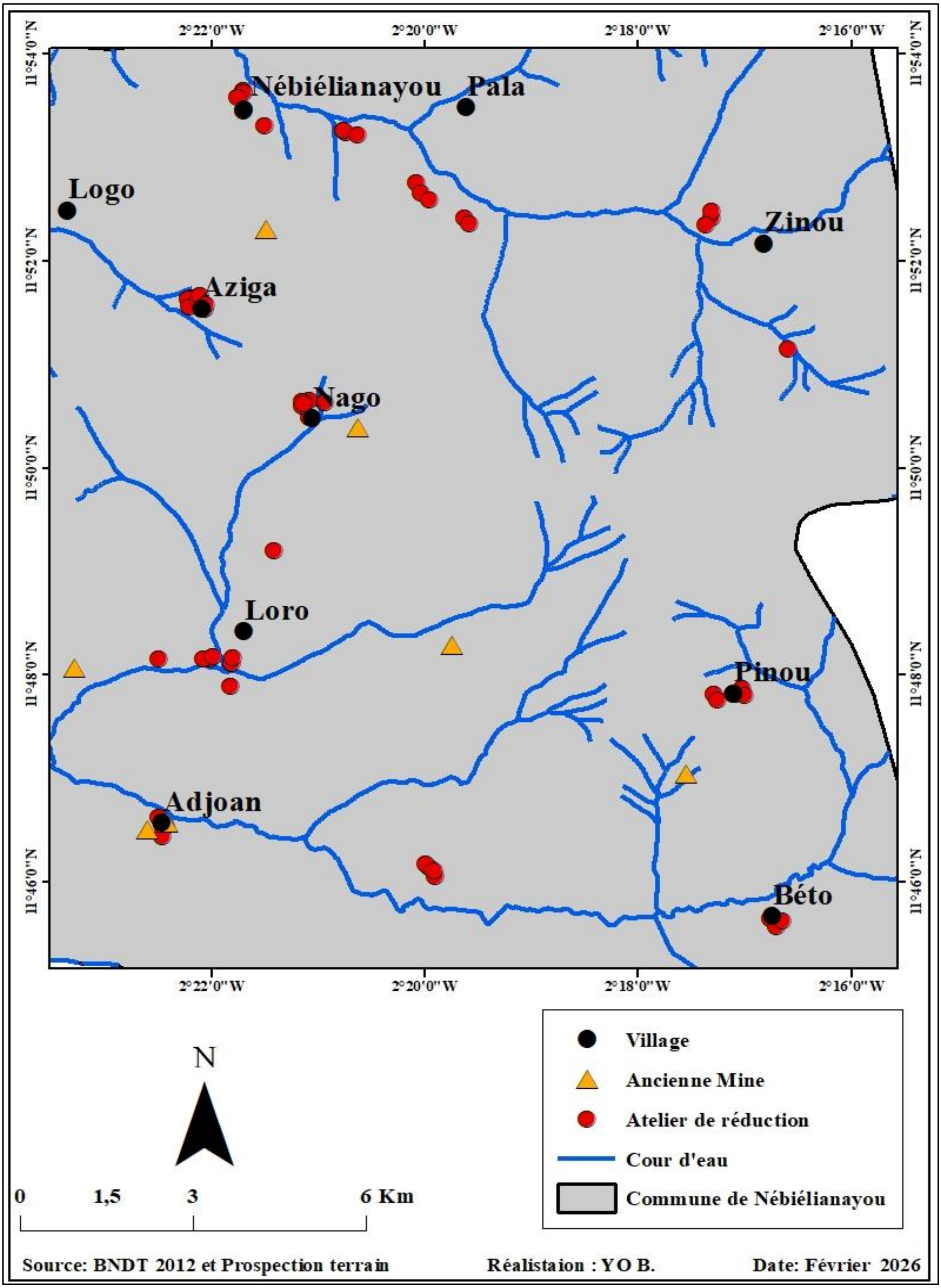

Fig 2 Distribution of Metallurgical Sites

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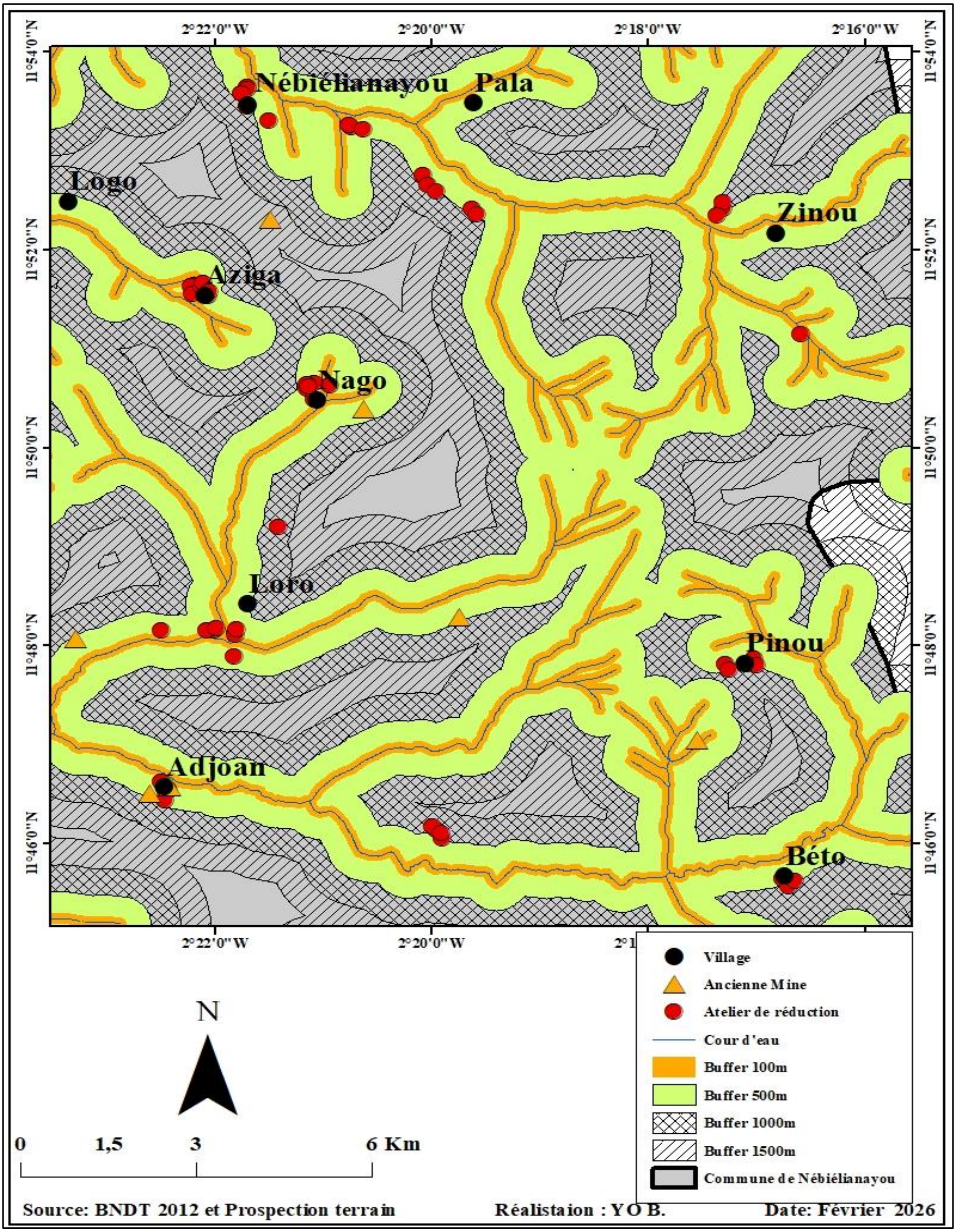

Fig 3 Analysis of Buffer Zones Around Waterways

The results indicate that 12.5% of the mines are located less than 100 m from a watercourse, 12.5% are located 200 m away, 12.5% 300 m, 37.5% at 500 m, 12.5% at 1,000 m, and 12.5% at 1,500 m (Figure 4).

