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DOI
10.1016/j.jasrep.2025.105412

Publication date
2025

Document Version
Final published version

Published in
Journal of Archaeological Science: Reports

Citation (APA)
García-De León, A., Braekmans, D., & Geurds, A. (2025). Reassembling quarried landscapes through non-destructive X-ray fluorescence: the decorated metates from Central Nicaragua. *Journal of Archaeological Science: Reports*, *67*, Article 105412. https://doi.org/10.1016/j.jasrep.2025.105412

Journal of Archaeological Science: Reports 67 (2025) 105412

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Reassembling quarried landscapes through non-destructive X-ray fluorescence: the decorated metates from Central Nicaragua

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ARTICLE INFO

Keywords:
Portable X-ray fluorescence (pXRF)
Volcanic rocks
Geochemistry
Decorated Metates
Isthmo-Colombian Area

ABSTRACT

Between 300 CE and 1550 CE, the Isthmo-Colombian Area had one of the highest concentrations of stone artisans. This is reflected in the decorated metates that extend from Honduras to northern Colombia. The Chontales department, in central Nicaragua, plays an important role due to its geographic location between different cultural regions. In fact, archaeological investigations point to a strong tendency towards a local ethnic identity due to the style of its standing stone sculptures. However, the production of decorated metates appears to share similarities with broader regional styles from northern areas of the Isthmo-Colombian Area. Considering that most of the decorated metates were collected throughout the early half of the 20th century and belong to museums where no or limited information on their original context is contained, the study of these materials must rely mostly on alternative lines of evidence such as archaeometric studies. In this research, we explore the relationship between artisanal production and the selection of (volcanic) raw material sources in the Chontales archaeological landscape. In this paper, we present the (1) non-destructive characterization of the collection and (2) explore the correlation between geochemical sources and stylistic characteristics. Contrary to previous assumptions, the study finds that a wide variety of volcanic material sources were used in decorated metate manufacturing and may, in fact, have been widely circulated. Furthermore, the study suggests that specific sources were used for particular tasks. These results may provide insight into our understanding of persistent crafting traditions and intergroup interactions in Central Nicaragua.

1. Introduction

The Isthmo-Colombian Area (ICA) witnessed a remarkable rise in the production of stonework during 300 CE – 1550 CE. Ground stones were used for daily activities such as food processing and its use goes from the emergence of agriculture to the present day (Hamon et al., 2023; Searcy, 2011). Moreover, artisans also created sculptures in the shape of grinding stones, commonly known as decorated metates. Often, decorated metates are supported by three or four legs and feature a curved top. However, various practices in terms of design can be seen across the ICA. This design flexibility makes the metates well-suited to engage with different raw materials (Hamon et al., 2025), for experimentation during the manufacturing process (Adams, 1993), and for the representation of ideas and beliefs in ritual settings (Castillo Ochoa, 2022; Preston-Werner, 2008). Due to their occurrence in funerary contexts, archaeological studies also emphasize these objects to ritual activities with sociopolitical significance (Cooke et al., 2019, p. 93; Hoopes, 2007; Jones, 1992, 1991). From an anthropological perspective, decorated metates are saturated with meaning and ways of perceiving the surroundings not only because they depict zoomorphic or supernatural imagery, but also in the way communities engage with surrounding landscapes through procuring the raw stone materials.

Central Nicaragua is one of the key regions for the study of decorated metates in the ICA (Fig. 1). Preliminary stylistic and iconographic observations have suggested that different styles converge in this region, including the so-called Northern Costa Rica-Pacific Nicaragua, and Southern Honduras styles, identifying it as a region of interactions (Jones, 1992). However, this wide scope of different communities of

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https://doi.org/10.1016/j.jasrep.2025.105412
Received 12 July 2025; Received in revised form 11 September 2025; Accepted 15 September 2025
Available online 2 October 2025

artisans producing aesthetically similar objects, makes it difficult to narrow interpretations about the circulation of the objects and to differentiate between local and non-local materials. In addition to that, raw material studies have predominantly focused on subsistence strategies and resource exploitation rather than material circulation and have mostly considered the nearest sources for the analysis (Abramiuk and Meurer, 2006; Agar and Stern, 2003). Sculptures, and especially decorated metates, are usually overlooked when examining long-distance interactions, prioritizing other raw materials like so-called green stones (Melgar Tisoc et al., 2021; Monterrosa Desruelles, 2019; Ruvalcaba-Sil et al., 2008), obsidian (Kolbenstetter et al., 2025; Sheets et al., 1990), and other geomaterials (Gassmann et al., 2023; Ménager et al., 2021; Weigand and Harbottle, 1993). The limited availability of socially valuable stones such as jadeite in specific landscapes is often associated with evidence of long-distance exchange. This has drawn attention away from investigating more readily available raw materials such as volcanic rocks. As a result, it is frequently assumed that decorated metates did not circulate in long distance exchange mechanisms, since igneous stones are typically dispersed in abundant quantities across Isthmo-Colombian landscapes. However, there is no consolidated evidence that supports this idea.

Early research on these materials pointed to iconographic and stylistic features to establish local traditions of production and exchange. The distribution of decorated metates has also been correlated to the styles of Pacific Nicaragua and Northern Costa Rica, mainly established already by early research into ceramic styles (Coe, 1962; Coe and Baudez, 1961; Lothrop, 1926; Norweb, 1962). These styles are suggested to be linked to human groups and spheres of interaction. However, metate distribution tends to be broader rather than specific, and placing these objects into a relative chronology remains challenging, since controlled excavations only infrequently yield decorated metates. Fragments of decorated metates have been reported in Chontales in the El Cóbano and La Pachona archaeological sites (Rigat, 1992, p. 391). Both sites are related to funerary practices. The fragmented pieces were chronologically placed between the Potrero (800–1200 CE) and Monota phases (1200–1550 CE). Therefore, by comparative ceramic styles and stylistic affinities, the lifespan of producing decorated metates is placed between 300 CE and 1500 CE.

The lack of contextual data for complete objects combined with the limited presence of records regarding the development of museum collections is a major drawback in the study of these objects. These objects have a complex provenance history. Early ethnographic research in the Miskito region in Caribbean Nicaragua, provides evidence of the reuse of metates, dug up from archaeological contexts, as seats in indigenous households during modern times (Conzemius, 1932, p. 43). In Chontales, members of the community stated that the quarrying of stones for the production of grinding tools took place until one or two generations ago. Furthermore, the production of decorated metates shifted towards the use of wood as a raw material. This is also reflected in other later wood-based Chibchan sculptural traditions (Romero Vidal, 2024). In addition, early scholarly reports proposed that the objects are associated with funerary contexts (Boyle, 1866), suggesting their importance as part of community rituals.

Reconstructing the archaeological context of these sculptures remains challenging since in several cases the objects lack provenience information. Rejoining the sources and patterns of exploitation of raw materials is a viable option through archaeometric techniques in order to trace the circulation of materials across broader geographical regions. Portable X-Ray fluorescence (pXRF) has proven to be a successful technique for the characterization of volcanic materials. Archaeological research posits that artisans exploited certain types of raw materials for specific tasks (Brouwer Burg et al., 2021; Palumbo et al., 2015; Tibbits et al., 2023). This research aims to (1) determine the variability of rock types selected and used by different communities in the Chontales department, (2) explore the possibility to reconstruct the sources of volcanic materials, (3) evaluate the correlation between stylistic

