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Tracing connections: Exploring links between Marandet (Central Niger) and the Chad Basin through pottery provenance analysis using pXRF☆

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A B S T R A C T

Long-distance connections in medieval West Africa are documented through written sources and exotic finds. However, both are relatively rare. As an abundant artifact category, pottery can provide a more comprehensive picture of past interactions. Portable X-ray fluorescence (pXRF) offers a rapid and cost-effective method for ceramic provenance analysis, allowing researchers to trace the exchange of vessels between different regions. In this study, we established reference groups for various regions in West Africa using research collections. Local ceramics were identified based on typological and geochemical characteristics, and their geochemical signatures were extracted using Linear Discriminant Analysis (LDA) and Principal Component Analysis (PCA). Additionally, pXRF was used to analyze ceramic assemblages and identify imported sherds. This approach was particularly useful for the identification of Sgraffito ceramics found in Marandet, which are atypical for the region. Through comparison with reference groups, these sherds were attributed to the western Lake Chad area. Other non-local sherds from Marandet could be linked to the northwestern Lake Chad Basin. This indicates diverse connections between Marandet and the Lake Chad Basin. These results demonstrate that pXRF is a valuable tool for the provenance analysis of widely exchanged ceramics in West Africa.

1. Introduction

Most of what we know today about interregional and long-distance contacts in West Africa and neighboring regions is based on historical sources, both written and oral. However, truly meaningful details about the nature and organization of contacts and trading activities only go back to the early second millennium CE. The further we move back from this point to the first millennium, the more the historical information dwindles until only archaeological sources remain. However, archaeological evidence of long-distance contacts is scarce: the vast majority of artifacts known to date that indicate connections between West and Saharan Africa or beyond date to after the Arab conquest of North Africa in the 7th/8th century (Magnavita, 2013). Noteworthy, for example, are the large quantities of glass, semi-precious stone beads and other luxury goods imported through long-distance trade and present in the archaeological record of sites such as Igbo Ukwu in southern Nigeria (ca. 9th–11th century CE; Shaw, 1970), Gao and Essouk-Tadmekka in Mali (from ca. 8th/9th century CE onwards: Takezawa & Cissé, 2016; Nixon, 2017). Before the very end of the first millennium CE, finds of such exotic trade goods are extremely rare – however, it can be assumed that contacts were much more frequent than is currently evidenced by luxury goods.

With the appearance of the first external written sources on sub-Saharan Africa, we are immediately acquainted with multi-staged long-distance trade routes between the Sahara and the lands further south. At present, however, we can only suppose that early medieval trade centers such as Essouk-Tadmekka (Nixon, 2009; 2017), Gao (Insoll, 1996, 2000) and Marandet (Mauny, 1961) also played a crucial role in regional and interregional trade networks. The problem with this hypothesis is that, for several reasons, we can hardly test it. As stated above, most of the tangible material evidence used to trace such contacts comes from so-called "exotics", i.e. objects made of materials that are rare at the place of their destination, such as glass and semi-precious stone beads, precious metals, or cowries. Tracing their approximate region of origin is often possible, and over the last two decades much progress has indeed been made particularly by means of archaeometric provenance studies of glass and metals in sub-Saharan and Saharan Africa (see e.g. Willett & Sayre, 2006; Fenn et al., 2009; Robertshaw

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et al., 2009; Cissé et al., 2013; Magnavita & Mertz-Kraus, 2019; Duckworth et al., 2016; McIntosh et al., 2020; Magnavita et al., 2024). Studies of this type bear great potential to contribute to our knowledge of long-distance contacts. However, several caveats must be considered. First, with few exceptions, both the number of relevant archaeological sites and the quantity of testable exotic objects available for such studies are currently rather limited (Magnavita, 2013; 2017). Archaeometric analyses of exotics from specific West African or Saharan sites are therefore far from being of statistical relevance. Secondly, luxury goods may have had very long "object biographies" due to their assigned value. Thus, it is more than likely that the region where a particular object was produced and the place where it eventually entered the archaeological record were never directly related. Third, if objects produced in region A end up in two discrete regions, B and C, what does that tell us about the relationships between B and C? For instance, although contemporaneous sites connected to the same long-distance flow of exotic products from North Africa are known throughout Saharan and Western Africa, the regional and interregional links between the latter in particular are largely elusive. On the one hand, this is a consequence of the lack of targeted research, as such connections have rarely been the focus of archaeological research in the region under consideration. On the other hand, most of the trade goods considered most important for the latter kind of transactions are barely preserved in the archaeological record, if they ever entered the ground at all: this concerns many fully consumable trade commodities (e.g., salt, honey and wax, oil, dry meat and fish, aromatics), animal and plant products with low preservation potential in the ground (e.g., textiles, hides, feathers, etc.), as well as valuable materials or recyclables (e.g., non-ferrous metals, glass). To sum up, the current dearth in suitable materials for tracing past contacts, connections and, eventually, trade on regional, inter- and supraregional scales calls for alternative materials for this purpose. Pottery, the most prevalent surviving material on archaeological sites in Africa at least since the late Holocene, is a highly promising material in this regard: ceramics are durable, and long or winding 'object biographies' are generally not to be expected.

Traditional ceramic studies in African archaeology were and are focussed on typological and technological analyses, primarily aiming at clarifying chrono-cultural issues. However, except for *trans*-Saharan imports in form of glazed and wheelmade ware to Saharan and sub-Saharan Africa, it is often difficult to differentiate pottery from neighbouring regions only on the basis of morphological traits, such as decoration or vessel form, or technological particularities. Even if potsherds appear alien to a particular region, it usually remains unclear whether the pot is indeed of foreign origin, or whether foreign potters were at work at this place, continuing to manufacture pots in their traditional way. This problem has come up also in the context of connections between Saharan and sub-Saharan Africa, when fibre roulette decoration, a very widespread decoration technique in sub-Saharan Africa from Senegal to Kenya, was found to have been applied to the majority of locally handmade pots in some Garamantian sites in the Libyan Sahara (Gatto, 2005; 2013). Archaeometric provenance analysis can provide answers to this questions as it shows if the ceramics were made locally or brought from another region.

Over the last years, natural scientific analytical methods have been increasingly applied on West African and Saharan pottery, usually within the broader frame of typochronological studies: these investigations are mostly due to questions related to manufacture, function and use of pottery (see, e.g., Brissaud & Houdayer, 1986; McIntosh & MacDonald, 1989; Stahl et al., 2008; Fraser et al., 2012; van Doosselaere, 2014). Other than those, archaeometric methods for sourcing the origin of ceramics have been as yet an only sporadically touched field in Saharan and West African archaeological research. Studies of this kind have primarily focussed on contacts or exploitation of resources *within* a particular region (see, e.g., Fontes et al., 1984; Artioli et al., 2005; Tandoh et al., 2009; Hatté et al., 2010; Leitch et al., 2016; Beck, 2017; Epossi Ntah et al., 2017; Cantin & Mayor 2018). In this regard, archaeometric provenance studies of West African ceramics for tracing interregional connections are a highly innovative approach (for other parts of Africa see: Punyadeera et al., 1997 (South Africa); Klein et al., 2004 (Sudan); Jacobson, 2005 (South Africa); El Ouahabi et al., 2019 (Morocco); Eramo et al., 2020 (Libya) Tsoupra et al., 2022 (Kongo); Maritan et al., 2023 (Sudan)). This is all the more astonishing as provenance analysis of ceramics has more than once shown its great potential for revealing connections between producing region and final destination elsewhere in the world (e.g., Steponaitis et al., 1996; Capelli et al., 2017).