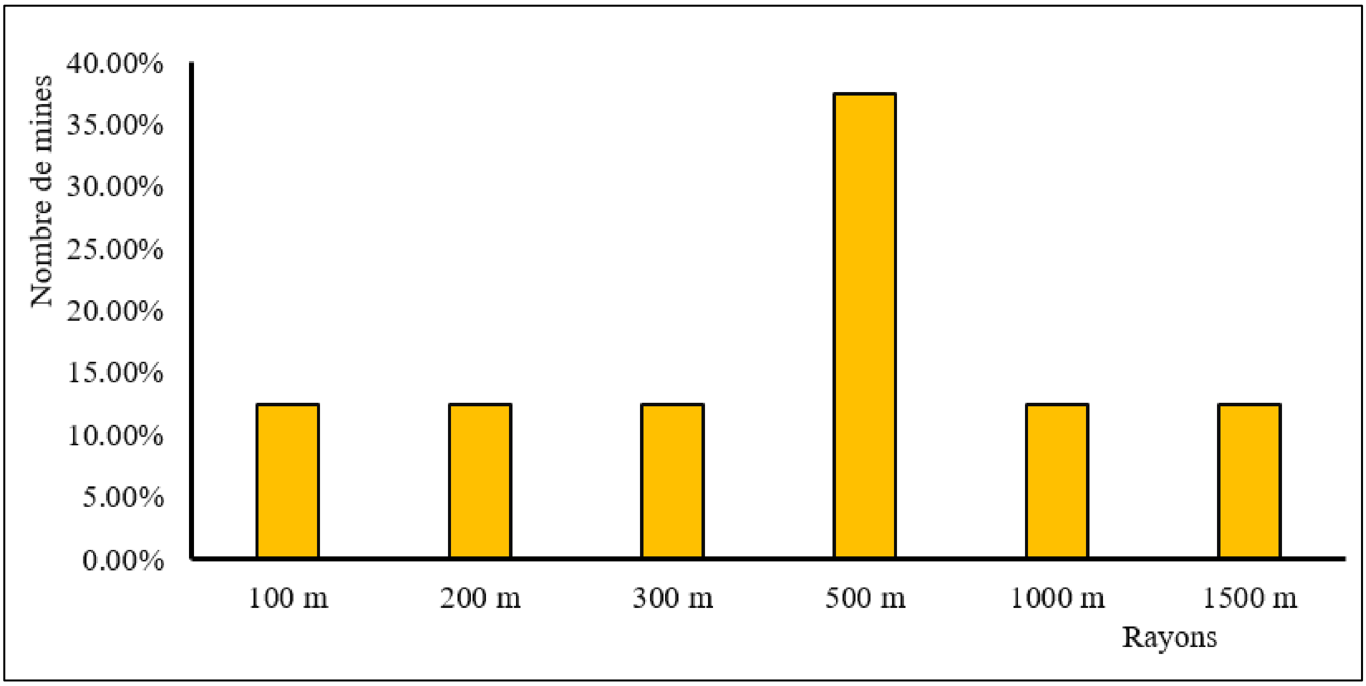

Fig 4 Distance of Mines from Watercourses

Thus, 75% of mining sites are located within 500 meters of waterways, while 25% are located at greater distances. This distribution indicates that, although proximity to water may be a favorable factor for certain activities associated with mining, it does not appear to be a determining factor in the location of mining areas. This situation is mainly explained by geological constraints related to the spatial distribution of iron ore deposits. Indeed, mines are primarily located where exploitable ore outcrops, which limits the miners' options regarding the location of these sites. The presence of certain mines relatively far from the river network suggests that ancient communities prioritized access to ore over the immediate proximity of water resources.

