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Using X-ray fluorescence to examine ancient Maya granite ground stone in Belize

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Abstract

While ubiquitous among ancient Maya sites in Mesoamerica, archaeological analysts frequently overlook the interpretive potential of ground stone tools. The ancient Maya often made these heavy, bulky tools of coarse-grained, heterogeneous materials that are difficult to chemically source, unlike obsidian. This paper describes an application of handheld, energy-dispersive X-ray fluorescence (XRF) to provenance ground stone artifacts (tools and architectural blocks) composed of granite: a nonhomogenous, phaneritic stone. We present a multicomponent methodology that independently tested whole-rock, thin-sectioned, and powdered samples by petrographic microscope, conventional, lab-based XRF, and portable XRF units, which yielded comparable results. After establishing distinct geochemical signatures for the three geographically restricted granite plutons in Belize, we devised a field-based XRF application on a whole rock that could replicate the compositional readings of lab-based XRF on powdered materials with sufficient accuracy and reliability. We applied this multishot XRF technique to granite ground stone items from a range of ancient Maya sites throughout Belize; we discuss two specific case studies herein. Our results underscore the widespread potential of multishot XRF applications for determining the provenance of coarse-grained, heterogeneous rock materials. These results can help push the boundaries from one-dimensional, functional explanations of ground stone items to their social and ideological dimensions, alongside deeper understandings of granite resource management.

KEYWORDS
ancient Maya, Belize, granite, ground stone, provenance, XRF

1 | INTRODUCTION

Within ancient Maya artifact studies, archaeologists have paid limited attention to the production of ground stone items and related resource management. Ground stone artifacts can shed light on broader socioeconomic processes of ancient production and exchange captured within archaeological contexts (Biskowski, 2000; Costin, 1991; Peregrine, 1991; Rowan & Ebeling, 2008; Spink, 1982). Ground stone items are manufactured through abrasion, polish, or impaction used to grind, abrade, polish, or impact (J. Adams, 2014,

p. 1). Ground stone tools are common in the archaeological record of Mesoamerica, and they figure prominently in ancient Maya illustrated histories alongside associated foodstuffs (García Barrios, 2017; Stuart, 2014). To this day, the ground stone *mano* (the hand stone or "handheld, active tool used to alter a contact surface or intermediate substance" [J. Adams, 2014, p. 94]) and *metate* (the nether stone or "passive tool upon which a contacting surface or intermediate substance is altered" [J. Adams, 2014, p. 94]) are familiar sights in many Maya homes (Cook, 1982; Hayden, 1987a; Searcy, 2011).

The most common questions archaeologists pose of ground stone assemblages in the Maya world are concerned with item function, focusing on final product design and form (e.g., Delu, 2007; Turuk, 2006). Few researchers have concentrated on provenance or sourcing studies of ground stone materials or on characterizing extractive, reductive, or distributional activities (cf., Abramiuk & Meurer, 2006; Brouwer Burg et al., 2021; Shipley & Graham, 1987; Skaggs et al., 2020; Ward, 2013). Much of this oversight has to do with difficulties associated with identifying extractive activities and their dating, the limited geographic distribution of and physical access to appropriate source zones, and a continued focus on elite, ritual-monumental areas instead of nonelite residential and resources zones (Odell, 2000). Additionally, ground stone raw materials tend to be more heterogeneous in composition, compounding the difficulties of provenance research. Consequently, there is a gap in our understanding of ground stone production and exchange compared to more thoroughly studied materials such as obsidian.

Another issue with many provenance investigations is their dependence on destructive analyses. Widely used compositional studies require a small whole sample, a powdered sample, or a sample that has undergone wet chemistry or thin-section preparation (Gill, 1997). Such studies include lab-based X-ray fluorescence (XRF), petrography, neutron activation, electron microprobe, etc. These are moderate to very destructive analyses, which are not ideal when working with archaeological materials. Nondestructive applications utilizing portable energy-dispersive XRF[1] (ED-XRF) are becoming more widely adopted in archaeological contexts to assess the chemical and mineralogical composition of artifacts. Researchers must develop replicable methodologies and evaluate their potential to accurately obtain and interpret data using these techniques.

This study focuses on granite as an essential raw material in ancient ground stone production. While granite was not the only material used in the Maya lowlands of Mexico and Central America, its coarse-grained, phaneritic texture would have allowed for the efficient reduction of kernels, seeds, and other substrates to flour or paste (Adams, 1989, 2014, p. 31; Hayden, 1987a). This quality appears to have made granite a popular choice among *metateros* (manufacturers and sellers of metates) and consumers alike in this part of the world. Further, granite occurs naturally within the three main plutons of the Maya Mountains of Belize. It is quite possible that obtaining granite would have required less effort for the ancient Maya living in the eastern portion of the lowlands than, for example, securing basalt from the nearest outcrop in Guatemala more than 300 km to the south and west.

This paper outlines a robust methodology developed by lead author Tawny Tibbits (2016)[2] to differentiate rock samples from the three geographically restricted granite plutons in Belize. We present side-by-side XRF analyses using destructive and nondestructive applications for a range of outcrop samples from each granitic pluton. The resulting experimental methodology tests the validity, reliability, and replicability of portable XRF, in concert with the more established, lab-based applications of thin-section petrography and XRF analyses. We describe each source's resulting bulk geochemical signatures as a reference against which we compare archaeological ground stone items.

We then demonstrate how archaeologists can apply this technique to enhance understandings of granite resource management by describing the results of two case studies from Belize. We use our preliminary XRF results to ask which plutons the ancient Maya targeted for granite extraction and production and why? The research presented here sheds light on these complex questions, although we still have many more questions than answers. Through continued provenance research, we hope to more definitively assess the timing, tempo, and spatial extents by which the ancient Maya exploited the granitic plutons of the Maya Mountains for ground stone material production and resource management. We conclude with suggestions regarding how this increasingly helpful and portable tool can continue to furnish new details about past granite procurement and resource management.

1.1 | Archaeological background

Ground stone artifacts occur in the archaeological record of many early societies (Rowan & Ebeling, 2008). The raw materials used in the production of manos and metates can vary and depend on what is available either locally or through accessible exchange routes (J. Adams, 1999; Drennan, 1984). However, they may also have been a product of personal or cultural preferences or expanded socio-political or economic connections as centers of influence shifted through time (e.g., Hayden, 1987b). Manufacturing items that could withstand the pressures and frictions associated with repetitive grinding activities appear to have been prioritized by the ancient Maya. Ideal materials included igneous and metamorphic rocks such as basalt, granite, rhyolite, andesite, and quartzite (Searcy, 2011, p. 82). These are superior in grinding performance to the more easily deteriorated sedimentary stones that dominate much of the Maya lowlands. Nelson and Lippmeier (1993, pp. 294–295) identify

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[1] Unless otherwise specified, reference to XRF in this paper denotes field-capable energy-dispersive XRF, or ED-XRF. Further, while all field-based ED-XRF is undertaken with a portable ED-XRF (pXRF) unit, lab-based XRF may also be completed with a pXRF or stationary instrument. See Section 1.3 for more details.