In this article we present our methodological approach on how interregional connections can be revealed, focusing on the example of early medieval pottery from the archaeological site of Marandet in Central Niger (Fig. 1). The site is thought to be the ruins of the early medieval trading town of *Maranda*, mentioned in 9th and 10th century CE Arabic text sources on West Africa as one halting place on an ancient trade route between Egypt and the kingdom of Ghana (Mauny, 1961; Magnavita et al., 2007a). Archaeologically, the site is best known for its impressive amount of copper working remains, which hint at the working of alloys on an almost industrial scale around the mid- to late-first millennium CE. A number of radiocarbon dates are available, most of which fall within the period between the mid-first up to the early second millennium CE (Délibrias et al., 1974, 1986; Grébénart 1985, 1993; Magnavita et al., 2007b). Targeted investigation at three refuse pits (Mar-I-1, -2 and -3) in the center of the former craft area show that this area of Marandet was particularly active between approximately the 6th and 9th centuries CE (Magnavita, 2018).[1] All pottery from Marandet used for this study stems from these three pits.

It can be assumed that metal worked in Marandet was exported to several regions in West Africa, but due to the rarity of relevant, testable and dated copper alloyed objects this could so far only be confirmed for very few items from sites at the Eastern Niger Bend (Fenn et al., 2009), about 800 km west of Marandet as the crow flies. Although we have thus tangible evidence for a supra-regional distribution of copper alloys from Marandet at least to the Niger Bend, and although we can also generally assume Marandet/*Maranda* to have been a linking point on a medieval long-distance trade route on the basis of written sources, we have so far lacked the means to substantiate these assumptions with more material-based evidence. Besides the metallurgical evidence, for interregional connections there is also pottery with attributes that are untypical for Marandet or the region in general and might indicate connections to other regions.

With the approach presented here, which considers ceramics as a material that could have also circulated between regions, we take an exploratory path — at least in the context of West African archaeological research. We argue that incorporating this largest category of archaeological artifacts is essential and can no longer be overlooked when investigating interregional and even long-distance contacts in sub-Saharan Africa. However, our study is not aimed at identifying relationships between specific sites or tracing particular clay sources. Rather, we take a macroscopic perspective to examine whether contacts extended beyond a given region to others, without claiming to identify an actual production site. For this purpose, we use already excavated and mostly archived archaeological material provided to us by cooperation partners. In the following, we outline our approach and demonstrate its effectiveness through the results of a case study.

[1] Four AMS dates were obtained, using charcoal (*Acacia* sp.) and a charred date palm endocarp (*Phoenix dactylifera*), in each case taken from the lowest part of the pit fill. Pit Mar-I-1 was dated to the mid-7th to late 9th century CE (Erl-11122: 1234 ± 40 BP, Erl-11123: 1330 ± 41 BP), Mar-I-2 to the mid-6th to late 8th c. CE (Erl-11124: 1391 ± 58 BP) and Mar-I-3 to the mid-7th to late 8th c. CE (Erl-11125: 1318 ± 39 BP) (calibrated dates are given with 2σ confidence) (Magnavita, 2018).

Fig. 1. Map of Sites: Map of the research area and the sites used for reference groups. The sites near N'Djamena are Mdaga and Lamadji.

2. Materials and method

2.1. Reference groups and sample preparation

For the provenance analysis of ceramics, it is necessary to establish reference data from potential places of origin (e.g., Mommsen et al., 2006; Helfert, 2013; Quinn, 2022, 395-396). The geochemical signature of these reference materials can be determined using various methods. Ideally, ceramic workshops serve as loci of local production, enabling direct comparison with artifacts produced at other sites (Arnold et al., 2000; Mommsen, 2001; Baklouti et al., 2014;). However, in sub-Saharan Africa, there are only a few excavated ceramic workshop sites (e.g. Kokolo, Mali; Keita 2014). An alternative approach involves using reference samples from clay deposits, which allow for direct linkage between artifacts and specific clay sources (Wieder & Adan-Bayewitz, 2002; Beck, 2017; Tanasi et al., 2017; El Ouahabi et al., 2019).

The supraregional scale of the study, however, presents an advantage (Golitko et al., 2024). Given that the study area encompasses diverse geological contexts, variations in the geochemistry of utilized clay sources are likely. Moreover, since the primary goal is to investigate relationships between regions as a whole, there is no necessity for pinpointing specific clay deposits. Consequently, pseudo-reference groups for the different regions based on prehistoric ceramics serve as the starting point of this study.

Ethnoarchaeological studies in West Africa have determined that the vast majority of pottery (at least 90 %), particularly everyday vessels, are usually obtained from local potters (Gallay and Ceuninck, 1998) and potters most likely use local clay sources (86 % of clay sources are within 7 km, Arnold, 2005). Therefore, it can be assumed that the pottery from an archaeological site primarily reflect local clay sources, albeit potentially multiple ones (Tykot et al., 2013; Wilke et al., 2016). In smaller assemblages, distinguishing different clay sources from natural variations within a single source might be challenging. This issue is particularly relevant at sites situated in regions with highly heterogeneous clay sources, as it can complicate the formation of reference groups and obscure the regional geochemical signature.

A significant proportion of the analyzed samples originate from various research collections. The sherds were often selected to document examples for different types of pottery or for further investigation of a specific research question. Such preselection can lead to a collection that is not necessarily representative of the abundance of sherds at a site. For instance, exotic sherds may be overrepresented while sherds from the much more common locally made pottery appear underrepresented. This might complicate extracting the regional geochemical "fingerprint" for pottery from these sites. Even though these sherds were sometimes taken for further archaeometric analysis, a minimally destructive approach increases the likelihood of access to artifacts. To ensure methodological consistency across all sampled sherds, a uniform analytical protocol was applied as recommended by Frahm (2024) and Johnson et al. (2024).