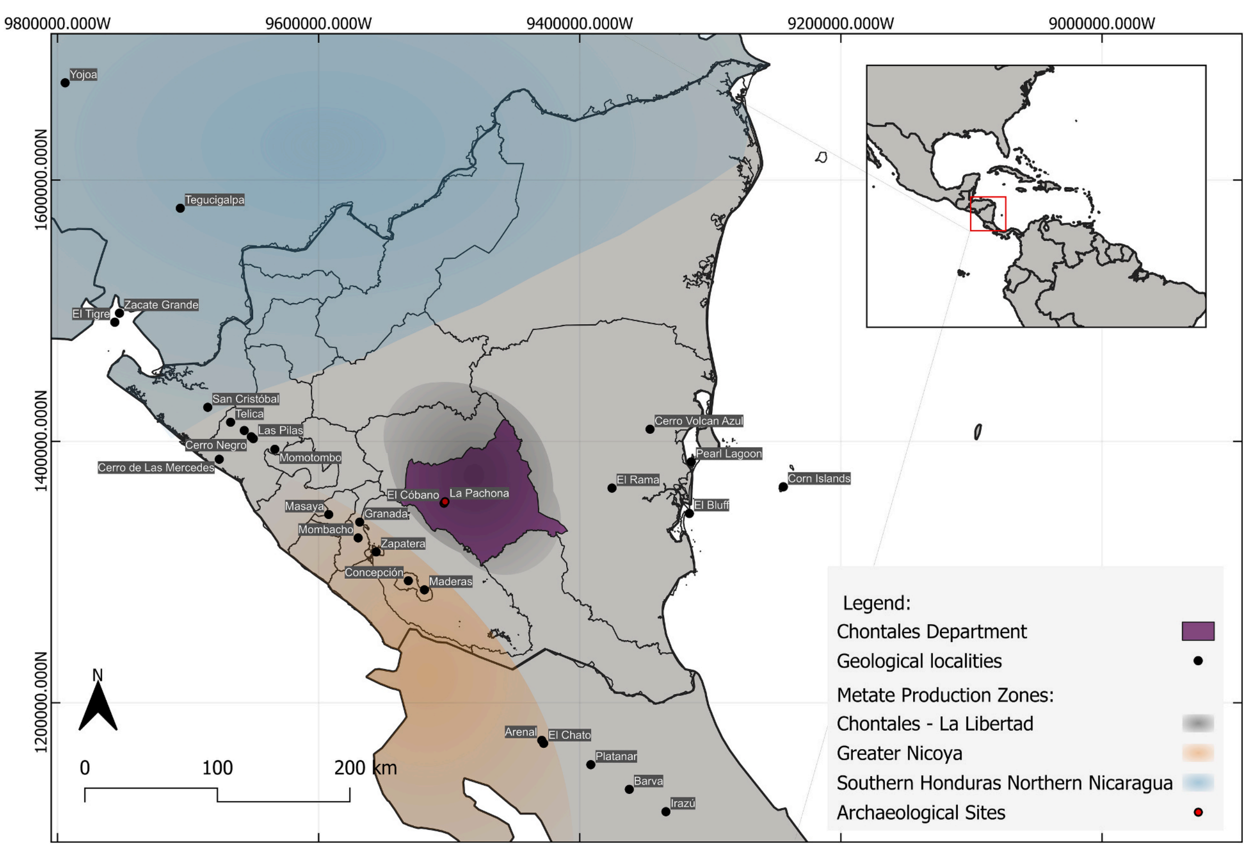

Fig. 1. Map showing the Chontales province, the geological localities, and the sites mentioned in the text.

features and the identified sources and (4) confront these observations with reference data presented from source materials, other contexts and regions. Ultimately, this paper aims to create a baseline for further archaeometric studies of igneous rocks in the ICA. The nature of igneous materials and the noticeable distribution and variability across the ICA, makes it an outstanding object category to study circulation in the indigenous social landscapes and hence contribute to our understanding of quarried landscapes in central Nicaragua.

1.1. Geological context

Regarding the potential geological sources for igneous raw material, Central Nicaragua is part of the Central America volcanic arc, where research has taken place for several decades (SI. 1). The Chontales department is situated on the margin of three main geological formations composed mainly of volcanic rocks: (1) Matagalpa fm, is the largest geological formation in Nicaragua and the oldest with a chronology between the Oligocene and the Miocene. It covers most of Chontales. The lithology is mainly composed of rhyodacite tuffs, andesitic to basaltic lavas, ignimbrites and sandstones; (2) the Upper Coyol Group fm is the second-biggest geological formation that surrounds Chontales. Stones in this geological formation includes ignimbrites, dacites, basaltic to andesitic lavas and pyroclastic rocks; and (3) more towards the eastern side, the Lower Coyol Group fm which dates back to the Middle Miocene and its lithology is composed of basaltic lavas, andesites, rhyodacite lavas; agglomerates, and pyroclastic rocks. Some other geological formations that surround Chontales are composed of Holocene sediment deposits, mainly pebbles, clay, and sand.

Sources and geochemical data of alkaline and subalkaline basalts, andesites and basaltic andesites from samples from Central America have been reported already in the literature (Carr et al., 2014; Ehrenborg, 1996; Janoušek et al., 2010) and will further act as reference for this study.

2. Materials and methods

2.1. Materials

The materials studied in this article belong to the collection of the Gregorio Aguilar Barea Archaeological Museum (MAGAB) located in the town of Juigalpa, the capital city of the Chontales, which hosts an extensive collection of metates, most of them decorated. Objects were collected from 1960s onwards, however, all of them were donated by community members aiming to enforce local identity through a regional

Table 1
Decorated metates and their respective geochemical sources groups.

Group	Sample	Style distribution [a]	Decorated	Representation	Leg Type	Grinding Top
AB-1	MET_MGA_2	NZ & GN	Decorated	Unidentified	Not decorated Trapezoidal	No decoration
	MET_MGA_6	NZ & GN	Decorated	Human/Bat	Not decorated Trapezoidal	No decoration
	MET_MGA_26	Unknown	Decorated	Mammalian	Trapezoidal Open fretwork	No decoration
	MET_MGA_9	NZ	Decorated	Unidentified	Not decorated conical	No decoration
	MET_MGA_10	NZ & GN	Decorated	Mammalian	Not decorated Trapezoidal	No decoration
	MET_MGA_31	GN	Decorated	Mammalian or Reptilian	Trapezoidal Open fretwork	No decoration
	MET_MGA_34	GN	Decorated	Mammalian	Trapezoidal Open fretwork	No decoration
	MET_MGA_35	GN	Decorated	Mammalian	Trapezoidal Open fretwork	Rectangular patterns
	MET_MGA_36	NZ & GN	Decorated	Avian	Rounded	No decoration
	MET_MGA_38	Unknown	Decorated	Human-like	Rounded	No decoration
	MET_MGA_39	NZ & GN	Decorated	Mammalian	Not decorated Trapezoidal	No decoration
	MET_MGA_40	GN	Decorated	Avian	Trapezoidal Open fretwork	Rectangular patterns
AB-2	MET_MGA_1	NZ & GN	Decorated	Avian	Not decorated Trapezoidal	No decoration
	MET_MGA_3	NZ & GN	Decorated	Unidentified	Not decorated Trapezoidal	No decoration
	MET_MGA_25	La Libertad	Undecorated	Undecorated	Squared conical	No decoration
	MET_MGA_8	NZ & GN	Decorated	Mammalian	Not decorated Trapezoidal	No decoration
	MET_OP_1	GN	Decorated	Unidentified	Unknown	Unknown
AB-3	MET_MGA_32	GN	Decorated	Mammalian	Trapezoidal Open fretwork	Rectangular patterns
RD-1	MET_MGA_14	Unknown	Undecorated	Undecorated	Rounded	No decoration
	MET_MGA_15	NZ & GN	Decorated	Unidentified	Not decorated Trapezoidal	No decoration
	MET_ZAR_1	Unknown	Undecorated	Undecorated	Rounded	No decoration
RD-2	MET_MGA_17	Unknown	Decorated	Unidentified	Rounded	No decoration
	MET_MGA_18	Unknown	Undecorated	Undecorated	Rounded	No decoration
SB-1	MET_MGA_4	NZ & GN	Decorated	Mammalian	Not decorated Trapezoidal	No decoration
	MET_MGA_4	NZ & GN	Decorated	Mammalian	Not decorated Trapezoidal	No decoration
	MET_MGA_5	NZ & GN	Decorated	Mammalian	Not decorated Trapezoidal	No decoration
	MET_MGA_28	NZ & GN	Decorated	Unidentified	Not decorated Trapezoidal	No decoration
	MET_MGA_37	NZ & GN	Decorated	Reptilian	Not decorated Trapezoidal	No decoration
	MET_MGA_42	Unknown	Decorated	Unidentified	Rounded	No decoration
	MET_MGA_19	NZ & GN	Decorated	Reptilian	Squared conical	No decoration
SB-2	MET_MGA_7	NZ & GN	Decorated	Mammalian	Not decorated Trapezoidal	No decoration
	MET_MGA_16	NZ & GN	Decorated	Unidentified	Not decorated Trapezoidal	No decoration
SB-3	MET_MGA_12	NZ & GN	Decorated	Avian	Not decorated Trapezoidal	No decoration
ABA-1	MET_MGA_30	NZ & GN	Decorated	Unidentified	Not decorated Trapezoidal	No decoration
	MET_MGA_11	NZ & GN	Decorated	Avian	Not decorated Trapezoidal	No decoration
	MET_MGA_21	La Libertad	Decorated	Unidentified	Trapezoidal Open fretwork	Unknown
	MET_MGA_23	Unknown	Decorated	Unidentified	Unknown	Incisions rectangular patterns
	MET_MGA_27	GN	Decorated	Mammalian	Trapezoidal Open fretwork	Incisions rectangular patterns
ABA-2	MET_MGA_29	NZ & GN	Decorated	Mammalian	Not decorated Trapezoidal	No decoration
Unknown	MET_MGA_24	Unknown	Undecorated	Undecorated	Not decorated conical	No decoration
	MET_MGA_20	Unknown	Decorated	Unidentified	Unknown	Rectangular and circular patterns
	MET_MGA_33	NZ & GN	Decorated	Reptilian	Not decorated Trapezoidal	No decoration
	MET_MGA_41	GN	Decorated	Avian	Trapezoidal Open fretwork	No decoration
	MET_MGA_43	NZ & GN	Decorated	Unidentified	Not decorated Trapezoidal	No decoration