[2] All methodological development and analysis presented here are derived from T. Tibbits' 2016 dissertation. From here on, Tibbits refers to the lead author.

granitic, metasedimentary (quartzites), and volcanic (basalts, rhyolites) rocks as the most durable of materials with the most preferred texture for ground stone manufacture and use. These materials produce grinding tools with the most extended use-lives, approximately 15–30 years or more, depending on the intensity and nature of use (Hayden, 1987c, p. 193). These ideal materials are limited in geographic distribution across the Maya area.

In the eastern lowlands of Belize, the ancient Maya made their ground stone tools primarily of limestone, sandstone, slate, quartzite, rhyolite, basalt (vesicular and nonvesicular), and granite. Its abundance, hardness, and favorable grinding characteristics made granite the preferred material for making both manos and metates among the ancient Maya of Belize. Archaeologists can infer the preference for this material based on its consistent appearance within the archaeological record of multiple subregions of the eastern lowlands (Graham, 1987). We chose granite for this study because of its widespread presence at Maya archaeological sites and its relatively restricted natural outcropping within the Maya Mountains in southern Belize. Further, as Tibbits' (2016) work has shown, each granite pluton has a distinctive geochemical signature that is readily distinguishable from one another and other naturally outcropping stones in the Maya Mountains (e.g., quartzite, sandstone, shale, slate, schist).

1.2 | Geological background

The exposed bedrock geology of Belize consists primarily of sedimentary rock and Quaternary alluvium with abundant limestone outcrops that include chert-bearing zones (Bateson, 1972; Cornec, 2010). Clastic sedimentary, metamorphic, and igneous rocks are confined to the tectonically uplifted Maya Mountains (Bateson & Hall., 1977; Dixon, 1956; Ratschbacher et al., 2009; Weber et al., 2012). The dominant lithologies within and surrounding the mountains are sandstones, conglomerates, slates, and granites. Several metamorphic rock types are also present in the foothill regions, including quartzite, phyllite, schist, gneiss, and metasediments.

There are three broadly defined, geographically separate granite plutons within the Maya Mountains of Belize (Figure 1): the Mountain Pine Ridge (MPR), Hummingbird Ridge (HBR), and Cockscomb Basin (CCB) (Martens et al., 2010). Cornec's (2010) map shows the extent of each pluton. Recent work using uranium–lead (U/Pb) zircon geochronology has dated MPR granite at 400 ± 9 Ma, HBR granite at 408 ± 7 Ma, and CCB granite at 423 ± 6 Ma (Tibbits, 2016; Weber et al., 2012). There are smaller regions, such as the Sapote and the Mullins River areas that have also been documented in the past, but for the purposes of this study, we use the broader terms listed here. MPR is the most studied (geologically) of the plutons, mainly due to ease of access and potential for economically important ore and mineral deposits (e.g., Dawe, 1984; Shipley, 1978). By comparison, geologists have only undertaken a minimal study of the less accessible HBR and CCB plutons, and limited background and comparative data are available.

MPR has the most geochemical variation of the three plutons, and it consists of granites, granodiorites, and tonalites. Geologists describe HBR and CCB as two-mica granites (Bateson, 1972). They are petrographically distinct; geologists characterize HBR as having more quartz than plagioclase, while CCB is the reverse (Jackson et al., 1995). MPR can often be visually differentiated from the other two plutons by the presence of bright pink potassium feldspar, but this is not always the case. When one compares MPR samples lacking the bright potassium feldspar with HBR or CCB, the three granites can be difficult to distinguish visually, making compositional analysis necessary.

1.3 | Field-based XRF

Recent advances in field-capable portable X-ray fluorescence (often referred to as pXRF) instrumentation have increased efficacy and suitability for archaeological sourcing studies (Barbera et al., 2013; Craig et al., 2007; Forster & Grave, 2013; Goodale et al., 2012; Menne et al., 2020). Although they are implemented in different environments, field-based (using a portable XRF instrument) and laboratory-based (using a larger, stationary instrument) XRF techniques operate under the same principles: an analyst uses an X-ray beam to excite the atoms in minerals present at or near the surface of an artifact. As field-capable XRF technologies improve, some researchers have found these portable instruments are performing as well or better than their immobile lab-based equipment. Our portable instrument utilizes polarized energy dispersive (ED) XRF (see Gauthier & Burke, 2011; Guthrie & Ferguson, 2012 for a full discussion of the pros and cons of each; see also e.g., Hermes & Ritchie, 1997; Lundblad et al., 2008; Williams-Thorpe, Philip, et al., 1999). The primary advantages of field-based XRF to archaeologists are its rapid analysis time, its nondestructive nature, and its ability to be used in the field, museum, or lab setting (e.g., Menne et al., 2020, p. 1). One instrument that can be used in a variety of settings presents a considerable saving in cost and time for training and maintenance. Not surprisingly, archaeologists are increasingly turning to such portable technology for use in the field to illuminate broad trends and subtle details of the management of stone resources in the past.

Archaeologists have effectively applied field-based XRF to fine-grained (aphanitic) rocks, such as basalt and obsidian (e.g., Frahm, 2012, 2014; Grave et al., 2012; Nazaroff et al., 2010; Palumbo et al., 2015; Williams-Thorpe, Aldiss, et al., 1999; Williams-Thorpe, Philip, et al., 1999). They have also used it to successfully source relatively finer-grained phaneritic and porphyritic rocks, such as dacite (Greenough et al., 2004). However, scholars have conducted minimal work on coarser-grained, more heterogeneous rock types, such as granite. This absence of study is primarily due to the difficulty of obtaining a representative geochemical signature from coarse-grained, heterogeneous whole rock comprised of many mineral grains of varying size, some of which may be similar to the instrument's beam size (10 mm). This size discrepancy can result in