Where possible, at least 30 sherds per reference group were sampled, as recommended by Helfert (2013) as a reasonable number for such purpose. This was possible for many sites (Table 1). The selection of sherds was based on diagnostic attributes such as form, fabric, and decoration, aiming to identify those most representative of the site and thus presumably the locally produced ones. This was done in close consultation with the researchers who had preselected the material, or through an in-depth literature review. These serve as the baseline for determining a local geochemical signature. For Marandet, also non-local sherds were measured for further investigation. Some of these non-local sherds were than compared to the reference groups to uncover potential regions of origins. A total of 348 sherds were analyzed.[2]

2.2. Instrumental measurement techniques and methods

Three measurements were taken at different locations of the break of the sherds, to compensate for the inhomogenous fabric of the pottery (Forster et al., 2011). The breaks are rougher than other areas of the sherd, but this allows for consistent measurement independent of vessel shape. No fresh break was produced, instead an existing one was cleaned using a sandblaster. To prevent contamination with Si or other elements, walnut shell powder was used as the abrasive medium. This approach ensures that the sherds undergo minimal visible alteration and that surface treatments such as painting remain intact, while allowing to measure the clay matrix.

Measurements were conducted using a Niton GOLDD + portable X-ray fluorescence (pXRF) device from Thermo Fisher. A 50 kV and 100 mA tube with an Ag anode generates X-ray and the secondary radiation is detected by larger silicon drift detector. The diameter of the measurement window is 8 mm. The "TestAll Geo" Mode was used as it is well suited for ceramics (Eslami et al., 2020). Before measurements, the device was powered on for one hour to achieve thermal stability. A pottery

[2] For the Raw and Calibrated data (Puerta Schardt & Magnavita 2025) see: https://doi.org/10.5281/zenodo.15002520; link: https://zenodo.org/records/15002520?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6IjJjYmQ3MmJkLTRhNmEtNDMxOS04OGZkLTI2Y2FiNjA0Y2IyMCIsImRhdGEiOnt9LCJyYW5kb20iOiI3ZGYwMWViYzU4NTg1ODgxODBhMDM3YjBjY2YzMzlkMCJ9.bL9EBt-wIl6w1PBA2Hd4h-LIjC09ErGtcBjf6lmJzdvcsPYAwSR-Ju2kMHobxc5cRiQVpxpCRcAHTj_lDju2Bw.

Table 1
Sites used for reference groups. Country, Reference group, date (where possible), the amount of sherds sampled with pXRF, the sherds used for the reference group (based on outlier detection), if the site has sgraffito sherds, if the site has cordwrapped sherds, elements relevant for geochemical signature, typical temper, context and reference are given.

Country	Reference Group	Date (century)	Sherds tested	Sherds used for reference group	local sgraffito	local cws	signature elements	main temper	Context	Reference
Niger	Marandet	6-9th CE	109	58	no	no	Al2O3+, Fe2O3-,Nb+, Y+, Rb-	grog, mineral, organic	refuse pit	Magnavita, 2018
Niger	Niger_Niamey	After 5th-3rd BCE	23	18	no	uncertain	Al2O3+, Fe2O3+,Rb-, Sr-	grog, mineral, organic	survey	Magnavita & Magnavita, 2017a
Niger	Lake_Chad_Northwest	Second half of second mil. CE	47	38	yes	yes	Al2O3-,Nb-,Y-,Zr-	grog, organic	settlement	Haour, 2008; Magnavita & Magnavita, 2017b
Nigeria	Lake_Chad_West	Second half of second mil. CE	7	7	yes	no	Nb+,Rb+,Zr+	organic	settlement	Connah 1976, 349; Magnavita, 2011
Nigeria	Lake_Chad_Southwest	8th-4th BC	15	13	no	yes	Fe2O3+,Y-,Zr-	grog, mineral	settlement	Magnavita et al., 2006
Nigeria	Lake_Chad_South	Second half of second mil. BC	30	21	no	yes	Al2O3-,Nb+, Y-	grog	settlement	Breunig & Franke 2019, 245
Mali	Essouk	8th-14th CE	43	33	no	yes	Fe2O3+,Nb-, Si-	mineral, organic	living floor	Nixon, 2017
Chad	Lake_Chad_East	12th-14th CE	31	25	yes	no	Al2O3-, Fe2O3-,Nb-, SiO2+,Sr-,Y-, Zr-	mineral, organic	fired brick building	Magnavita & Bouimon, 2020
Chad	Lake_Chad_East	12th-13th CE	14	11	yes	no	Al2O3-, Fe2O3-,Nb-, SiO2+,Sr-,Y-, Zr-	mineral, organic	satelitte settlement	Magnavita, 2021
Chad	Lake_Chad_Southeast	none	20	16	no	?	Rb+,Fe2O3+, Nb+,Rb+, SiO2-,Zr+	grog, mineral	settlement	Lebeuf et al., 1980
Chad	Lake_Chad_Southeast	10th-14th CE	11	9	no	?	Rb+,Fe2O3+, Nb+,Rb+, SiO2-,Zr+	grog, mineral	settlement	Lebeuf et al., 1980

standard was measured at regular intervals to ensure consistency. Each measurement took 330 s (filters: standard 60 sek; low 60; high 90; light 120), ensuring the accurate detection of lighter elements (Beck 2017, 56).

2.3. Data preparation and element selection

All calculations were done using R and Rstudio as a programming environment.[3] The first step was to select only the elements that are viable for analysis. From the 46 elements the tool can detect, we excluded those that were not detected properly due to insufficient sensitivity (below the LOD in 25 %) as a high number of missing values is problematic for statistical analysis (Quinn 2022, 354). Values below the LOD were replaced by half of the lowest measured value (ibid.). The pXRF also provides the margin of error for each measurement. If the mean of this margin was higher than 10 %, the element was removed to ensure only measurements with high precision are used.

The measurements were coefficient corrected using 32 ceramic samples from the "Forschungstelle Keramik" of the Goethe University Frankfurt previously measured with WD-XRF (Furger & Helfert 2023), in order to ensure data comparability and usability by other researchers. An automated version (Suppl. 1,IV.d) of the Munich procedure (Schauer et al., 2024) was used to find good correction slopes. The criteria were an r2 over 0.85, an rSEE under 15 % and a slope between 0.75 and 1.25. A bootstrap was used to further access the robustness of the correction, and it was deemed robust if the confident intervals did not deviate more than 7.5 % from the bootstrap. These criteria are slightly less strict than those proposed by Schauer (2024) or the Ministry for the environment (New Zealand) (MENZ, 2024), but this only concerns the elements Si and Y. These elements are too important to not use in further analysis, so we included them for this study, but the use of the results in further studies should take their lower robustness into account.

As each sherd was measured three times, it was possible to detect elements that vary strongly within a sherd. Therefore, we excluded those elements where the three measurements at a sherd had a mean deviation greater than 10 %. As elements that vary inside a single sherd are not suitable for comparing sherds with each other. These criteria leave us with eight elements to conduct analysis with Aluminum (Al), Iron (Fe), Niobium (Nb), Rubidium (Rb), Silicon (Si), Strontium (Sr), Yttrium (Y) and Zirconium (Zr). Aluminum, Iron, and Silicon are major components that constitute a significant portion of ceramics. Their use in provenance studies is not without problems, as they can be influenced by technological factors such as tempering (Quinn, 2022, 357) which is also true for trace elements, but to a lesser degree (Frahm, 2018). However, there are provenance studies including them (e.g., Beck, 2017, 57; Daszkiewicz & Schneider, 2021; Rivero et al., 2025) as they can hold information about the clay sources.