[a] Distribution of styles was proposed by Jones (1992). NZ = Northern Zone, includes Northern Nicaragua, Gulf of Fonseca, and Central and Caribbean Honduras. GN = Greater Nicoya, includes Pacific Nicaragua and the Guanacaste Peninsula. La Libertad, Nicaragua, refers to a slight description of the style reported by Boyle (1866).

and communitarian archaeological museum (Geurds, 2011a). No systematic information regarding the exact provenience of the metates was collected. A total of 27 complete pieces are in the permanent exhibit today. Community members that donated the objects state that all the materials have their origin in the province of Chontales or its immediate surroundings. Given the quantity and aesthetics of these objects, these metates are one of the highlights for museum visitors.

This study considers the entire collection of metates in the MAGAB, including the metates on permanent display as well as 15 additional ones, mostly fragmented or incomplete metates, held in the museum's depot. A total of 44 metates (SI 2.1, Table 1) including fragments, were included in this investigation. Most of them are tripod effigy metates, aesthetically related to the ones reported for Northern Costa Rica and Pacific Nicaragua (Lothrop, 1926), as well as Southern and Caribbean Honduras (from now on Northern Zones = NZ) (Stone, 1957; Strong, 1935, p. 76). The collection also portrays local styles of metates similar to the ones anecdotally described near the Chontales town of La Libertad (Boyle, 1866). In addition to the MAGAB metate collection, two additional fragments from previous archaeological surveys conducted by the Central Nicaragua Archaeological Project (PACEN) under direction of Geurds were considered. One is an undecorated metate found at the surface at the La Zarcita archaeological site, and another decorated fragment with an incised grinding top was found in the Sábana Grande archaeological site.

2.2. Stylistic typologies

Metate sculptures from the ICA were previously studied by Jones (1992) from a stylistic and iconographic perspective, including materials from Honduras, Nicaragua, Costa Rica, and Panama hosted in different museums, both in Europe and across North and Middle America, and collected during the first half of the XX century. As a result of Jones's research, a regional typology including a proposed distribution was established. Several stylistic similarities are also shared across the ICA and therefore, the distribution of similar objects tends to be geographically spread. Arguably, there could thus be a mix present between local and foreign ideas in sculptural practices. Nonetheless, this stylistic observation has been helpful in museum contexts to relate objects to particular geopolitical boundaries when lacking provenience information.

Following the idea of reconnecting the objects to particular landscapes, as a step prior to the geochemical characterization, the typology proposed by Jones (1992) was used to determine the stylistic and macroscopic features of the assemblage (SI 2.1). In terms of the distribution and provinience of the metates, it is only possible to relate them to regional styles, as initially defined by Willey and Phillips (1954, p. 34–39). Some individual features in the metates are particularly useful to relate them to specific manufacturing traditions and therefore, to a geographical area, especially leg types. The stylistic characteristics were documented separately in order to understand the design decisions

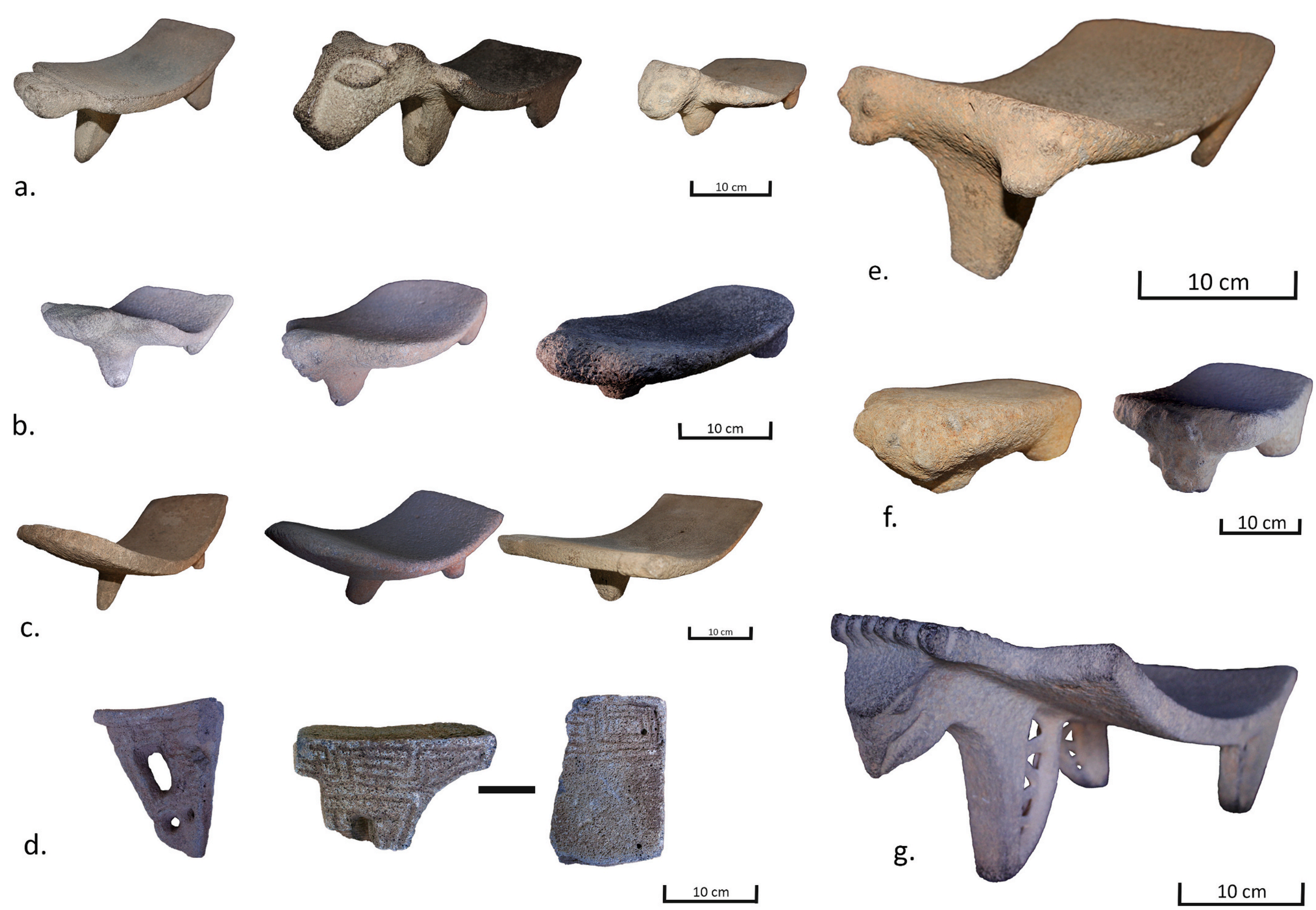

Fig. 2. Some metate sculptures considered in this study from the Museo Arqueológico Gregorio Aguilar Barea Collection. (a) Avian and mammalian representations with trapezoidal legs: met_mga_11, met_mga_03, met_mga_04; (b) mammalian representations with rounded and trapezoidal legs: met_mga_09, met_mga_06, met_mga_13; (c) undecorated metates: met_mga_24, met_mga_18, met_mga_25; (d) fragments of decorated metates with incisions in the grinding top and in its lateral side: met_mga_21, met_mga_23, (e) two heads mammalian metate: met_mga_10; (f) rounded legs effigies: met_mga_17, met_mga_38,; (g) avian metate with trapezoidal open fretwork legs: met_mga_40.

made by the artisans to produce these artefacts. The categorization of the styles includes the morphological description of the legs (trapezoidal, angular, conical or rounded); the design on the legs (no decoration or open fretwork), as well as the designs on the grinding top or on the sides. Incisions with rectangular patterns are common in decorated metates from Pacific Nicaragua and Northern Costa Rica, therefore, the presence or absence of this was also recorded. Tripod decorated metates with trapezoidal open fretwork legs or heads are representative for Pacific Nicaragua and Northern Costa Rica traditions, and effigies with trapezoidal and undecorated legs are typically found across Northern Costa Rica towards Southern and Caribbean Honduras. The tripod metates with angular and rounded legs are more commonly found in Southern and Caribbean Honduras. Another metate type proposed from Central Nicaragua, while not an effigy like the other styles, shows knobs in the distal part of the grinding top with rectangular incisions in the top (Jones, 1992, p. 42) (Fig. 2.C). From an iconographic standpoint, it was considered whether the effigy represented a mammal, a reptile, an avian species, a human-like or if it is without clear association to a specific iconography.