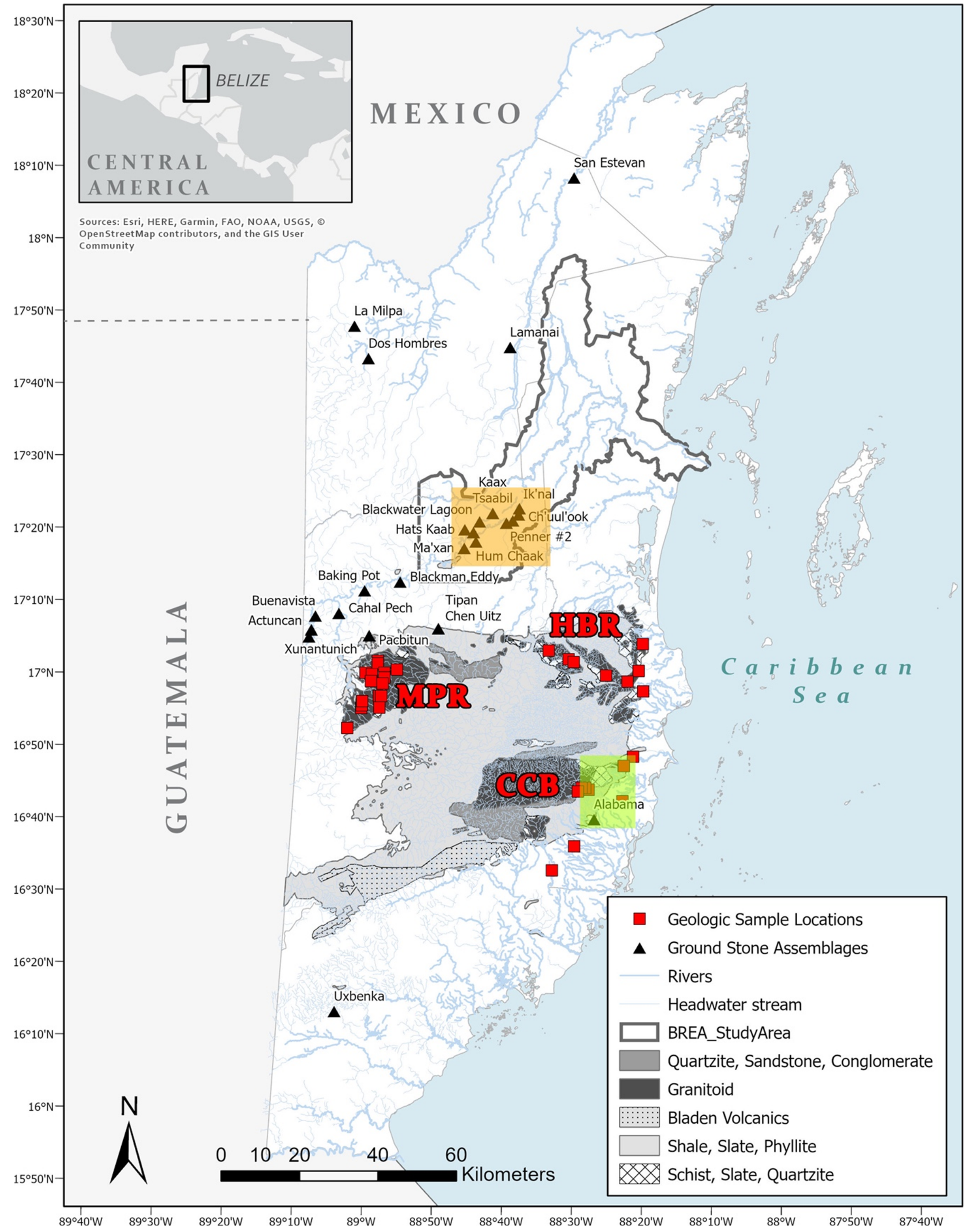

FIGURE 1 Geology of the Maya Mountains with sampling and assemblage locations. Note the proximity of Upper Belize Valley sites to MPR sources. SCRAP study area highlighted in green; BREA study area highlighted in orange. Map by M. Brouwer Burg. BREA, Belize River East Archaeology; CCB, Cockscomb Basin; HBR, Hummingbird Ridge; MPR, Mountain Pine Ridge. [Color figure can be viewed at wileyonlinelibrary.com]

readings too narrow to encompass the full spectrum of mineralogical components that make up the rock sample. A strategic sampling method is necessary to generate an averaged geochemical signature that provides a consistent and replicable marker for coarse-grained rock (Brouwer Burg et al., 2021).

While there were some pitfalls during the early phases of portable, handheld XRF applications in archaeology, these have been resolved by high-quality research in the field (e.g., Frahm, 2013b, 2014; Frahm & Doonan, 2013; Mitchell et al., 2012; Piercey & Devine, 2014; Ross et al., 2014). Through these works, it has been shown that handheld XRF can provide quantitative data that is accurate, precise, and 'fit for purpose' for archaeological and geologic questions. For example, Piercey and Devine (2014), examined the ability of handheld XRF to accurately and precisely generate data on powdered silicate rocks. The powdered samples were from known geologic reference materials and could be used to determine which elements behaved normally for the specific instrument utilized in the study. Ultimately, when dealing with a fine powder, they found that a single point of analysis could accurately and precisely capture the geochemical variation within the sample. Furthermore, while some questions have arisen surrounding instrument reliability and chemical measurement validity (Conrey et al., 2014; Nazaroff et al., 2010; Speakman & Shackley, 2013), recent improvements in the technology have alleviated most of these issues for many of the models used for archaeological purposes (Frahm, 2013a; Goodale et al., 2012).

In addition to ascertaining the analytical advantages and disadvantages of a portable XRF unit, building a robust quantitative database containing the established range of variation of source-rock geochemical signatures is vital to sourcing research. Without known source-rock geochemical signature ranges, the results from portable XRF analyses remain qualitative, representing only signature differences from within a sample set of artifacts. To construct a detailed and location-specific source-rock database for this study, we needed to thoroughly sample within the three granite outcrops in the Maya Mountains and record sample geolocations. Below, we outline how we compiled such a database and the multipronged method to source coarse-grained, heterogeneous geological materials successfully.

2 | MATERIALS AND METHODS

2.1 | Experimental methodology for whole rock XRF analysis

This research was conducted in phases to establish congruency between the geochemical results of powdered samples using well-established, lab-based instruments and solid granite materials tested in the field using portable XRF units. We aimed to identify an XRF application that returned valid, reliable, and replicable results through a multipronged experimental methodology. The initial phase of this work involved establishing a baseline understanding of the geochemical signature range for the MPR, HBR, and CCB granite outcrops in Belize. Through lab-based XRF of powdered samples and thin-section petrography of the raw source materials, Tibbits demonstrated that the mineralogical differences between the outcrops were sufficiently distinct. She then confirmed that a handheld XRF could replicate the compositional readings derived from lab-based XRF with sufficient accuracy and reliability without requiring samples to be crushed and powdered before analysis. We detail below the multishot XRF technique that Tibbits devised to this end. Last, we discuss how she applied this technique to granite ground stone artifact assemblages throughout the eastern Maya lowlands. We present two case studies focused on the ancient town of Alabama in east-central Belize and various settlement sites in central Belize. These findings illustrate the potential widespread applicability of XRF for sourcing granite from relatively restricted outcrops and with well-defined compositional signatures.