To compensate for the inhomogeneous fabric of the sherds the mean

[3] Following packages were used: MASS (Venables & Ripley, 2002) for statistics; FactoMineR (Lê et al., 2008) for multivariate analyses; caret (Kuhn, 2008) for classification; tidyverse (Wickham et al., 2019) for data processing; cowplot (Wilke, 2019) for visualization; here (Müller, 2020) for file paths; factoextra (Kassambara & Mundt, 2020) for multivariate analyses; plotly (Sievert, 2020) for interactive visualization; GGally (Schloerke et al., 2021) for multiple biplots; PCAtest (Mardia et al., 2022) for significance testing of principal components; gt (Iannone et al., 2020) for table creation; scales (Wickham & Seidel 2022) for color scaling. For the code, see: https://github.com/JuanMarcops/Tracing-Connections-Provenance-Analysis-of-West-African-pottery-using-pXRF or the html provided as Supp. 1.

value of the three measurements on each sherd was calculated. Outliers caused by individual mineral inclusions or tempering materials were identified using the Dixons Q method, which is especially suited for small size datasets (Efstathiou, 2006). To counteract biases resulting from varying abundance of different elements, logarithmized values (based on the whole dataset) were used (Quinn, 2022, 362). The main elements were given as oxides, and their abundance is normalized to 100 percent (Helfert, 2013). Trace elements are given as ppm.

2.4. Statistical analysis

Principal Component Analysis (PCA) was used to analyze the pXRF measurements and determine the geochemical signature, i.e. the "fingerprint" of each region. PCA facilitates the examination of variability within a multivariate dataset by summarizing interrelated variables into principal components. This approach enables visualization and assessment of similarities and differences in ceramic composition, as well as relationships between elements.

Initially, individual sites were analyzed separately to gain an overview of the chemical composition of their clay sources. In cases where sites were in close proximity, data from multiple sites were analyzed collectively. To exclude outliers which might be non-regional sherds from the reference groups, the Mahalanobis Distance was employed (Quinn, 2022, 376). The core group was defined using a low chi-square value (0.7), resulting in smaller and more stringent local clusters while possibly excluding local sherds with a deviant geochemical composition. Nevertheless, groups were not exclusively defined based on statistical methods. Given that some sites lacked a representative sample of local sherds due to the selection process, PCA results were cross-referenced with sherd attributes and literature sources.

Using Linear Discriminant Analysis (LDA) on the refined groups, it was possible to determine which elements most effectively distinguish between regions. LDA is a common tool to analyze geochemical compositions based on already defined groups (Baxter, 2016; Badawy et al., 2022). In combination with the mean concentration and standard deviation of these elements within each group, a comprehensive overview of regional geochemical signatures was obtained. In order to identify imported ceramics at Marandet, PCA was used in combination with a typological analysis of pottery features, particularly of the decoration techniques. Uncommon sherds of presumed non-local origin were identified. The reference groups were then utilized to investigate the potential origin of some of these exotic sherds using PCA and Biplots.

3. Reference groups

The groups are based on sherds from one or multiple sites within a particular region (Fig. 1). To get a broader spectrum of regions and sites and to compensate for research gaps, samples from contexts and sites that are older or younger than the pottery assemblage from Marandet were also used. In addition, the sites differ considerably in their character and the state of current research (Table 1). The description of the ceramics' chemical fingerprint focuses on their relative proportions compared to other reference groups. A table showing the mean abundance of the different elements and the mean RSD of the measurements inside a reference group (Table 2; see Suppl. 1,VIII.a for PCA of reference groups and Suppl. 1,VIII in general, for statics on quality of reference groups.).

Marandet lies about 85 km southwest of Agadez near the Falaise de Tiguidit, the southern margin of the Aïr Massif, whose geology is dominated by granites and volcanic sediments (Schlüter, 2008, 190–191; IAEA 2020, 287–288). Pottery assemblages comprise mainly mat-impressed or undecorated bowls and everted-rim pots. Mat impressions reflect forming in a concave mould; the associated ceramic pestles support local production (Sterner & David, 2003; Mayor, 2011, 33; Magnavita et al., 2007b).

Southwest of Marandet, Misgoungou is a site on the eastern Niger

Table 2
Mean proportion and relative standard deviation of elements for each reference groups. Main elements are given in percentage, trace elements in ppm. The SD is calculated to check how similar the content of an element is across the group.

Region	SiO2_mean	SiO2_sd_prop	Al2O3_mean	Al2O3_sd_prop	Fe2O3_mean	Fe2O3_sd_prop	Rb_mean	Rb_sd_prop	Sr_mean	Sr_sd_prop	Y_mean	Y_sd_prop	Zr_mean	Zr_sd_prop	Nb_mean	Nb_sd_prop
Essouk	4,208	0,780	2,685	3,245	2,417	4,767	4,384	2,315	5,611	4,143	3,493	1,351	5,878	1,845	2,918	3,019
Lake_Chad_East	4,392	0,452	2,236	4,151	1,671	11,903	4,279	3,699	4,705	7,471	3,225	2,106	5,424	2,944	2,740	3,943
Lake_Chad_Northwest	4,299	0,930	2,403	5,319	1,959	9,895	4,272	4,946	5,313	6,352	3,210	3,041	5,569	2,456	2,897	5,802
Lake_Chad_South	4,289	0,662	2,634	6,034	2,018	8,619	4,549	3,227	5,573	10,853	3,529	1,724	5,766	2,887	3,424	2,611
Lake_Chad_Southeast	4,169	0,557	2,935	2,413	2,276	3,429	4,921	1,629	5,346	3,009	3,700	1,394	6,040	1,051	3,775	1,946
Lake_Chad_Southwest	4,217	0,498	2,846	2,207	2,267	4,520	4,286	2,241	5,703	4,180	3,360	1,652	5,440	2,686	3,091	2,710
Lake_Chad_West	4,254	1,321	2,741	6,295	2,096	9,100	4,871	4,046	5,480	7,114	3,637	3,887	5,967	2,996	3,474	6,098
Marandet	4,237	0,547	2,982	3,581	1,734	10,643	4,116	4,215	5,591	6,568	4,230	4,815	5,955	2,016	3,496	3,194
Niger_Niamey	4,154	0,607	3,070	2,387	2,298	6,359	3,847	3,240	5,065	4,190	3,402	1,568	5,703	1,979	3,050	2,312

bank near Niamey that has two occupations, an LSA site and an iron age site that dates after 8th to 5th century BCE (Magnavita & Magnavita, 2017b). Pottery decorations include mat impressions, twisted cord and folded strip roulette.

Essouk, an archaeological site of the ancient trading center in northeastern Mali, was occupied mainly from the 8th to 14th centuries CE (Nixon, 2017). The ceramics from living floors are dominated by cord-wrapped-roulette–decorated and undecorated wares, with mineral and organic tempers; most are considered locally made (Nixon, 2017; Nixon & Benoit, 2017; Nixon & MacDonald 2017; Nixon, pers. comm.). The site lies at a Wadi (Nixon, 2009) between granite cliffs (Schlüter, 2008, 163).