2.3. Portable X-ray fluorescence analysis

Portable X-Ray Fluorescence (pXRF) was selected as the main method to gain compositional information due to its required non-destructive nature and portability to the museum itself. The conservation of archaeological objects in regional museums in Central America is an important agenda for future generations. While drawbacks of this method have been discussed (Frahm and Doonan, 2013; Liritzis and Zacharias, 2011; Williams-Thorpe, 2008), it has proven to be a relevant non-destructive technique in the right circumstance for the characterization of archaeological igneous rocks (Charleux et al., 2014; Lundblad et al., 2011; McAlister and Allen, 2017). Previous applications in the Americas have mainly focused on archaeological obsidian. Coarser grain materials have also been sourced through this technique (Brouwer Burg et al., 2021; Tibbits et al., 2023). Due to its semi-quantitative nature (Scott et al., 2014), this technique is effective when combined with techno-stylistic data.

In general terms, an early concern of portable XRF regarding the grain size has limited the studies of coarser materials. In materials with large phenocrysts, it is important to evaluate the area measured in rock analysis, which can be quite variable depending on rock type. However, most of the igneous rocks in this study have phenocrysts in the range of 0.2 to 7 mm (SI 2.2). A specific focus was to measure the polished surfaces of the metates, avoiding the large phenocrysts, and to maximize comparability.

Regarding geochemical data approaches, provenance studies have focused on discriminating different sources by (trace) elemental content and/or through statistical methods such as principal component analysis (PCA). However, when working with volcanic materials, it is argued that giving a detailed characterization about the volcanic rock types must be a first step prior to statistical methods. Hence, only compare materials that match volcanic rock type and narrow the possible sources to geological localities where the volcanic rock types are present. Another disadvantage of pXRF studies in the region is the complex geological substrate, which poses difficulties in attributing detailed material types and geographical association with specific outcrops. On one hand, geological research has used rare earth elements such as Thorium (Th) and Lanthanum (La) and Ytterbium (Yb) to build geochemical trends across the Central American volcanic arc (Lindsay 2009). However, it is not possible to consider those elements only through portable XRF. Thus, any non-destructive approach must rely solely on trace elemental data, and exploring the trace elemental variation in the region remains a key factor to foreshadow sourcing and circulation of volcanic archaeological materials in Central America.

In order to confront the non-destructive challenges of the portable XRF and to narrow possible sources due to the lack of geological material from Chontales, the Pearce W-F diagram was used as a primary method to associate the metates with various volcanic rock types (Pearce, 1996; Winchester and Floyd, 1977), as outlined in Richards (2019). The Pearce W-F diagram was successfully employed previously to classify volcanic rock type. This bivariate plot uses ratios from immobile elements Niobium (Nb)/Yttrium(Y) on the X-axis ($\log_{10}$), vs Zirconium (Zr)/(Titanium dioxide (TiO_2)/1000) on the Y axis ($\log_{10}$). The pXRF data from these elements are far less prone to weathering processes, making them more reliable for semi-quantitative geochemical analysis. Immobile elements and the Pearce W-F diagram have been successfully used to fingerprint archaeological materials in Oceania (Nutman et al., 2025; Richards, 2021, 2019), Asia (Utting, 2022), and North Africa (Jesse et al., 2023). However, it has never been tested extensively in the ICA and in archaeological contexts near volcanic arcs. Other approaches to determine volcanic rock types such as the Total Alkali Silica have uses elements such as SiO_2, NaO_2, K_2O have proven too inaccurate on many occasions when using non-destructive XRF instruments, given the limits of detection and weathered surface complications (Lundblad et al., 2011, p. 77).

This study utilised standardized recommendations (Frahm, 2024; Johnson et al., 2024). The equipment used in this study is a Bruker Tracer 5 g portable ED-XRF, with an energy resolution of <140 eV at 250,000 counts per second at Mn Kα. The instrument features a silicon drift detector and a ∼ 8 mm beam collimator was used. Measurements were conducted on location in air under two different conditions to optimize for both light and heavy element detection. Conditions were set at a livetime of 30 s at 50 kv − 17.7μA with a 25 μm Ti − 300 μm Al filter in place, followed by a 60 s measurement under 15 kV − 22.2 μA without a filter on the exact same location.

The surfaces of the archaeological materials were cleaned with water 24 h prior to the measurements. After assessing relative standard deviation <10 % in trace elements through six measurements in different spots of one artifact, three measurements in different spots in 25 artifacts, two measurements in different spots were taken for 17 artifacts and one object was only possible to take one measurement. All measurements were run handheld on each object on flat surfaces. Net peak areas are calculated from these spectra using proprietary Bruker ARTAX software and a Bayesian deconvolution approach. In order to allow relative comparisons to other datasets for the relevant elements, a proprietary Bruker factory calibration for solid rock materials ('Mudrock Air') was employed to obtain a semi-quantitative dataset. Six certified reference materials (BIR-1a, GSP-2, NIST-278, NIST-610, NIST-612, SGR-1b) were measured to monitor the instrument for precision and accuracy. The precision is estimated as relative standard deviation (RSD % = stdev/average*100 %) and the accuracy is calculated as (Certified – Measured value) / (Measured) * 100). Precision of the XRF unit for the elements under study here (Fe_2O_3, TiO_2, Ni, Cu, Rb, Zr, Sr, Zn, Nb, Y) is generally within the 1–5 % range, with the exception of Ni (max. 8.3 %) and Zn (max. 5.2 %). Accuracy is assessed generally for Fe_2O_3, Zr, Sr (∼5%); TiO_2, Rb, Zn (∼10 %), Cu, Y, Nb (∼15–20 %), with the exception of very low compositions that approach the detection limits of the instrument such as Ni.

After assessing the variability of the raw materials in the assemblage, the objects were divided into volcanic type groups. In order to attest to different geochemical groups, which are believed to be related to different volcanic complexes and source localities, bivariate plots using trace elements were implemented. This approach has proven to be successful when grouping geomaterials for archaeological purposes (Brouwer Burg et al., 2021; McAlister and Allen, 2017).

2.4. Statistical approach

Linear discriminant analysis (Baxter, 1994, p. 185–218) is a suitable tool when comparing different geochemical signatures and stylistic predefined groups. All statistical procedures were carried out using PAST statistical software (Hammer et al., 2001) to evaluate this group attribution and check whether known and established stylistic categories have any correspondence with the geochemical groups (SI. 2.1). Mid-Z elements Fe_2O_3, TiO_2, Ni, Cu, Rb, Ba, Zr, Sr, Zn were considered, and data were normalized to $\log_{10}$ (Baxter, 2001; Baxter and Freestone, 2006).

2.5. Geochemical framework

Geochemical data from different volcanoes have been published in the literature including reference data related to materials from various volcanoes in Costa Rica, Nicaragua, and Honduras covering different volcanic complexes (Carr et al., 2014, 1982; Janoušek et al., 2010). This is one of the most representative geochemical datasets from the region since it includes both the volcanic front arc and the volcanic back arc. The samples were collected by different researchers at different times in history and for different porpouses, mainly the study of the volcanic evolution of Central America and therefore, some geographical areas towards the Caribbean are missing. In order to address this geographical void, geochemical ICP analysis by Janoušek et al. (2010) in Central and Caribbean Nicaragua was considered. Bulk geochemistry of the lava stones was collected through ICP-MS, NAA and XRF and the overall quality of the data was evaluated by geologists (see Carr et al. 2014 for specific details). While different whole-rock geochemistry techniques were used in these studies, ratios between elements should be fairly constant, enabling a relative comparative approach (see Fig. 6). This comparative database has been successfully implemented to provenance ceramics in Pacific Nicaragua (Dennett et al., 2019). Furthermore, geological references from geographically larger areas are suitable for this investigation due to the lack of provenance data in museum collections.