➢ *Spatial Concentration of Reduction Workshopsnear Watercourses*

Unlike mines, the spatial distribution of ore reduction facilities (Figure 5) reveals a much stronger correlation with the river network. Analysis of the 55 identified facilities shows a high concentration in areas near watercourses. The distribution of facilities by distance from watercourses shows that 3.6% of facilities are located within 100 m, 27.3% within 200 m, 21.8% within 300 m, 16.4% within 400 m, 14.5% within 500 m, 12.7% within 600 m, 1.8% within 700 m, and 1.8% within 800 m.

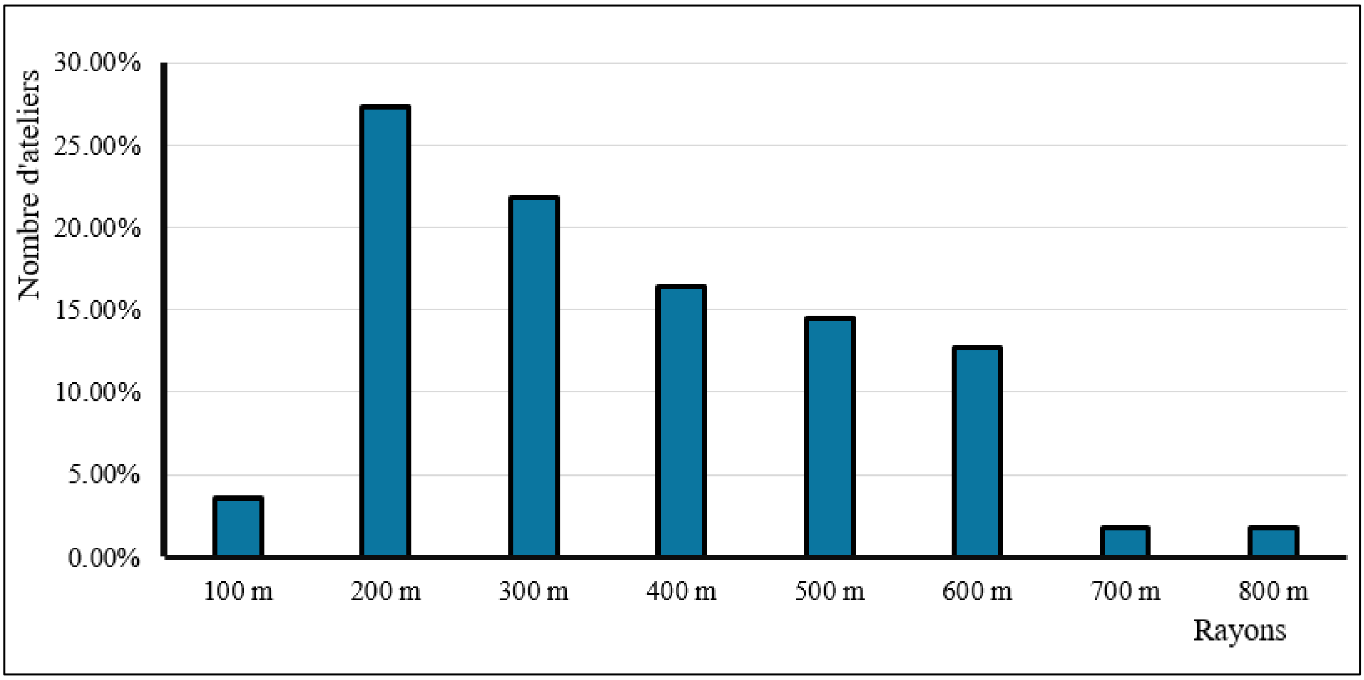

Fig 5 Distance of Log-Processing Facilities from Waterways

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The cumulative analysis shows that 52.7% of the workshops are located less than 300 m from watercourses; 69.1% less than 400 m; 83.6% less than 500 m; and 96.4% less than 600 m. These results reflect a very clear concentration of workshops in areas close to waterways, indicating that access to water resources and valley environments played a decisive role in the spatial organization of steel production. The decreasing distribution of the number of workshops as the distance to watercourses increases suggests the existence of a spatial gradient of attractiveness linked to the hydrographic network.