The sherds from Tié and Kamaka (*Lake_Chad_East*) date to the 12th and 14th centuries CE, when the area was part of the Kanem-Bornu sphere (Magnavita, 2021; Magnavita & Bouimon, 2020; C. Magnavita, pers. comm.). Both sites lie on aeolian dunes over lacustrine clays formed by past episodes of Lake Mega-Chad, underlain by sandstone (Schneider & Wolff, 1992; Schlüter, 2008). Their pottery repertoire is dominated by twisted cord and strip roulettes. Garumele (*Lake_Chad_Northwest*), a fortified settlement dating to the second half of the second millennium CE and later political center of Kanem-Bornu, shares this geological setting. The pottery is decorated with folded strip or cordwrapped stick roulette. It also features a notable proportion of sgraffito (Haour, 2008; Magnavita & Magnavita, 2017a), which occurs in smaller amounts at Tié and Kamaka.

In other parts of the Chad Basin, sediment composition is influenced by fluvial inputs from rivers such as the Komadugu Yobe and Chari (Huneau, 2017, 7). Birni Gazargamo (*Lake_Chad_West*), a Bornu capital in the later second millennium CE, lies within such a fluvial corridor; its ceramics include folded strip–decorated wares and sgraffito, with organic tempering (Connah, 1976, 349; Magnavita, 2011). Similarly, Mdaga and Lamadji (*Lake_Chad_Southeast*) near N'Djamena occupy the southeastern plain affected by Chari River inputs. Mdaga dates mainly to the tenth–fourteenth centuries CE (Lebeuf et al., 1980, 13), while Lamadji is unpublished but likely coeval. Mat impressions and carved roulette are common decorations in Mdaga (Lebeuf et al., 1980, 120-23).

Both Zilum (*Lake_Chad_Southwest*) and Walasa (*Lake_Chad_South*) are situated in landscapes characterized by sandy dunes interspersed with clayey depressions of the Chad Basin. At Zilum, a fortified settlement dating to the eighth–fourth centuries BCE, this setting supported the local production of thick-walled, voluminous vessels, as evidenced by abundant forming tools such as pestles for concave mat-lined moulds (Magnavita et al., 2006, 167). Walasa, occupied in the second half of the second millennium BCE, is similarly located on sandy dunes adjacent to a clay depression; its ceramic assemblage is dominated by bowls decorated with comb impressions or incisions (Breunig & Franke 2019, 245–246).

4. Pottery assemblage of Marandet

The aim of the reference groups is to classify imported pottery and trace long-distance contacts in West Africa. The identification of both imported and local pottery is based on geochemical signatures, typology, and their proportion within the overall assemblage. The latter

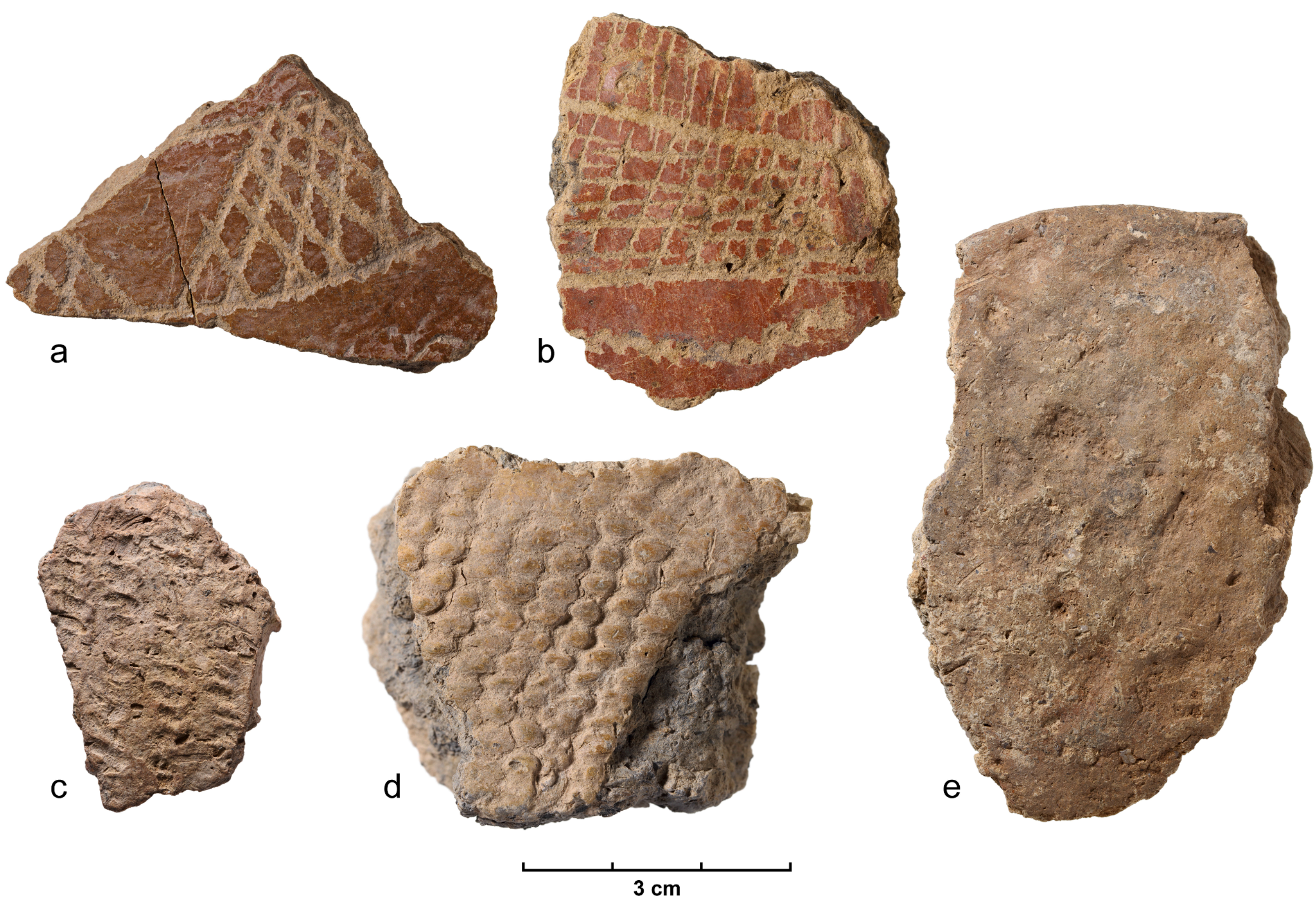

Fig. 2. Example sherds for decorations: Sherds with different decoration techniques. a-b: Sgraffito sherds from Marandet (a) and Birni Gazargamo (b); c: Cord-wrapped stick impression/roulette from Marandet; d: Folded strip roulette from Marandet; e: Mat impression from Marandet. Fotos by: Gaby Försterling.