2.1.1 | Phase 1: Establishing a baseline

From 2013 to 2015, Tibbits and various field crews obtained samples from each granite pluton in the Maya Mountains. They sampled each pluton as extensively as physical access and private property permission allowed. Forty-three discrete localities were chosen (HBR, *n* = 11; CCB, *n* = 13; MPR, *n* = 19). These field samples were exported whole to the Department of Earth and Environmental Sciences Thin Section Lab at the University of Iowa. These field samples were nonartifactual; therefore, they could be analyzed with both non-destructive and destructive compositional techniques without issue.

Of the 43 field samples, Tibbits selected 29 representative specimens for petrographic analysis (CCB, *n* = 6; HBR, *n* = 11; MPR, *n* = 12). Funding limitations precluded testing all 43 specimens and from pursuing additional chemical analyses such as NAA, which may be able to provide additional insight in the future. Lab-based compositional analysis of the 29 field samples began with thin sectioning of the specimen (Tibbits conducted all lab work). Petrographic thin sections were prepared at the Department of Earth and Environmental Sciences Thin Section Lab at the University of Iowa. Thin sections measured 2 in x 1 in and had no slide cover; quick polish was applied to all sections. Petrographic analysis of each thin section used a Nikon Alphapot-2 POL petrographic microscope with both polar and cross-polar light with ¼ wave and tint plates (see Tibbits, 2016, p. 46).

After thin sectioning, the remaining portions of the field samples were powdered. Care was taken to ensure that all crushed materials were retained and heavy minerals were not lost. All equipment was cleaned before the introduction of a new sample. Whole-rock samples were fed into a steel jaw crusher. Small chips from the jaw crusher were reduced to fine flour in a ceramic ball mill. Pieces still coarser than 5 mm were separated from the finer pieces to avoid damaging the ball mill. Next, the powders were placed in small plastic containers covered with a Chemplex© prolene film; these powdered samples were sent to the Illinois State Geological Survey for lab-based XRF analysis using a Rigaku NeX CF EDXRF spectrometer. Samples were sent as loose powder per the instructions of the Illinois State Geological Survey lab. This instrument utilizes indirect excitation of samples via a 50w palladium anode and has five secondary targets: LEO, RX9, copper, molybdenum, and aluminum. The Rigaku spectrometer has a silicon drift detector ranging from 127 to 145 eV at manganese K1. Concentrations were calculated using proprietary fundamental parameter software from Rigaku.

The lab-based XRF and thin-section petrography yielded convergent data indicating that the three granitic plutons in the

TABLE 1 Observed average modal abundances of MPR, HBR, and CCB granites

Pluton	Major minerals	Accessory minerals	Additional minerals
MPR	Quartz: 25% Plagioclase: 30% K-Spar: 35%	Biotite, chlorite, muscovite, apatite, Fe–Ti oxides (approx. total 10%)	–
HBR	Quartz: 30% Plagioclase: 25% K-Spar: 30%	Muscovite > biotite, chlorite, apatite, Fe–Ti oxides (approx. total 15%)	–
CCB	Quartz: 25% Plagioclase: 30% K-Spar: 30%	Biotite > muscovite, chlorite, margarite, Fe–Ti oxides (approx. total 15%)	Bateson and Hall (1977) reported monazite and rutile

Abbreviations: CCB, Cockscomb Basin; HBR, Hummingbird Ridge; MPR, Mountain Pine Ridge.

Maya Mountains have distinguishable and distinctive geochemical signatures (Table 1). While the plutons vary only slightly in the proportions of major minerals, the proportions of minor minerals readily differentiate each. MPR has sheet silicates present in the spaces between major minerals. The sheet silicates are small and comprise a smaller percentage of the overall rock. HBR and CCB both have higher proportions of sheet silicates; however, CCB has more biotite, while HBR has more muscovite. Bateson and Hall (1977), also noted minor amounts of accessory magnetite in MPR and HBR, while CCB has monazite and rutile. Rather than using mineralogy, this research phase verified that we could differentiate plutons by comparing Rb/Sr and Sr/Y ratios, representing the fractionation curve for the unique cooling sequences of the three igneous plutons.

2.1.2 | Phase 2: Determining validity and replicability

This phase aimed to determine whether the readings taken on whole rock samples with a portable XRF could replicate lab-based XRF readings on more homogenized powdered samples and the results of thin-section petrography with sufficient accuracy and reliability. To maintain as much experimental control as possible during this phase of the work, Tibbits carried out the XRF analysis in the lab (vs. in the field) and on the same powdered and whole-rock samples as were analyzed in Phase 1 by thin section and XRF analyses. Furthermore, the same rock samples were used across the analyses, and the results of the different analyses were compared for each field sample. For this analysis phase, remaining rock samples were washed and cut with a rock saw to obtain a flat, unweathered surface. These flat surfaces were analyzed to minimize issues with the beam hitting the surface at an oblique angle. Of the original 29 specimens, only 21 samples (MPR: 10, HBR: 7, CCB: 4) were still large enough after thin sectioning to collect 10 XRF shots in the lab.

FIGURE 2 Scaled comparison of the 10 mm pXRF beam diameter compared to a 3.5 cm long petrographic thin section of CCB granite. CCB, Cockscomb Basin; pXRF, portable X-ray fluorescence.

Tibbits used an Olympus Delta© handheld XRF with a beam diameter of 10 mm for all analyses conducted during this project. This instrument utilizes an energy-dispersive technique and was set to Geochem mode, which engages two energy beams (10 keV, 30 keV). Each beam was set to run for 30 s. The detection range on Geochem mode is from magnesium to uranium. While the manufacturer reports that the unit can analyze from magnesium to uranium, the limits of detection are not always particularly useful for all projects. The 10 mm beam diameter on this unit can bias the results from a coarse-grained rock by analyzing a single mineral at a time or a subset of minerals that may or may not be representative of the modal abundances of the mineral phases present (Figure 2). Maya Mountain granite typically contains a mix of quartz, plagioclase, and potassium feldspar crystals that average 8–10 mm in length but can reach up to 2 cm. The micas present are on average less than 1 cm on the longest axis. The potential for large grains to occur within Maya Mountains granite could lead to simplistic geochemical readings, as one XRF shot may only penetrate a single mineralogical crystal. To overcome this potential pitfall, we determined the minimum number of data points (or XRF shots/readings) necessary to obtain a representative chemical signature for a field specimen and an indistinguishable chemical signature from one generated by lab-based XRF on powdered samples.

To accomplish this task, Tibbits ran a Monte Carlo simulation involving the analysis of 50 data points taken in a grid pattern every centimeter for a granitic sample from each pluton. The Monte Carlo Simulation produced averages of 1–50 randomly selected points (Tibbits, 2016, p. 194). The results indicate that five XRF data points are the minimum number needed in this study to consistently generate geochemical results within one standard deviation of the expected value defined by lab-based XRF. For each element tested, the average of five randomly selected points was within one standard deviation for the results of a 50-point average.