- *Analysis of the Spatial Density of Steel Production Sites*

The kernel density analysis (Figure 6) applied to iron reduction workshops highlights a non-random spatial distribution of metallurgical remains in the municipality of Nébiélianayou. The density map reveals several areas of marked concentration, corresponding to former centers of steel production.

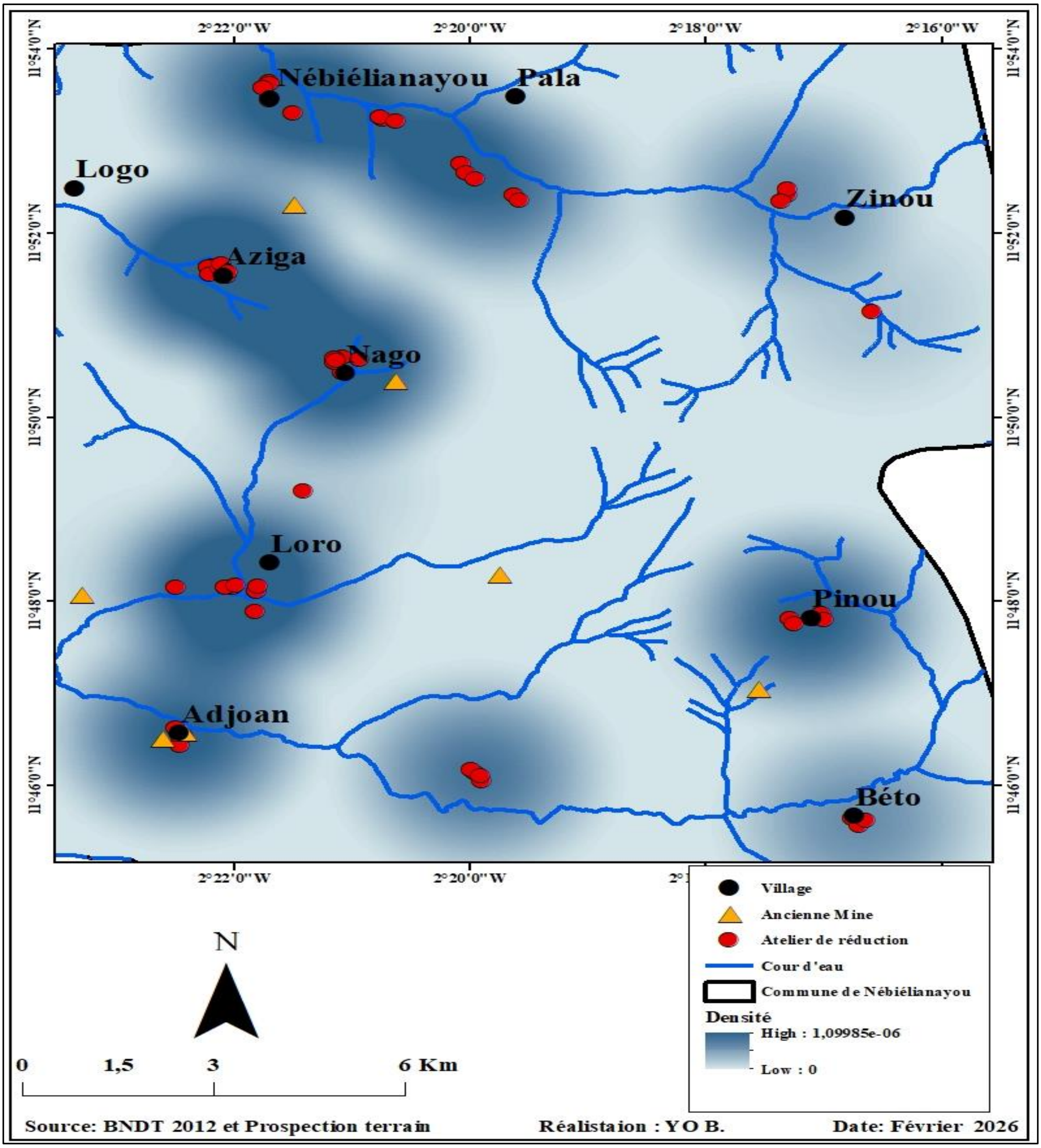

Fig 6 Distribution of Iron Reduction Workshops, Showing the Main Areas where Historic Steelmaking Activities were Concentrated in the Municipality of Nébiélianayou

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The highest concentrations are found mainly in the areas of Loro, Aziga, Nago, and Nébiélianayou, where smelting workshops appear to be clustered within relatively small areas. These concentrations suggest the existence of distinct specialized zones of metallurgical production, likely linked to the local availability of resources necessary for traditional iron production, notably iron ore, wood for charcoal production, and access to water. Furthermore, the analysis shows that these high-density zones are primarily located near the river network. This spatial relationship suggests that waterways played a decisive role in the establishment of metallurgical activities, by providing the water resources essential to technical processes as well as by facilitating the organization of human activities within the landscape. Conversely, certain areas of the municipality exhibit lower densities or a complete absence of metallurgical sites, which could reflect either environmental constraints or reduced access to the resources necessary for iron production. Thus, density mapping makes it possible to highlight the territorial structure of steelmaking activities, revealing the existence of production hubs integrated into an industrial landscape where environmental factors have strongly influenced the location of the plants.

➢ *The Decisive Role of Valleys*