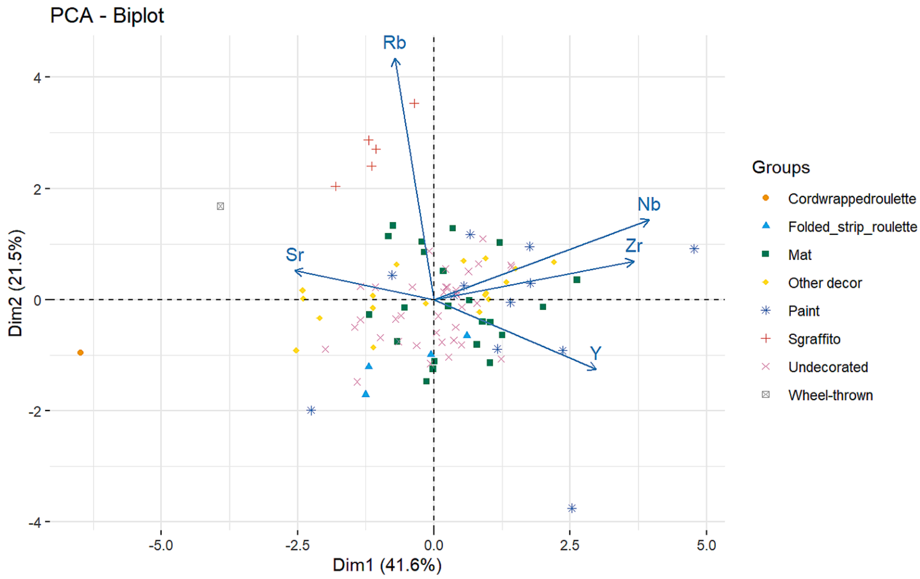

Fig. 3. PCA Marandet (Dim1&2): PCA-Plot of Dimension 1&2 of the geochemical data of sherds from Marandet. Key signatures according to the decoration techniques mentioned in the text.

serves only as an indication, as the most common ceramic types are very likely of local production, whereas rare types may represent either locally produced exotic goods or imports.

While most of the sherds share common attributes, atypically decorated sherds and those with an unusual, exceptionally fine fabric were also deliberately sampled. As a result, these appear overrepresented in our dataset. Overall, decorated sherds make up only 13 % of the approximately 3,000 sherds found. Among these, around 70 % feature mat impressions. The sampled exceptional sherds—such as those with sgraffito decoration (Fig. 2a; b for example from other site)—thus account for only a very small fraction of the total assemblage.

For the PCA (Fig. 3, Suppl. V. for biplots and more dimensions of PCA), the elements Nb, Rb, Sr, Y and Zr were used, as these trace elements show the difference between local and non-local sherds clearly. The first two dimensions explain 42 % and 22 % of the variance, respectively, amounting to 64 % in total. Nb and Zr contribute more to the X-axis, while the primary contributor to the Y-axis is Rb. Dimension 3 (Suppl. 1,V.b.) explains an additional 17 % of the variance and is foremost correlated with Sr and Y.

Two clearly distinct groups of sherds can be identified, along with individual outliers. The largest group appears to represent the local geochemical signature, as it includes sherds featuring the main decoration technique (mat impressions) (Fig. 2e) and the most common vessel forms (bowls and vessels with rounded everted rims). Sherds with vessel forms and decoration techniques that are not common in Marandet, e.g. folded strip roulette (Fig. 2d) and paint decorations, also fall partly into this group. While some of the decorated pottery was produced locally, other pieces were probably made in different regions. The diversity observed at Marandet reflects both contacts with other settlements and variation in pottery production at the site.

A second geochemically distinct group—characterized by lower Y and higher Rb compared to the larger assemblage—consists of sgraffito-decorated sherds (Fig. 2a). This technique involves scratching linear patterns into burnished pottery before firing (Connah 1981). Several sherds also differ significantly, in geochemical terms, from those produced locally. Even without identifying their exact regions of origin, these differences already point to Marandet's wide-ranging external contacts, since the outliers also diverge strongly from one another geochemically. One such outlier—a sherd from a wheel-thrown vessel—provides clear evidence of *trans*-Saharan connections, as this technology was not in use in sub-Saharan Africa during this period.

5. Sgraffito and cordwrapped stick pottery compared to reference groups

The second group does not only consist of a typologically distinct set of ceramics but also represents pottery that is not characteristic of Marandet. Sgraffito pottery is primarily attested for the second millennium CE in the Lake Chad region, although it rarely constitutes a significant portion of ceramic assemblages. Another sherd whose geochemical signature clearly stands out, is the one decorated with a cordwrapped stick (CWS) (Fig. 2c). This technique appears at various sites in the Chad Basin but is generally widespread in sub-Saharan West Africa. To determine the region of origin of the Sgraffito and the CWS pottery found in Marandet, their geochemical signature was compared with those of the reference groups.

For the PCA (Fig. 4; Suppl. 1, IX for more axes and biplots of elements) 8 elements were included to comprehensively capture the geochemical signatures of all reference groups. The first two dimensions account for over three quarters of the variance (61 % for Dimension 1 and 17 % for Dimension 2, totaling 78 % which means that these dimension alone explain a vast chunk of the variance in the dataset). Dimension 3 (Suppl. IX.a.) explains 9 % of the variance (resulting in a total of 87 % explained variance for the first three dimensions). The elements primarily contributing to Dimension 1 are SiO2, Al2O3, Fe2O3, Nb and Y while Dimension 2 is mainly influenced by Rb. Dimension 3 (Suppl.) is primarily shaped by Sr, which is often highly variable within the reference groups and therefore does not contribute much to the understanding of the provenance of our sherds. SiO2 has a strong influence on Dimension 1, which could be associated with the use of mineral temper (particularly quartz). However, since the pottery from the *Lake_Chad_Northwest* reference group is mostly not mineral-tempered, this indicates that SiO2 levels are not solely the result of technological choices.