We note that Tibbits explicitly generated this technique for granite field samples from the Maya Mountains. If similar studies attempt such a process in other parts of the world, researchers must perform a Monte Carlo Simulation within the contextual specifications of the new field context. Rock samples with different grain sizes could require a different minimum number of XRF data points to generate an averaged geochemical signature.

To verify the Monte Carlo Simulation results described above, Tibbits captured five randomly selected XRF data points for the set of whole-rock samples. Afterward, these whole-rock samples were ground into a powder (see the procedure described above). The powders were then analyzed by XRF in the lab using the Geochem mode with the same settings used previously on the whole-rock samples. Tibbits then sent the powders to the Illinois State Geological Survey for XRF analysis.

Before proceeding, we note that a sampling bias does exist between the use of powder and whole rock. The powdered samples effectively represent a 3-D view resulting from mixing the sample, while the whole rock is more representative of only the surface of a sample. This surficial view may or may not represent the modal abundances of the mineral that would be present in a powdered sample. Only one or two minerals will likely be analyzed with a single data point when analyzing a coarse-grained whole rock. Because of the disparity between grain size, beam diameter, and depth, it is necessary to take multiple data points to generate an average geochemical signature for a sample.

When compared, we found that the geochemical results from the powdered samples analyzed by lab-based XRF and handheld XRF were statistically significant (Figure 3; Table 2). Pearson's correlation and Spearman's ρ values in 51 of 52 analyses indicate the correlation between the field-capable XRF and exclusively lab-based XRF values is statistically significant at the 0.01 value in a two-tailed test. These results support the validity of applying the five-shot methodology described above when using XRF technology on coarse-grained, whole rock samples whether in a lab or field context. Further, in all cases, statistical analyses in SPSS indicate there is a significant correlation at the 0.01 level for a two-tailed analysis in both Pearson's correlation value and Spearman's ρ between field-capable XRF results on whole-rock samples (five points averaged) and field capable XRF results on powdered samples (with only one point of analysis; Tibbits, 2016; fig. 3.4, Appendix B).

2.1.3 | Note on calibration

Four geologic reference materials were selected to test and calibrate the Olympus Delta© XRF unit before each analysis session. They included GS-N granite from SARM-CNRS France, JA-1 andesite from the Geological Survey of Japan, and BCR-2 and AGV-2 basalt and andesite from the USGS. These materials contain the broadest range of elements present in Maya Mountain granites. By constructing bivariate plots of the results from the loose-powder geologic reference materials, it was possible to determine which elements were consistent or varied significantly over time.

Using the r^2 values generated from a bivariate comparison, Tibbits determined that Al, Si, Mn, Ti, and Th were not accurately measured and therefore were not used in provenance work with this unit. K_2O, P_2O, Fe_2O_3, Zn, Pb, Ca, Rb, Sr, Y, and Zr were all accurately measured via XRF but could not separate the plutons (Tibbits, 2016, pp. 52–53). Over 3 years, Tibbits built a data set of values for all elements discussed above using the geologic reference materials. These loose-powder reference samples were analyzed, and the reference database was established before the field-based XRF analyses on outcrops or archaeological samples.

Throughout the project, Tibbits used these geologic reference materials to cross-check instrument accuracy and precision, assess instrumental drift and calibration issues, and identify errors of over-detection of certain elements. Two powdered geologic reference materials were analyzed 25 times on a repeated run setting to assess the accuracy and precision of the XRF unit (GS-N, AGV-2). In addition to this single run, data obtained from the geologic reference materials throughout the 3-year use period of the unit were compiled to assess any instrument drift or change in internal calibration over time (see Tibbits, 2016, p. 53, Appendix B).

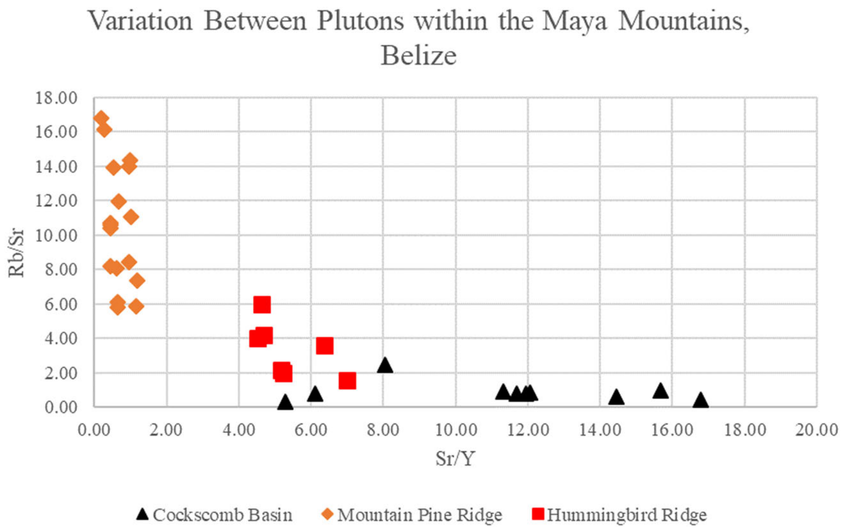

FIGURE 3 Variation within and between plutons characterized by Rb/Sr and Sr/Y ratios based on whole-rock pXRF data. Note the zone of overlap between HBR and CCB, which may result from crystal fractionation, implying a close genetic relationship between the plutons. There are petrographic differences between the samples in the overlap zone between HBR and CCB. CCB, Cockscomb Basin; HBR, Hummingbird Ridge; pXRF, portable X-ray fluorescence. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Comparison of pXRF and lab-based XRF techniques showing Rb, Sr, and Y results