3. Results

3.1. Stylistic overview

From the total of 44 metates studied here, including decorated ($n = 39$) and undecorated metates ($n = 5$). 25 objects were found to be stylistically related to the Greater Nicoya, Northern Zones of Nicaragua, Southern Honduras semiotic traditions. This is by far the most geographically spread style in the ICA. The metates reported solely in the Northern Zones of Nicaragua and Southern Honduras semiotic traditions are represented in the collection only by one object. In addition, some metates were related to those found exclusively in the Greater Nicoya region ($n = 9$). Only two showed characteristics of the autochthonous types reported in central Nicaragua, while the rest could not be associated with any of the semiotic traditions due to the fragmentary nature of the decoration or due to the lack of decoration.

Regarding iconography, mammalian animals are highly represented, with 12 examples, followed by avian species ($n = 7$) and reptilians ($n = 3$). A single decorated metate features a human-like representation. For the remaining ones, no decoration could be or was identified.

During this investigation, preliminary observations of the assemblages suggested that leg morphology plays an important role in the differentiation of the styles across semiotic traditions. Therefore, this feature was recorded separately. The entire assemblage consists of tripod metates, and it features legs with trapezoidal morphology and no decoration ($n = 21$), trapezoidal morphologies with open fretwork designs ($n = 9$), rounded ($n = 8$), squared conical ($n = 2$), conical ($n = 2$) and in some cases it was not possible to determine ($n = 3$).

Five metates showed rectangular decorations in the grinding top. Rectangular along with circular patterns were observed in one metate. Other metates showed no decoration in their grinding top ($n = 37$), and in some cases, this feature could not be recorded due to the object being a fragment ($n = 2$).

3.2. Analytical chemistry

The Pearce W-F diagram was used as a primary method to associate the metates with various volcanic rock types (Pearce, 1996; Winchester and Floyd, 1977). The Pearce W-F diagram was successfully employed previously to classify volcanic rock type, and the same approach as defined by Richards (2019) has been followed. This bivariate plot uses ratios from immobile elements Niobium (Nb)/Yttrium (Y) on the X-axis ($\log_{10}$), vs Zirconium (Zr)/Titanium dioxide (TiO_2)/1000 on the Y axis ($\log_{10}$) (Fig. 3). The pXRF data from these elements are far less prone to weathering processes, making them more reliable for semi-quantitative geochemical analysis. We considered only the average values from the measurements for this procedure.

Four volcanic types were established: alkaline basalts, subalkaline basalts, andesite and basaltic andesite and rhyolite-dacites. In some objects, Nb was below the limits of detection (< LOD). Therefore, a category named unidentified volcanic types was created for these objects and therefore, not included in this section. We proceeded with each group individually to determine the geochemical groups and intra-group variability.

3.2.1. Alkaline basalts (AB)

Alkaline basalts represent the majority of the rock types used for the production of metates within the collection under study, with a total of $n = 21$. Further geochemical groups could be differentiated within this rock type through bivariate plots using Cu, Nb, Zirconium (Zr) and TiO_2, these are now identified as AB-1, AB-2 and AB-3 (Fig. 4.A).

AB-1 is the geochemical source that has the most alkaline basalts. It is characterized by high levels of Cu and slightly more Zr concentrations. Furthermore, this geochemical group also shows lower concentrations of Nb. Discrimination was also possible through other elemental data, such as TiO_2 against Cu ppm. AB-2 has a smaller number of objects, and it seems to have less intra-source variation than AB-1. AB-2 shows systematically lower concentrations of Cu and Zr, but slightly higher concentrations of Nb. TiO_2 concentrations show more overlap with AB-1. AB-3 has a significantly higher concentration of Nb and Zr, but a low concentration of Cu, making it stand out from the rest. According to the community members and staff of the MAGAB, the sculpture that belongs to this group was found in the Nueva Guinea community, which is more than 100 km away from Juigalpa. It is, therefore, reasonable to separate this particular source for further study. Besides these geochemical groups, two outlier individuals were identified as having a different trace elemental content, pointing at different outcrops as well. For these alkaline basalts, especially Nb and Cu provided the clearest markers for internal differentiation and geochemical fingerprinting.

3.2.2. Subalkaline basalts (SB)

Nine metates were classified as subalkaline basalts, although most of these are in proximity of the alkaline basalt range. All the objects of this type are decorated. However, geochemical differences in this volcanic type do not seem as clear as the alkaline basalts. By using bivariate plots of Zinc (Zn) vs Yttrium (Y), Niobium (Nb), Copper (Cu) and Zirconium (Zr) we could differentiate two and tentatively a third geochemical source. SB-1 is the source with where most of these metates are attributed to. This group is characterized by lower concentrations of Zn and slightly higher values for Cu. Furthermore, SB-2, with only two objects, shows significantly higher Zn concentrations. Nb, Y and Zr do not vary within both SB groups. However, when plotting Zn against these elements, this group differentiation becomes clear. One metate is an outlier from both previously mentioned groups on the basis of these Zn concentrations (Fig. 4.B).

3.2.3. Andesites and basaltic andesites (ABA)

Three objects were placed into this category. Object (id met_mga_30) can be differentiated from the other two due to its high Sr, low Zr and Rb content. This metate defines the ABA-1 geochemical group. The other

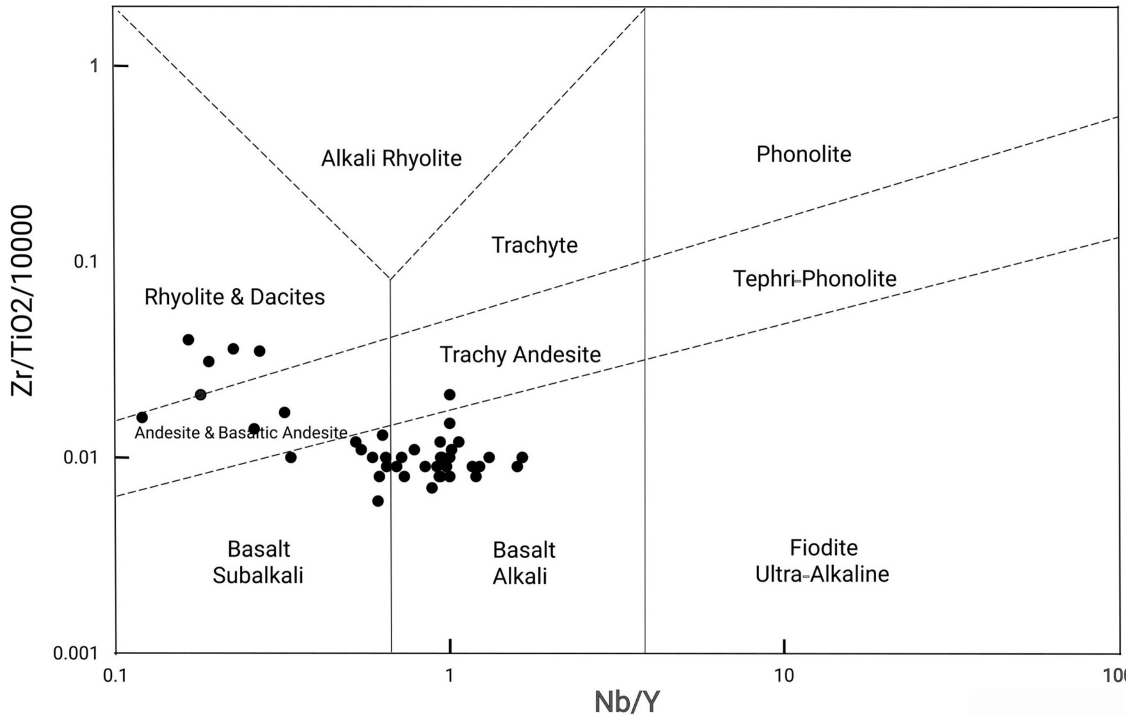

Fig. 3. Pearce W-F diagram for volcanic rock geochemical classification considering the average values of each material.