In the organization of the metallurgical landscapeThe high concentration of reduction workshops in areas located less than 500 m from watercourses suggests that valleys constituted prime locations for the establishment of metallurgical activities. Several factors may explain this attractiveness of valley environments. On the one hand, valleys generally offer greater availability of wood resources, essential for the production of charcoal used as fuel I reduction furnaces. Since early iron metallurgy was particularly wood-intensive, access to these resources was a strategic factor in the location of workshops. On the other hand, the presence of water could facilitate certain operations related to the metallurgical process as well as the domestic needs of artisanal metalworkers. Valleys also represent relatively sheltered areas, offering microclimatic conditions favorable to the establishment of production facilities. Finally, watercourses can also play a role in the settlement of populations, which is.

➢ *Spatially Differentiated Organization of the Metallurgical Production Chain*

A comparison between the distribution of mines and that of reduction workshops reveals a marked spatial differentiation between the sites of extraction and the sites of iron ore processing. While the mines appear relatively scattered and linked to the geological distribution of the raw material, the reduction workshops show a much higher spatial concentration near the river network. This organization suggests the existence of a functional separation of the different stages of the metallurgical production chain. In this production system, ore extraction could take place in several areas of the territory, while reduction operation were concentrated in environmentally favorable areas, characterized by the availability of water and plant resources. This spatial structure reflects the metallurgical communities' adaptation to the landscape's environmental constraints, as well as a relatively elaborate territorial organization of iron production.µ

The proximity of waterways is a major determining factor in the location of iron reduction workshops, whereas mining sites are primarily determined by geological constraints. This reveals a hierarchical spatial organization of metallurgical production; the adaptation of ancient metallurgists to the landscape's resources; and the probable existence of a genuine, structured metallurgical landscape within the municipality of Nébiélianayou.