Most of the reference groups can be clearly distinguished within the first two dimensions. There is, however, some overlap at the margins, for example between *Lake_Chad_Southwest* and *Essouk*. The sgraffito sherds from Marandet mostly correspond geochemically to the Lake_Chad_West and *Lake_Chad_South* reference groups. The *Lake_Chad_West* reference group is relatively small, with some sherds geochemically closer to *Lake_Chad_South* (one of these sherds is decorated with sgraffito (Fig. 2b)) and others closer to *Lake_Chad_Southeast*; the Sgraffito sherds are more similar to the former. The CWS sherd also appears to originate

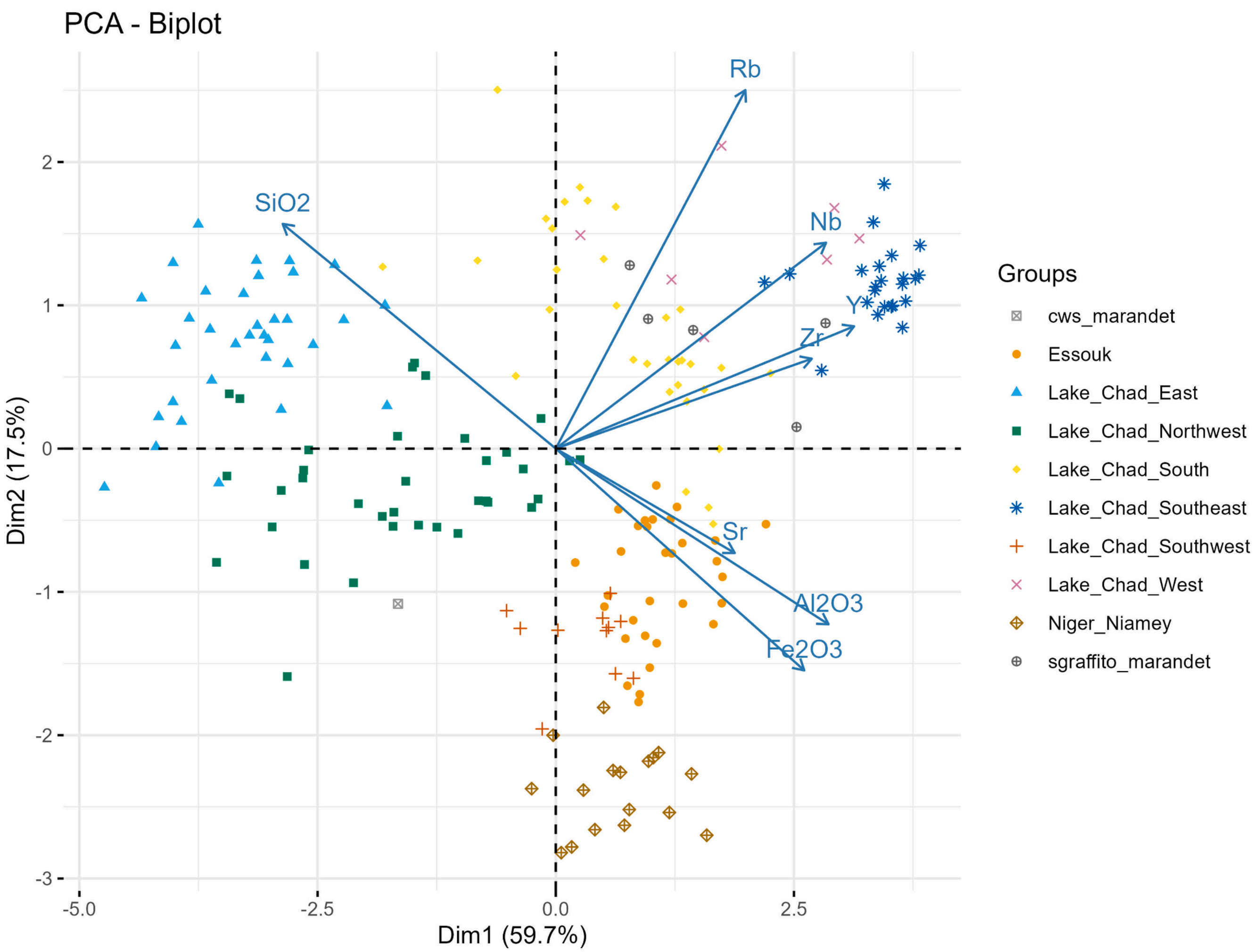

Fig. 4. PCA of Sgraffito, CWS and reference groups (Dim1&2): PCA-Plot of Dimension 1&2 of the geochemical data of Sgraffito and CWS sherds from Marandet and the reference groups. Key signatures according to the reference groups.

from the Chad Basin, more specifically its northwestern part, as its geochemistry resembles—but does not fully match—that of this reference group.

6. Discussion

The attribution of the sgraffito pottery to the Lake Chad region aligns with its known distribution. Most sites where this type of decoration appears date to the second millennium CE. Only one site, Yau (Nigeria), where the oldest known Sgraffito pottery in West Africa was found (Connah, 1976), possibly dates to the same period as Marandet. However, the C14 dates are difficult to interpret. They range from the 8th to the 14th century CE, with the earliest settlement dates falling between the 8th and 12th centuries CE. Yau is located along the same river valley as Birni Gazargamo, the site upon which the reference group *Lake_Chad_West* is based.

In the southern Chad Basin, ceramics with sgraffito decoration appear only in more recent contexts. In sites such as Mege and Ngala, it is found exclusively in the latest layers, despite these settlements being occupied since the LSA (Mege) and first millennium CE (Ngala) (Gronenborn, 1998). The spread of Sgraffito pottery is frequently associated with the rise of the Kanem-Borno Empire, which expanded within the Lake Chad Basin (Gronenborn & Magnavita, 2000; Haour, 2011). Connah (1976: 349) calls such decoration in Borno the “fineware” of Kanuri pottery and associates it with the elite of the empire.

At the site of Garumele, in the northwestern Chad Basin—potentially the capital of the Kanem-Borno Empire before Birni Gazargamo (Gronenborn, 2001, 106)— Sgraffito pottery (Fig. 2b) accounts for ca. 11 % of all decorated ceramics (Haour, 2008, Magnavita & Magnavita, 2017b). In the older Kanem territories east of Lake Chad, where Tié may have been the center of power (Magnavita & Bouimon, 2020), Sgraffito pottery was found in three sites (C. Szymanski pers. comm. 2025). Two sgraffito-decorated sherds from Kamaka, another site from the surroundings of Tié, was analyzed using pXRF and is part of the reference group of the eastern Chad Basin.

The results of the pXRF analysis allow for a more differentiated perspective on the origin of the imported sgraffito-decorated pottery found in Marandet. While an origin south of Lake Chad or in a region not yet sampled geochemically cannot be entirely ruled out based on the geochemical signature, current archaeological evidence suggests that a provenance west of the lake, perhaps in the Komadugu Yobe River region, is more likely. The pits at Marandet date to the 6th–9th centuries CE, making the Sgraffito sherds found there additional evidence for the production of this ceramic type west of Lake Chad already in the second half of the first millennium CE.

The Sgraffito sherds from Marandet predate the flourishing of the Kanem-Borno Empire with which this decoration technique is associated. This said, in its earlier phases the core of the empire was located east of Lake Chad. This brings up new questions as it either shows that Sgraffito pottery predates the Kanem-Borno Empire, or that the empires’ influence in the region started earlier than previously thought. As the archaeological evidence that would be needed to answer these questions is still scarce, further research will be needed. This makes the sherds found in Marandet and the uncovering of their region of origin a valuable contribution to the early phases of this Sgraffito pottery.