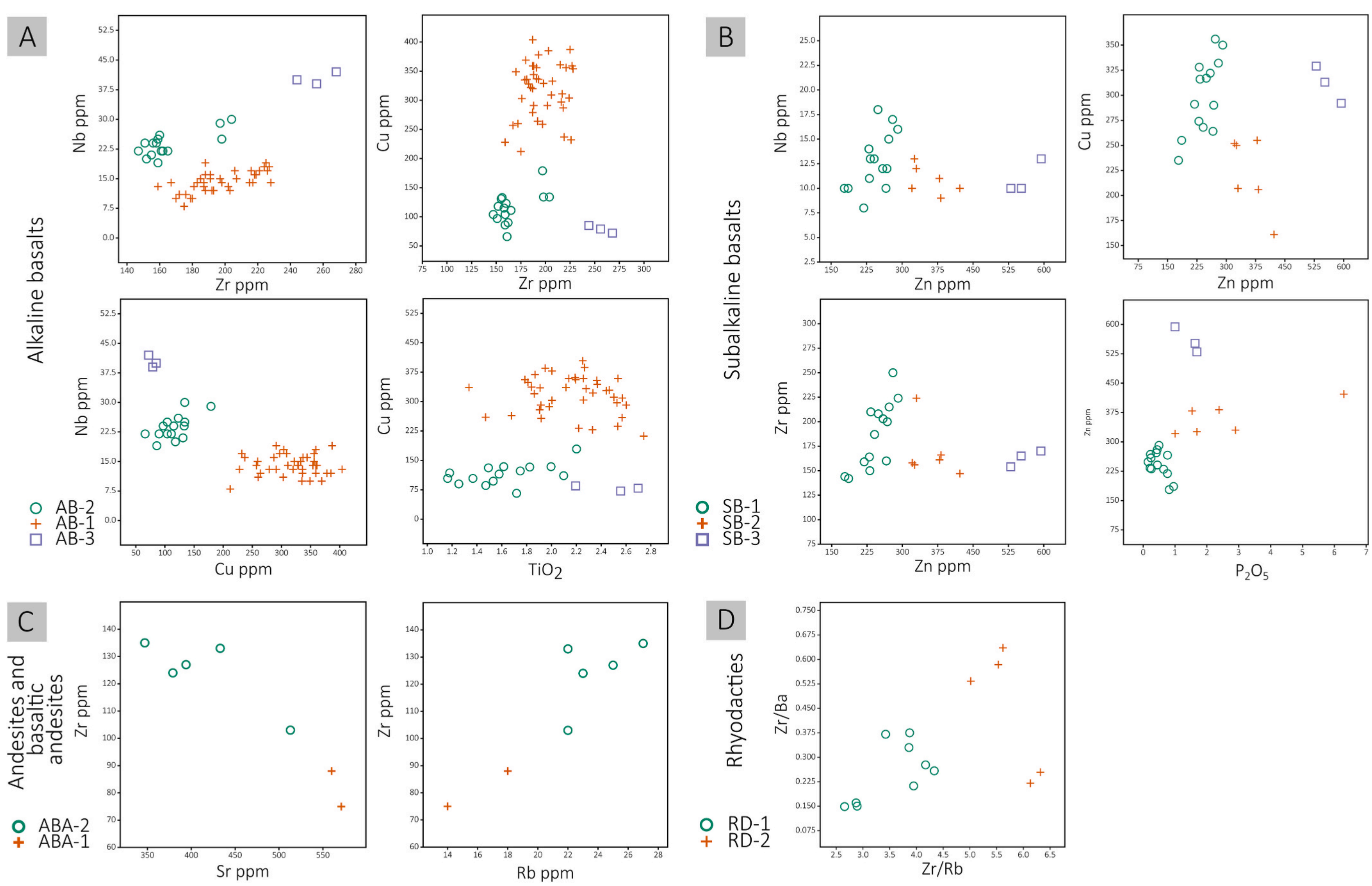

Fig. 4. Bivariate plots for alkaline basalts (A), subalkaline basalts (B), andesites and basaltic andesites (C), rhyodacites (D). All measurements were considered.

two objects (met_mga_13; met_mga_29) are closer to each other and, considering trace elemental data, are more enriched in Zr and Rb. These two objects are placed in the ABA-2 geochemical group (Fig. 4.C).

3.2.4. Rhyodacites (RD)

Few metates were geochemically classified as rhyodacites, although further characterization remains difficult due to the limited variation in trace element concentrations. Differentiation was only obtained through elemental ratios of Zn, Zr, Rb, and Ba elements. On the basis of these observations, two major groups are proposed. From the five objects, three can be grouped in RD-1 geochemical group, characterized by the lower content of Zn and Zr and especially Zr/Ba and Zr/Rb elemental ratios. Although relatively variable, the RD-2 group for two objects is based on Rb and Ba elemental concentrations (Fig. 4.D).

3.2.5. Unknown volcanic rocks

Four metates could not be further attributed in this study. The materials belonging to this group could not be associated with any volcanic rock type due to the absence of Nb in the measurements required for the Pearce W-F diagram. From a style perspective, this group has a lot of variability that can be attributed between Northern Costa Rica towards Southern and Caribbean Honduras. Three are decorated with both trapezoidal open fretwork and trapezoidal undecorated legs. It also includes avian and reptilian iconography, and one of them also displays geometric designs in the grinding top (Table 1).

4. Discussion

4.1. Style vs geochemistry

No single morphological variation or animal representation was restricted to any specific geochemical group. However, clear patterns can be identified when comparing animal representations and geochemical groups (see Fig. 5.A, SI 4). Alkaline basalts dominate linear discriminant 1 (LD1), relating to enrichments in Fe_2O_3, TiO_2, Zr, and Cu. Linear discriminant 2 (LD2) on the other handis dominated by the rhyodacites and basaltic andesites geochemical groups (correlated with Y, Ba and Rb values). Decorated metates, especially with animal depictions, are enriched in Fe_2O_3, TiO_2, Zr, and Cu, and are related to the AB, ABA and SB source groups. Conversely, non-decorated metates and unidentified effigies are generally high in Y, Ba, Rb that are related to the rhyodacites groups. A noticeably strong evident pattern is the case of alkaline basalts. Decorated metates belonging to this rock type display a wide variety of stylistic characteristics, including, squared and trapezoidal legs including open fretwork designs (Fig. 5.B). Only one undecorated metate with stylistic affinities to the ones reported in the La Libertad town was manufactured in alkaline basalt. From an iconographic perspective, this group also displays several animal representations, including mammals, avians, reptilian and human-like imagery. Specific sources seem to have been used for particular tasks as AB1 source was used repeatedly to create complex metate sculptures, in contrast to AB2 which is not necessarily restricted to specific iconographies. The latter includes a wider spectrum of shapes and forms, including unidentified effigies. Source AB3 was used to manufacture a single metate with a mammalian shape (see Table 1).

Moreover, subalkaline basalts are restricted to reptilian, mammalian and unidentified representations. Source groupings SB1 and SB2 were selected to create mammalian and reptilian imagery, while SB3 was used solely for an avian metate effigy. In addition, sources of andesites and basaltic andesites and specific ABA2 were chosen for mammalian, undecorated and effigies that could not be associated with any representation. Source ABA1 could not be associated with any tendency in the iconography. As for rhyodacites, these raw materials seemed to have seen flexibility in their use, since data is distributed between undecorated and unidentifiable effigies. The materials that could not be associated with a specific volcanic type portray a reptilian, an avian and undecorated metates.

A linear discriminant 1 (LD1) vs linear discriminant 2 (LD2) plot (Fig. 5.B) shows that both representation and leg type were mostly produced using the alkaline basalt source groups. If we narrow it a bit more, we can also notice that mammalian representations were the preferred representation made on alkaline basalts. Some metates manufactured in alkaline basalts are stylistically representative from Southern and Caribbean Honduras, while others can be ascribed to Northern Costa Rica and Pacific Nicaragua. Subalkaline basalts also show more variability between zoomorphically unclear zoomorphic not well-defined objects, also including avian and reptilian representations. All subalkaline basalts are stylistically similar to the metates found across Northern Costa Rica and Honduras, in contrast to both andesites and basaltic andesites and alkaline basalts groups, both the latter were used to craft more diverse stylistic types. These only included undecorated, trapezoidal-legged effigies. Undecorated metates were, however, manufactured using rhyodacites with more varied morphologies and sizes.