IV. DISCUSSION

➢ *Influence of Watercourses on the Spatial Organization of Ancient Metallurgy*

The results of the spatial analysis show that the vast majority of iron ore reduction workshops are located in the immediate vicinity of watercourses, with more than 83% of the workshops situated within a radius of less than 500 m from the hydrographic network. This spatial distribution reveals the existence of a close functional relationship between ancient metallurgical activities and valley environments. This spatial configuration aligns with observations made in several regions of West Africa where ancient iron production appears to be strongly linked to hydrographic landscapes.

The work of Hamady Bocoum (2004) has shown, in particular, that pre-colonial metallurgical systems in the Senegal-Mali region often developed in ecologically favorable environments, characterized by the presence of essential natural resources such as water, plant biomass, and mineral raw materials. Similarly, research conducted by Augustin F. C. Holl (2009) on the metallurgical landscapes of West Africa highlights that the establishment of reduction workshops is closely tied to the availability of the environmental resources necessary for iron production. In traditional direct iron reduction systems, production requires significant quantities of charcoal as well as regular access to water for domestic and artisanal needs associated with metallurgical activities. In the commune of Nébiélianayou, the high concentration of workshops in areas near watercourses thus appears to confirm the hypothesis that river valleys were prime locations for the establishment of metallurgical activities. The presence of denser vegetation in these environments indeed facilitates the production of charcoal, a fuel essential for the operation of reduction furnaces.

➢ *Valleys as Prime Locations in the Metallurgical Landscape*

The importance of valley environments in the spatial organization of ancient metallurgical activities has been extensively documented in African archaeological literature. In particular, the pioneering work of Thurstan Shaw (1993) has shown that ironworking activities are frequently embedded in territorial systems closely linked to the natural resources available in the immediate environment. From this perspective, river valleys can be considered true ecological and economic hubs within ancient metallurgical landscapes.

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They indeed concentrate several strategic resources, notably water, plant biomass, and natural transportation routes that facilitate human movement and the transport of raw materials. The results obtained in the commune of Nébiélianayou confirm this logic of spatial organization. The distribution of smelting workshops shows a gradual decrease in the number of sites as the distance from watercourses increases. This configuration suggests the existence of a gradient of environmental attractiveness structured by hydrographic proximity. This type of spatial structuring corresponds to what Graham Connah (2001) describes as a technical landscape, in which artisanal and productive activities are organized according to the ecological potential of the territory.

➢ *Spatial Differentiation Between Ore Extraction and Processing*

Another important finding of this study concerns the difference in spatial distribution observed between the old mines and theore processing facilities. While mines appear relatively scattered across the territory and are sometimes distant from the river network, the reduction workshops, on the other hand, show a high concentration in areasclose to waterways. This spatial dissociation corresponds to an organizationalmodel already observed in several African metallurgical systems. Research by Scott MacEachern (2005) has shown that the various stages of the ironproduction chain ore extraction, fuel preparation, andmetallurgical reduction can be spatially differentiated based ongeological and environmental constraints. In this model, mining areas are primarily determined by the location of iron ore deposits, which limits the options available to mining communities. In contrast, reduction workshops can be established in more ecologically favorable environments, particularly in valleys where access to water and plant resources is greater. The results observed at Nébiélianayou thus appear to correspond to this type of territorial organization characterized by a functional separation between extraction sites and processing sites.

➢ *Toward the Identification of an Ancient Metallurgical Landscape in the Sissili*

The body of archaeological work (test pits, surveys, dating) carried out in this study suggests that the municipality of Nébiélianayou may correspond to a structured ancient metallurgical landscape, in which iron extraction and processing activities were organized on a regional scale. Indeed, archaeological excavations of several furnace bases have identified at least three distinct techniques for producing iron and have allowed us to date the ironworking activity to around the 11th century CE using carbon-14 dating. The high density of identified reduction workshops, combined with the presence of several ancient mines, indicates that the region was likely a major center of iron production in the past. Similar technical landscapes have been documented in several regions of West Africa, notably in the Niger and Senegal valleys, where metallurgical remains attest to complex production systems involving the intensive exploitation of local natural resources (McIntosh, 1999; Holl, 2009). From this perspective, the spatial distribution of metallurgical sites in the commune of Nébiélianayou can be interpreted as an expression of a territorial organization of the iron production, in which geological constraints, environmental resources, and socio-economic factors combine to shape the landscape.