Despite these uncertainties, the sherds are tangible material evidence for long-distance contacts between Marandet and the Lake Chad region or potentially the wider sphere of influence of the early Kanem-Borno Empire. The ceramic vessels were thus likely transported over distances of several hundred kilometres. Although the reasons for this remain unclear today, we can assume that such a transport required a certain amount of organization and effort, which obviously makes those vessels special in some way. Unfortunately, no vessel shapes can be reconstructed from the sherds, so we do not know yet whether this fine ware was used for transporting goods or rather used for other purposes. Since specific vessel types have been associated with political organization (Haour, 2011) and the Kanem-Borno Empire was involved in trade (Magnavita et al., 2019) Sgraffito pottery may even have functioned as a status symbol (Haour, 2011).

The other sherd found in Marandet that appears to come from the Chad Basin, though not from the west but the northwest, is the CWS sherd. Unlike sgraffito, this decorative technique is widespread across West Africa (from the Sahara to the Chad Basin) and exists in numerous variants (MacDonald & Manning, 2010). Small variations in the tools or their application can produce very different decorative outcomes.

Within our reference groups, CWS occurs particularly in the early phases of Essouk (Nixon & MacDonald, 2017), at sites along the Niger Bend (Magnavita & Magnavita, 2017a), at Garumele (Haour, 2008; Magnavita & Magnavita, 2017b), in the earlier phases of Tié, and in the southern and southwestern Chad Basin (Wiesmüller, 2003, 162-164). However, none of the decorative styles found at these sites exactly matches the type of the Marandet specimen. Thus, there is no direct typological evidence pointing to an origin in the northwestern Chad Basin. On the other hand, a relatively high proportion of sherds from Garumele (25 %) are decorated with CWS. Although Garumele is chronologically later than Marandet and no direct evidence exists for CWS in the northwest Chad Basin during Marandet's period, the technique was at least in use in the broader region. Given the current state of research, the origin of the sherd in this region therefore seems quite plausible, while other possible provenances (e.g., Essouk) can reasonably be ruled out.

Although other provenances cannot be entirely excluded, and despite the lack of direct evidence for CWS in the northwest Chad Basin during the period of Marandet, this region currently appears to be the most likely origin. In addition to the Sgraffito sherds, this would provide further evidence of contacts between Marandet and the Chad Basin. Such a connection highlights the diversity of these interactions in two respects: not only does the sherd likely come from a different part of the basin, but unlike the Sgraffito ceramics it is relatively coarse and corresponds to typical household ware. While not impossible, it seems less likely that such pottery would have been transported over long distances as gifts or trade goods.

As detailed above, the sherds were found in refuse pits within a craft production area in Marandet, alongside a large number of clay crucibles used for copper alloys. While the Sgraffito pottery at Marandet might not necessarily indicate trade, much like most other imported goods (Chirikure, 2017), they could nevertheless hint at the artisans' involvement in long-distance networks, either directly or indirectly. In historical periods, peripheral groups—including artisans in West Africa—are known to have had higher mobility and broader networks of interaction (Haour, 2013, 117-118). This aligns with the fact that both the raw materials (partly from North Africa) and the processed products (some distributed along the Niger Bend) of Marandet's copper industry were moved over vast distances (Magnavita, 2018). The Sgraffito sherds provide key evidence for such interregional connections in sub-Saharan West Africa. However, a more comprehensive interpretation of its character requires further provenance analyses of artifacts from additional contexts.

7. Conclusion and outlook

The long-distance contacts presented in this paper demonstrate that Marandet was connected not only to the Niger Bend and the *trans*-Saharan trade network, as indicated by the archaeometric analysis of metal artifacts, but also to the Chad Basin. This highlights its importance as a trade hub and provides further evidence of the interconnectedness of sub-Saharan West Africa in pre- and early historic times. As the pXRF results show, the CWS and sgraffito sherds are not the only non-local ceramics, and the links to Lake Chad represent only one aspect of Marandet's broader interregional networks. The classification of the imported ceramics demonstrates that pXRF analysis can be used for large scale provenance analysis in this part of the world.

The archaeometric and typological analyses complement each other, helping to contextualize the evidence provided by each approach. This applies both to the identification of local ceramics and the attribution of non-local pottery. The two examples we presented illustrate different aspects of this approach: in the case of sgraffito, archaeometric analysis was used to confirm an already suspected region of origin and potentially refine it further, whereas in the case of CWS, the attributes of the sherd alone did not point to a specific region, making pXRF essential for narrowing down the possible places of origin.

For most sampled regions within the study area, a distinctive geochemical signature could be identified. Given the broad regional scope of the study, the geological differences between the clay sources are substantial, resulting in minimal overlap between regions. However, such similarities can occur, as illustrated by the geochemical resemblance between the northwestern and eastern Chad Basin. This is likely due to the fact that clay deposits in both areas originate from the same ancient lake sediments of Lake Chad.

The reference groups established through pXRF analysis represent only a first step and have an exploratory character. Due to the limited number of elements that can be accurately measured, the application of pXRF in provenance analysis has certain constraints. Reference groups are often distinguished by only a few elements, which can pose challenges when comparing a large number of reference groups or those from geologically similar but geographically distinct regions (Wilke et al., 2016). Additionally, while pXRF analysis can determine the geochemical composition of ceramics, it does not provide insights into their mineralogical properties. Therefore, further archaeometric analyses are required to refine the reference groups.

For refinement through chemical analysis, ICP-MS (e.g., Marengo et al., 2005; Rivero et al., 2025; Tsoupra et al., 2022) or ICP-OES (e.g., Mannino & Orecchio, 2011; Dias et al., 2017; Bernardini et al., 2024; Pérez et al., 2024)—or a combination of both—would be a particularly useful complement. These techniques significantly increase the number of elements available for provenance analysis, with Rare Earth Elements (REE) playing a crucial role. The increased dimensionality allows for a more comprehensive comparison of reference groups without significant overlap in their signatures. This, in turn, enables the creation of more detailed reference groups for a refined analysis of specific regions, as well as the inclusion of additional reference groups to cover larger parts of West and Central Africa.

The geochemical signature can be further complemented by mineralogical and technological analyses (Quinn, 2022, 384). While XRD primarily addresses the mineralogical composition, thin-section petrography can be used to examine both aspects (Thierrin-Michael et al., 2018). Understanding the mineralogical signature allows for a more precise characterization of the geological origins of the clay sources. Identifying specific minerals can also help linking geochemical signatures to geological formations (Sarhaddi-Dadian et al., 2015; Pourzarghan et al., 2017). Additionally, thin-section analysis aids in distinguishing the impact of tempering and other technological choices on the geochemical composition of ceramics (Stoner, 2016).

These analyses, however, are destructive and can be both labor-intensive and costly. The reference groups established through pXRF provide a means to selectively sample and analyze sherds, thereby optimizing resource allocation. By further refining these reference groups through additional analyses, they can contribute significantly to tracing contact networks and connectivity in sub-Saharan and Saharan Africa, extending beyond the study of exotic artifacts and written sources.

CRediT authorship contribution statement

Juan-Marco Puerta Schardt: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sonja Magnavita:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105382.

Data availability

Some data is not published because it will be used for further publications for Puerta Schardts PhD. All geochemical data and code regarding its analysis is published with a link.

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