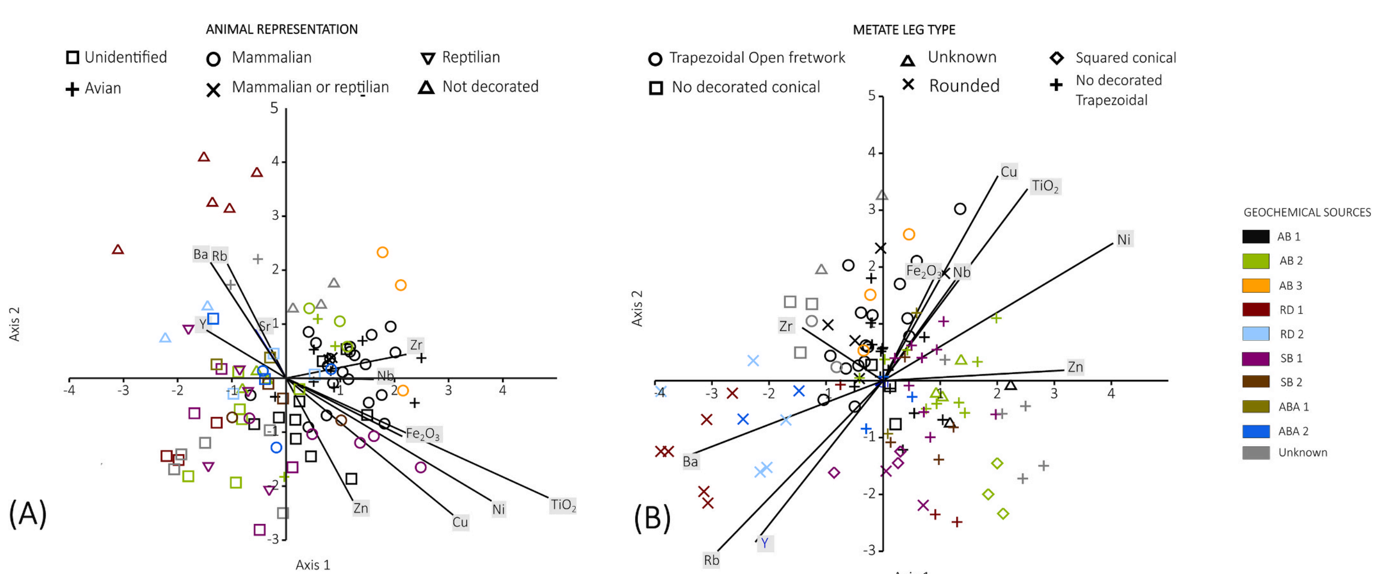

Fig. 5. Discriminant analysis, including TiO_2, Fe_2O_3, Ni, Cu, Ba, Sr, Zr, Zn. Animal representation (A) and the leg types (B).

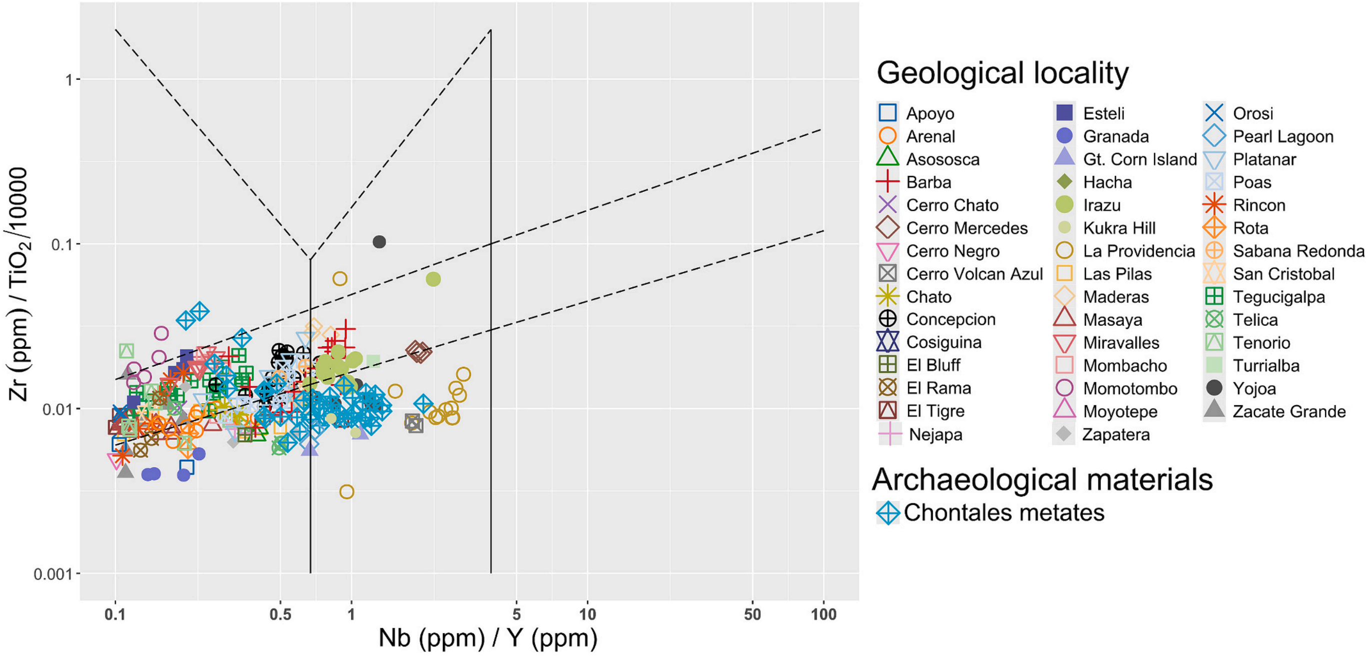

Fig. 6. Geological samples from volcanic complexes in Honduras, Nicaragua, Costa Rica vs decorated metates. Geological data from previous research in Central America (Carr et al., 2014; Janoušek et al., 2010).

Another clear pattern of raw material choice is the preference of artisans to select rhyodacite sources to produce undecorated metates. Rhyodacites are highly available in Chontales, especially towards the Nicaraguan depression near the Lake of Cocibolca (Ehrenborg, 1996). This material is generally described as having a softer matrix (Giordano et al., 2024), being easier to break but also less predictable when being sculpted than mafic or intermediate lavas. Thus, rhyodacites appear to be less durable. Furthermore, artisans were selecting alkaline basalts and subalkaline basalts to produce the styles that are distributed in both Northern Costa Rica towards Southern Honduras.

4.2. The provenance of decorated metates

The limited availability of sources of alkaline basalt in central Nicaragua makes it challenging to relate archaeological materials to a specific geographical location. Alkaline basalts are also restricted to isolated localities. Therefore, volcanic types are potential candidates to establish a differentiation between local and non-local raw materials. Even if the Pearce W-F diagram is not aimed at provenancing materials, it is helpful for discarding possible sources. Geological sources from La Providencia (Colombian island off the Caribbean coast of Nicaragua), Lake Yojoa and El Tigre Island (Honduras), Barva, Las Mercedes and Irazú (Costa Rica), Pearl Lagoon and El Rama (Caribbean Nicaragua), are suitable sources to compare with metates made on alkaline basalts.

In addition, sources surrounding Lake Cocibolca are sub-alkaline basalts. Sources of sub-alkaline basalt near Central Nicaragua that might be similar to the metates reported in this paper are Maderas, Mombacho, Momotombo, and Zapatera Island. Further sources of sub-alkaline basalts in Costa Rica have been reported around Barva volcano. In addition, subalkaline basalts might be a local material. The same goes for the basaltic andesites and andesites: the material appears to be more common in central Nicaragua with samples reported from the Mombacho, Concepción, and Masaya volcano complexes. Other further sources with similar materials are near Tegucigalpa (Honduras) and Barva (Costa Rica).

Only two sources of rhyolites and dacites were selected for this study due to the scarcity of sources previously reported. Those outcrops belong to the Masaya and Momotombo volcano complexes.. Furthermore, rhyodacitic sources are highly available in Chontales, according to previous geological research, specially in zones near the Lake of Cocibolca (Ehrenborg, 1996). Therefore, it is difficult to establish any comparison only through non-destructive analysis.

Even though the Pearce W-F approach to basalt classification does not aim for provenancing materials, it is useful to discard possible sources of the same material type in Central America. Further rare earth elements ratio analysis could be carried out to be able to relate our geochemical groups with high-resolution data that has been published in the geological literature. However, further studies should also consider that geological samples were collected for geological and other purposes, different from the characterization of archaeological materials. Lastly, observations also point out that the distribution of previous geological sampling strategies in the Central American volcanic arc may have been biased (Carr et al., 2004).