Furnace base (Figure 7) excavated in the village of Loro. It has an external diameter of 120 cm and an internal diameter of 100 cm, for a thickness of approximately 20 cm. The excavation revealed a structure featuring seven openings and a main opening. The depth of the excavated furnace measures 65 cm from the wall. Charcoal was collected and dated to the 11th century AD.

Fig 7 Blast Furnace Base

The results of this study show that waterways played a key role in the establishment of iron reduction workshops in the municipality of Nébiélianayou. The high concentration of workshops near the river system underscores the importance of valley environments in the spatial organization of ancient metallurgical activities. Furthermore, the more dispersed distribution of the ancient mines confirms that extraction sites are primarily determined by the geological location of iron ore deposits, whereas ore processing sites are more responsive to environmental and economic constraints. Thus, the entirety of the metallurgical remains observed appears to be part of a structured technical landscape, revealing the existence of a territorial organization of iron production in this region of Burkina Faso. These results contribute to a better understanding of the interactions between ancient societies, the environment, and metallurgical production in

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West Africa, and highlight the value of geoarchaeological and spatial approaches for the study of ancient technical systems.

V. CONCLUSION

The objective of this study was to analyze the influence of the river network on the location of ancient metallurgical sites in the rural commune of Nébiélianayou, located in the province of Sissili in Burkina Faso. Using a geoarchaeological approach that combined field surveys with spatial analyses within a geographic information system (GIS) environment, it was possible to highlight the relationships between metallurgical remains and the environmental characteristics of the territory. The results reveal a differentiated spatial pattern of metallurgical activities. While the ancient mines appear relatively scattered across the territory and seem primarily determined by the geological distribution of iron ore deposits, the smelting workshops show a very marked concentration near the river network. Analysis of buffer zones shows that more than 80% of the reduction workshops are located within 500 m of watercourses, reflecting a significant dependence of these activities on valley environments. This spatial organization demonstrates how ancient metallurgical communities adapted to the constraints and opportunities offered by their environment.

Valleys thus emerge as prime locations for the establishment of smelting workshops, due to the availability of water, the relative abundance of timber resources needed for charcoal production, and their potential role in transport and trade networks. The study also highlights a spatial separation between ore extraction sites and metallurgical processing sites, revealing a relatively structured territorial organization of the iron production chain. This differentiation suggests the existence of a production system in which geological constraints related to the location of deposits are linked to environmental and technical considerations in the choice of production sites. Beyond the local scale, these findings contribute to a deeper understanding of ancient metallurgical landscapes in West Africa by demonstrating how pre-colonial societies integrated the resources and constraints of their environment into the organization of their technical activities. The municipality of Nébiélianayou thus emerges as a territory marked by a structured metallurgical landscape, where the mining an processing of iron ore have left significant traces in the landscape.

This research also highlights the value of spatial and geoarchaeological approaches to the study of ancient technological systems. The use of GIS tools, particularly buffer zone analysis, adds a quantitative dimension to the interpretation of relationships between archaeological sites and landscape features. Finally, these results open up several avenues for further research. Additional investigations into the chronology of metallurgical sites, archaeometric analysis of slag, and the study of land-use dynamics would provide a better understanding of the evolution of iron production systems in this region of Burkina Faso. Such approaches would help to place the metallurgical landscape of the Sissili within a broader context, at the scale of West Africa's metallurgical networks. Thus, the study of the relationships between metallurgical sites and waterways in the commune of Nébiélianayou highlights how ancient societies were able to combine technical expertise with the sustainable use of environmental resources, revealing the existence of a territorial iron production system deeply embedded in the landscape.

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