Sample	Analysis	Rb, ppm	Sr, ppm	Y, ppm	Sr/Y	Rb/Sr
CS 5-28-5	Whole rock, pXRF	151	201	17	0.7	11.9
	Powdered sample, pXRF	154	227	22	0.7	10.3
	Powdered sample, XRF	152	230	24	0.7	9.5
CS Aug Cr	Whole rock, pXRF	139	196	41	0.7	4.8
	Powdered sample, pXRF	168	184	29	0.9	6.3
	Powdered sample, XRF	179	197	46	0.9	4.2
HB-HRQ	Whole rock, pXRF	276	46	10	6.0	4.6
	Powdered sample, pXRF	273	48	10	5.7	4.8
	Powdered sample, XRF	299	54	14	5.5	4.0
HB-MC	Whole rock, pXRF	296	74	16	4.0	4.5
	Powdered sample, pXRF	339	76	22	4.5	3.4
	Powdered sample, XRF	324	79	26	4.1	3.0
HB-Teak	Whole rock, pXRF	212	106	17	2.0	6.4
	Powdered sample, pXRF*	173	119	20	1.4	5.9
	Powdered sample, XRF*	234	104	24	2.2	4.3
HB-Teak-D	Whole rock, pXRF	57	210	20	0.3	10.4
	Powdered sample, pXRF	87	225	24	0.4	9.4
	Powdered sample, XRF	88	233	28	0.4	8.4
MPR 6-4-2	Whole rock, pXRF	297	28	61	10.6	0.5
	Powdered sample, pXRF	355	47	79	7.5	0.6
	Powdered sample, XRF	341	34	64	9.9	0.5
MPR BP	Whole rock, pXRF	252	18	19	14	0.9
	Powdered sample, pXRF	362	29	42	12.5	0.7
	Powdered sample, XRF	371	31	51	12	0.6
MPR-BRF	Whole rock, pXRF	312	37	38	8.4	1.0
	Powdered sample, pXRF	327	38	38	8.6	1.0
	Powdered sample, XRF	340	45	47	7.8	0.9
RC-1	Whole rock, pXRF	284	45	53	6.3	0.9
	Powdered sample, pXRF	313	61	45	5.1	1.4
	Powdered sample, XRF	331	67	52	5.0	1.3
RC-3	Whole rock, pXRF	135	148	35	0.9	4.3
	Powdered sample, pXRF	122	134	35	0.9	3.8
	Powdered sample, XRF	140	154	40	0.9	3.8
SR-1	Whole rock, pXRF	117	140	22	0.8	6.4
	Powdered sample, pXRF	140	148	29	1.0	5.1
	Powdered sample, XRF	150	158	37	1.0	4.2
SR-2	Whole rock, pXRF	115	183	28	0.6	6.5
	Powdered sample, pXRF	130	175	38	0.7	4.6
	Powdered sample, XRF	128	185	49	0.7	3.7

TABLE 2 (Continued)

Sample	Analysis	Rb, ppm	Sr, ppm	Y, ppm	Sr/Y	Rb/Sr
WP-13	Whole rock, pXRF	380	24	37	15.6	0.7
	Powdered sample, pXRF	416	28	66	14.9	0.4
	Powdered sample, XRF	419	34	72	12.2	0.4

Note: The single outlier is marked with an asterisk, and results are typical of most analyzed elements in this project. Spearman's ρ and the Pearson correlation value are statistically significant at the 0.01 level for a two-tailed analysis for all but the comparison of powdered pXRF and XRF values for HB Teak.

Abbreviations: CCB, Cockscomb Basin; HBR, Hummingbird Ridge; MPR, Mountain Pine Ridge; pXRF, portable X-ray fluorescence; XRF, X-ray fluorescence.

TABLE 3 Comparison of values obtained on known granite geologic reference materials AC-E and GS-N (from Tibbits, 2016, p. 52)

	Rb/Sr	Sr/Y	Al_2O_3	K_2O	MnO	P_2O_5	SiO_2	TiO_2	Zn	Y	Sr	Rb	Zr
AC-E[a]	54.29	0.015	14.70	4.49	0.06	0.01	70.35	0.11	224	184	2.8	152	780
AC-E, *n* = 31	130.5	0.006	14.05	4.82	0.07	0.16	55.59	0.68	252	190	1.5	151	822
Standard deviation	–	–	0.38	0.17	0.003	0.017	24.3	1.28	9.0	1.28	1.5	2.12	10.3
GS-N[a]	0.32	35.6	14.90	4.63	0.06	0.28	65.80	0.68	48	16	570	185	235
GS-N, *n* = 44	0.31	32.9	15.1	4.94	0.05	0.21	54.05	1.2	55	18	607	188	219
Standard deviation over time	–	–	1.53	0.25	0.005	0.04	21.4	1.37	8.7	1.8	9.4	4.6	6.6
GS-N standard deviation repeated run	–	–	0.25	0.04	0.00	0.01	0.7	0.03	4.8	1.5	6.4	2.8	5.0
AGV-2 standard deviation repeated run	–	–	0.22	0.02	0.00	0.01	0.38	0.03	4.6	1.5	5.3	2.0	3.2

[a] Values obtained from results published on GeoReM. The other value is the average of multiple runs over time. Major elements are shown in percent oxide. Minor and trace elements are shown in ppm. Experimental data shown are from a year of analyses. The standard deviations for running these analyses on GS-N on repeat 25 times consecutively are included to demonstrate the consistency within a run. The results shown here are representative of the results for all geologic reference materials measured during this project.

2.1.4 | Summary of experimental methodology

In addition to determining that we can accurately differentiate between plutons, this work has tested the accuracy and precision of the Olympus Delta© portable XRF. Repeated, long-term analysis via XRF shows minimal variation in the data generated over time, indicating that the Olympus Delta© instrument does not share the accuracy issues found in the Olympus X5000 (Piercey & Devine, 2014). Additionally, when we compare these results to published data available on the Geological and Environmental Reference Materials online database (Jochum et al., 2005), there is little difference between the results obtained in the lab by handheld XRF or those obtained by other techniques (Table 3). GS-N and AGV-2 were analyzed on the repeat setting to assess the variation within a single day. This analysis made it possible to determine which elements were consistently measured accurately and precisely. Elements such as Al, Si, Mn, and Th were not accurately measured over time and would require a secondary calibration to be used in this study. Therefore, they were not considered fit for purpose within the confines of this study. Instead, Rb, Sr, and Y were used as they were accurately recorded by handheld XRF. The results for these three elements were statistically indistinguishable from those generated by the Illinois State Geological Survey XRF.[3]

Using the geologic reference materials consistently made it possible to compare obtained XRF values with the expected concentrations. This control allowed the assessment of the quality of data generated by the unit. During the field phase of this project, the XRF unit was internally calibrated within the range of expected variation for the geologic reference materials for most elements. The bivariate plots indicate that K_2O, Zn, Rb, Sr, Y, Zr, and Ca were accurately and precisely measured throughout this project and, therefore, ideal for determining provenance.

The results of Spearman's ρ and Pearson's correlation tests combined with the calibration curves and the results of the Monte Carlo Simulation indicate that five data points can accurately differentiate between plutons. This experimental methodology did not aim to generate high-resolution data to distinguish between outcrops within a pluton. For these reasons, the level of accuracy that can be achieved

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[3] Because of these statistical results and this being a pilot study to prove the efficacy of XRF use on coarse grained whole rock samples, no secondary calibrations were used. The authors acknowledge that secondary calibrations are likely to be needed for future quantitative work

by the XRF instrument using five data points is acceptable for our purposes.

Rubidium, strontium, and yttrium in granite are relatively immobile elements. Weathering, alteration, or cultural activities do not strongly impact them, and they are present in high enough concentrations that they can be measured with the XRF unit (Weyer et al., 2008). These elements were consistently measured in each sample and artifact, yielding consistent results during each analysis of standards. The analyses on standard geological powders also show that this XRF unit accurately measures Rb, Sr, and Y.