Nonetheless, the geochemical fingerprint of the decorated metates points to Central Nicaragua as a center for the circulation of materials, and the geochemical profile matches what is expected from the geological make-up of the region. It suggests that travelers from distant areas were recurrently visiting, principally, Chontales itself, bringing to the region their sculptures, probably for the activities carried out at monumental sites that still mark the Chontales landscapes today (Geurds, 2025). The fact that different styles converge in this region points to the important role played by indigenous communities in Chontales in constructing local identities and embarking on complex exchange systems across Lake Nicaragua, towards the Gulf of Fonseca and into Central Honduras. Furthermore, the presence of Northern Costa Rica styles matching geochemical groups with styles from Southern Honduras and Northern Nicaragua suggests that this circulation also occurred towards the south of Central America. Yet, a more detailed geochemical analysis of volcanic raw materials should be done both towards the north and south of the Isthmo-Colombian Area to complement the findings presented here.

4.3. Reconstruction of quarried landscapes

The characterization of the metates has suggested that communities preferred for selecting specific raw materials for the production of specific animal representations and styles. Different types of raw materials and different sources of those materials converge in the same region to demonstrate how communities engaged with the landscape. This shows that, among all the rock types and geochemical sources reported in this paper, communities were creating and maintaining crafting traditions with several raw materials.

No quarry or workshop related to metate production has yet been identified during archaeological surveys in the region. However, possible sources of volcanic rock for standing sculptures have been reported (Geurds, 2011b, 2009). Yet, the suitability of igneous rocks as primary sources in Chontales to produce metates needs to be tested. The lack of spatial data of quarries makes any accurate provenance attempt challenging in Chontales at present. Based on the current geological information and analytical evidence presented, it is substantiated here that metates were mobile and that a flow of raw material across Costa Rica, central Nicaragua and Southern Honduras was occurring, probably for prolonged periods, especially between 300 and 1550 CE. It is worth noticing that the lack of contextual information makes it impossible to affirm that the circulation and mobility of metates was occurring simultaneously across the ICA.

More widely traditions for selecting raw material for grinding tools have been reported across Middle America. It includes the andesite raw materials in Central Mexico (Hamon et al., 2024) and granites and sedimentary rocks in Belize (Brouwer Burg et al., 2021; Tibbits et al., 2023). The analysis of the physical characteristics, together with the ethnographic observations, indicates that the quality of the material for each specific craft plays an important role in the choosing of raw materials (Hamon et al., 2025). This is mirrored in this study, since most of the special and complex crafts were made using alkaline basalts. In terms of technology, further mineralogical analysis of Nicaraguan volcanic materials, including both sub-alkaline and alkaline basalts, might shed light on the specific physical properties artisans selected for their crafts.

In contrast with carved stones from Pacific Nicaragua and Northern Costa Rica, in Central Costa Rica and Western Panama decorated metates tend to more frequently represent anthropomorphic iconography, mainly through small heads surrounding the grinding top. This decoration is associated with the displaying of trophy heads, as part of decapitation during ritualized warfare (Hoopes, 2007; Muñoz, 2016, p. 66). Another remarkable metate type is the flying panel metate which shows a three-dimensional design under the grinding top, accompanied by four or three legs (Graham, 1992; Stone and Balser, 1957, p. 177). This type of metate spread across Southern Costa Rica up to the Barriles archaeological site, in western Panama (Linares et al., 1975). Since alkaline basalts are more restricted towards the south of Central America (Carr et al., 1982; Saginor et al., 2013), a detailed archaeometric exploration of those sculptures might shed more light on how metates relate to the ones found in Central Nicaragua.

Other archaeological connections between Southern Honduras, and Nicaragua are suggested in the semiotics of petroglyphs (Kolbenstetter, 2022). Moreover, ceramic types from the Gulf of Fonseca, Nicaragua, and Northern Costa Rica have been reported in Chontales (Gorin, 1990). However, more archaeometric research is needed to propose patterns of trade and exchange across these region, specially involving the boundaries of the ICA and southeastern Mesoamerica, in the understanding that such boundaries were in the past made up of constellations of practices (Joyce 2022). Furthermore, metal objects stylistically affiliated to ICA traditions have been reported in Chontales (Zelaya-Hidalgo et al., 1974). Therefore, a research program such as this plays an important role when understanding the interactions of ICA communities over time.

Even though archaeometric analysis cannot reconstruct the archaeological context of the decorated metates in central Nicaragua, it can improve our understanding about how the material properties of these sculptures relate to their stylistic aspects. The approach taken also enables reconnecting these artisanal objects to their surrounding igneous landscapes by comparing them with different established natural sources. Nonetheless, the non-destructive approach also negotiates between the lack of archaeological data and indigenous landscape use across central Nicaragua when the dataset is situated within broader existing geological datasets.

As for the non-destructive approach, pXRF was successful when reading trace elemental data except for Rb and Ba, since rhyodacites were the only material where pXRF yielded sufficient concentrations for those elements in all the measurements. Despite the technical and detection limitations of a surface technique, the trace elemental data acquired has proven to be successful in differentiating sources of the metates.

5. Concluding remarks

The potential of non-destructive portable XRF analysis has been assessed for the first time on archaeological igneous materials from Central Nicaragua. Even though mitigating the lack of provenience data for museum objects is challenging, this paper provides the baseline for further archaeometric studies in the region. Furthermore, this article provides evidence that correlating stylistic data, geological data published in the literature, and archaeometric studies can be a reliable approach to improve our understanding of archaeological objects that were collected without archaeological control. It is demonstrated that it is possible to discriminate geochemical groups through pXRF trace elemental analysis and relate the objects to specific landscapes. The possibility of using this technique to discern between volcanic stone types through immobile elements and the W-F Pearce diagram has also been demonstrated for the first time in the Central American volcanic arc geoarchaeological context.

Furthermore, the goal of this article was to explore how many raw material types and sources of those raw materials were being exploited by indigenous communities in the production of decorated metate in Central Nicaragua. A second goal was to test whether similar decoration features share the same –or approximate- geochemical groups. The results indicate that specific stone source materials, such as alkaline and subalkaline basalts, were selected for in most of the cases of these masterfully crafted decorated metates. By contrast, non-decorated metates were made of a more diverse variety of stones. If we reflect on the distribution of the decorated metates styles proposed previously (i.e. Northern Costa Rica, Northern Nicaragua and Honduras), we demonstrate that Chontales played an important role as a central place for cultural expressions using stone, congregating communities of artisans and exchanging ideas and different ways of perceiving and representing the natural surroundings. This research suggests that there was a tendency by a community of artisans to select a specific source of raw material recurrently. Considering the wide regional chronology of the decorated metates, the engagement with a particular source during long time spans also mirrors the persistence of quarrying as a cultural practice, in particular also when considering how such quarrying practices could have varied across central Nicaragua and how those practices were adapted to different volcanic landscapes.

CRediT authorship contribution statement

Arturo García-De León: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dennis Braekmans:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Alexander Geurds:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition.

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.

Acknowledgments

The authors would like to thank the Museo Arqueológico Gregorio Aguilar Barea, for providing access to the samples and to Marta Villanueva, Alondra Villanueva and Carlos Villanueva for their invaluable support during the data collection process. We are also grateful to Eric Mulder who provided assistance in the Laboratory for Material Culture Studies of the Faculty of Archaeology, Leiden University, to Dr. Dita Auzina regarding the coordination of the Aguas Buenas field campaign and to the Archaeological Directorate at the Nicaraguan Institute of Culture for their support throughout. We are grateful to Dr. Adam K. Benfer, who provided remarks regarding the typological description of the assemblage, and to Tamara Michaelis and Marie Kolbenstetter, whose valuable comments improved the early versions of the manuscript. We thank the two anonymous reviewers for their valuable feedback and comments. This article is part of the PhD dissertation of Arturo García-De León, who holds a doctoral scholarship from the National Council of Science, Technology, and Innovation of Panama (SENACYT) (contract No. 270-2023-130). This publication is part of the project 'Resilience as Human-Environmental Engagement: Sustainability in pre-Columbian Central America' (PI Geurds) with file number VI.C.221.093 of the research program VICI SGW which is financed by the Dutch Research Council (NWO).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105412.

Data availability

Data will be made available on request.

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