Through multiple bivariate analyses of lab-based XRF data on geological reference materials and outcrop samples, Tibbits found that Sr/Y and Rb/Sr ratios best differentiate between plutons in the Maya Mountains by measuring the amount of magmatic differentiation that the magma had undergone before cooling (Figure 3). We can readily separate MPR from the HBR and CCB granites using the current data set, though it remains difficult to differentiate between HBR and CCB granites. Both plutons tend to have a low Rb/Sr ratio; however, HBR tends to have slightly lower Sr/Y ratios, resulting in a small region of overlap between the two. This overlap requires further work to resolve; additional samples may clarify the relationship or make it more complex.

2.2 | Phase 3: Applying XRF to archaeological granite assemblages

We used the five-shot XRF technique described above in field laboratories to provenance multiple granite ground stone assemblages from Belize, dating from the Preclassic to Postclassic periods (ca. 500 BCE–1500+ CE). A total of 442 granite artifacts were analyzed from nine archaeological projects and 20 archaeological sites, spanning four districts: in the north/northwest (Orange Walk), Programme for Belize sites (La Milpa North and Dos Hombres), the Lamanai Archaeology Project, and the San Estevan site; from the west (Cayo), the Belize Valley Archaeological Reconnaissance sites (Cahal Pech, Baking Pot, and Blackman Eddy), the Buenavista del Cayo site, the Pacbitun Regional Archaeological Project, and the Actuncan Archaeological Project; from the middle reaches (Cayo), the Belize River East Archaeology (BREA) project (Hats Kaab, Beaver Dam, Dueck East, Hum Chaak, Kaax Tsaabil, Ik'nal, and Ma'xan sites) and the Central Belize Archaeological Survey (Tipan Chen Uitz); from the east (Stann Creek), the Stann Creek Regional Archaeological Project (Alabama); and from the south (Toledo), the Uxbenka Archaeological Project (Uxbenka).

The assemblages tested in this work were selected such that at least one representative collection was tested from each district of Belize. Despite this effort, we realize that the lack of a broader geographic distribution of assemblages is a potential limitation of this study and we plan in future work to apply XRF to a wider sample of artifacts. For each archaeological site, all available granite artifacts were analyzed with the exception of Pacbitun, which has such a large collection that a sampling strategy was needed. For each analyzed artifact, no fewer than five randomly selected data points were taken with the XRF unit. When possible, both dorsal and ventral surfaces were analyzed; however, the cleanliness of the surface took precedence. If the grinding surface was occluded, the unused surface was analyzed. Only areas of the artifacts that were either free from dirt or could be wiped off were analyzed to avoid background noise from analyzing sediment. There were no instances when an artifact could not be analyzed due to sediment cover. Additionally, all granite artifacts encountered in this work experienced limited exposure to harsh weathering during their post-use-life and were, therefore, free from oxidation and weathering that would have impacted analysis.

As noted above, not all of the artifacts from the site of Pacbitun were analyzed since there was such a large volume of the material available. Instead, Tibbits analyzed all formal tools and preforms in the site collections. The ground stone production debitage recovered from excavations at the Tzib Group, a ground stone production site near Pacbitun, was sampled randomly due to the overwhelming amount of the material present. From the collection of mano preforms and the innumerable amount of debitage, 79 pieces of granite were analyzed. All additional artifacts ($n = 10$) from the Pacbitun collections that were not from the Tzib Group were also analyzed (Tibbits, 2020).

It is essential to underscore that we operated on the a priori assumption that the granite artifacts tested here derived were from the Maya Mountains and were not imported from granite outcrops in Honduras or Guatemala. While granite from another pluton could plausibly fall within the range of variation (Rb/Sr and Sr/Y) established for the Maya Mountains, the MPR, HBR, and CCB granites typically have higher amounts of Rb, Zn, and Y (for a discussion of granite in Guatemala, see Clemons & Long, 1971; Solari et al., 2011). To distinguish granites from different regions of Mesoamerica, we would have to test beyond Rb/Sr and Sr/Y ratios and compare amounts of K_2O, Rb, Zn, and Y. This is future research we hope to carry out.

We focus here on two contextualized case studies to demonstrate the utility of the experimental methodology. The first includes surface-collected and excavated assemblages from the ancient Maya community of Alabama, investigated by the Stann Creek Regional Archaeology Project (SCRAP) under the direction of Meaghan Peuramaki-Brown. This case study focuses on granite resource management undertaken by ancient Maya who resided in the vicinity of CCB outcrops. The second consists of assemblages from various Maya settlements within the BREA area, directed by Eleanor Harrison-Buck and co-directed by Marieka Brouwer Burg. This case study highlights how the ancient Maya undertook granite resource management in the middle reaches of the Belize River Valley, which is roughly equidistant (linear distance) to both MPR and HBR.

3 | RESULTS

3.1 | Alabama assemblage

Residents of the ancient Maya site of Alabama lived in an alluvial pocket surrounded by broad-leaf forest amid the eastern foothills of the Maya Mountains, southeast of the main CCB pluton. Today, remains of the townsite lie within citrus groves. As mentioned above, CCB is the least studied of the three granitic plutons partially due to physical and safety issues but also administrative access issues (Peuramaki-Brown & Morton, 2021). The northern-interior portion of the CCB pluton is inaccessible by vehicle, requiring over 8 h of hiking. CCB has a wide metamorphic zone that makes up its aureole's southern and eastern sides. The archaeological site of Alabama is situated in a quartzite-rich portion, with direct access to the southern outcrop zones of the granite pluton (Peuramaki-Brown, 2017).

During the initial SCRAP settlement survey of Alabama (Figure 4), we encountered three exposed, primary granite source zones (outcrops) of the CCB within a 30- to 60-min walk from the monumental site core (L004, L005, L009/10) and multiple closer secondary source zones (L001/2, L003, L006/7, L008) (Peuramaki-Brown et al., 2017). This proximity characterized CCB granite materials as a local resource to the Maya living at the Alabama site. SCRAP team members collected field samples from six source locales near Alabama to contribute to the experimental methodology described above.

Both granite tools and architectural materials have been found within the archaeological record of Alabama, including finished manos and metates, preforms, debitage, so-called “doughnut stones” or chuunteel (J. Adams, 2014, pp. 207–209; Searcy,

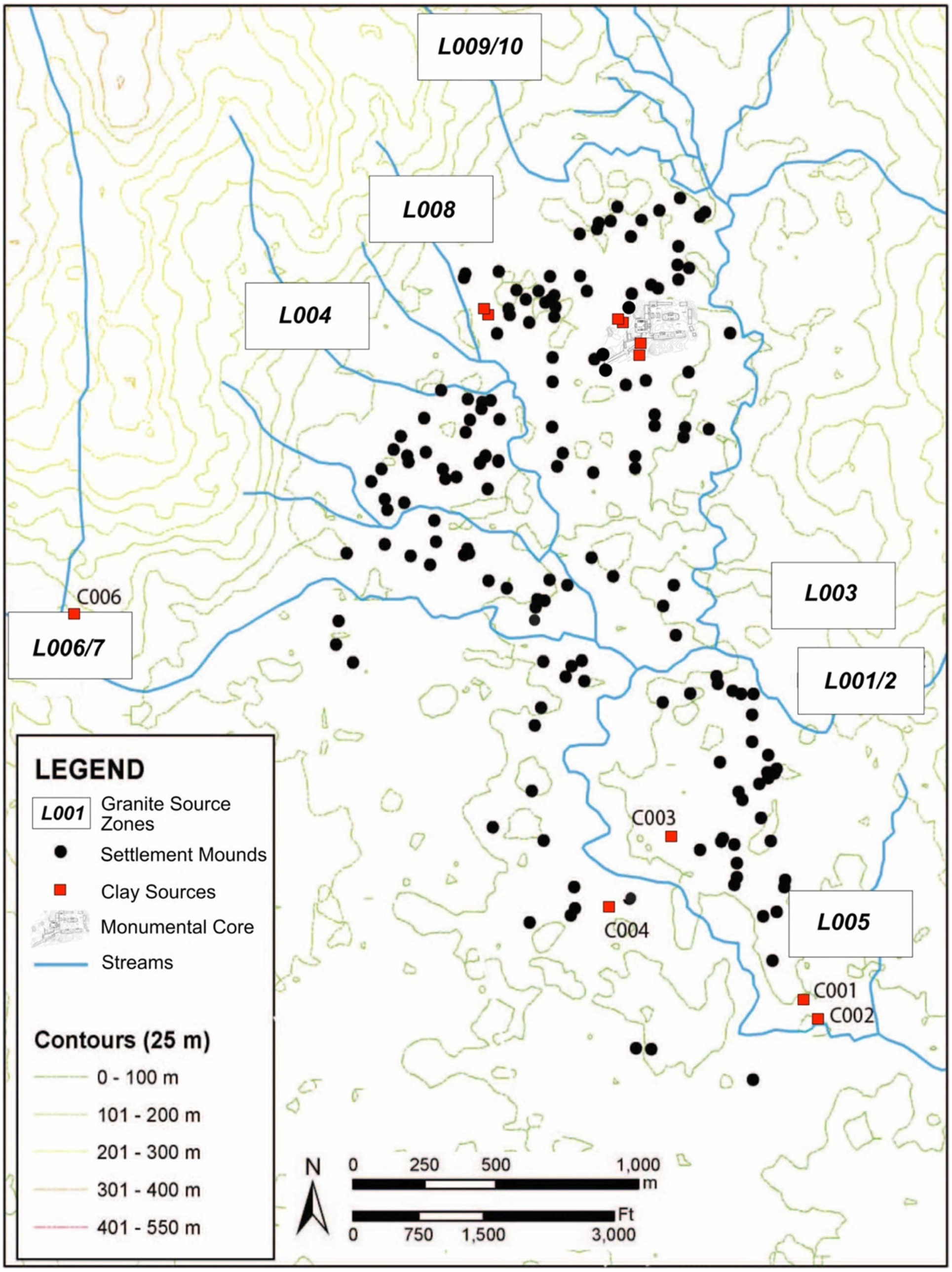

FIGURE 4 Overview of the Alabama site with nearby granite plutons indicated [Color figure can be viewed at wileyonlinelibrary.com]

2011, p. 129), hewn construction blocks and slabs, as well as stelae. The use of granite ashlars (hewn facing blocks) and slabs, some weighing over 900 kg, is rare in Maya architecture (MacKinnon et al., 1993). Elsewhere in the Maya world, such architectural elements are more commonly made from limestone. While granite abounds, limestone does not occur in abundance in east-central Belize, the closest source lying at least 60 km (in linear distance) to the south of Alabama. Archaeologists report granite architectural elements at many other sites in east-central Belize (Graham, 1994; Peuramaki-Brown et al., 2020). Dunham et al. (1995) and Peuramaki-Brown and Morton (2019b) also report a granite monument workshop at the Pearce site in the Cockscomb Basin, roughly 10 km north of Alabama. Granite is not only used in monumental undertakings in Alabama. It also appears as the standard construction material in the humblest of house platforms, making it the primary construction material in Alabama (Peuramaki-Brown & Morton, 2019b). It is also a natural inclusion in local clays and mortars as well as an intentionally added temper to ceramic pastes (Jordan et al., 2021).

We applied field-based XRF to a total of 60 granite artifacts. Of this assemblage, 39 (78% of the total granite assemblage) were surface-collected and excavated granite ground stone tools found within the Alabama settlement. This sample was not random and included either complete tools or specimens that could be identified as a tool. Debitage and unidentified fragments were not included. Additionally, we tested a large sample of granite ashlars (*n* = 20) and a single slab, from in-situ excavated contexts. The results indicate that most of the granite used in Alabama for both portable artifacts and for construction materials was of local CCB origin (Figure 5). Compared to the MPR source represented at Pacbitun and the nearby production site at the Tzib Group, there have been relatively few ground stone artifacts found in and around the Alabama site center. This suggests that procurement and production associated with the CCB source at the site of Alabama may have been less intensive and/or was likely relatively short-lived (Peuramaki-Brown & Morton, 2019a).

Unsurprisingly, all architectural elements returned geochemical signatures matching locally available CCB granite. However, we found geochemical variation within the portable granite tools in Alabama, indicating that factors other than proximity were important when choosing associated resources. Of the 39 portable ground stone tools, two metates fell within the HBR geochemical range of variation, while two others fell within the HBR/CCB overlap and one originated from MPR. Additionally, one mano was sourced to HBR, while three others fell within the range of variation expected from MPR. As mentioned, there is a geochemical overlap between HBR and CCB granite, which is likely due to the granite batholiths' similar origins and formation timing. For the purposes of this study, we underscore that only 6% of the assemblage was of indeterminant origin; the bulk of the material returned a geochemical signature that fell within well-established plutonic ranges. Future work sampling within and between the northern portion of the CCB and the southern portion of HBR is planned to help clarify the relationship between these two plutons. Current and ongoing research at Alabama is also exploring variation within the nearby CCB granite source zones, with nine distinct granitic "types" identified to date using traditional geological methods (see Figure 4; Potter, 2018); this subtle variation will help to guide our further investigations of local chemical signatures of the CCB granite resources managed by Alabama residents.

3.2 | BREA assemblages

The Maya sites in the mid-to-lower reaches of the Belize River Valley lie on the karst plateau of central Belize. This mid-section of the valley marks the transition from the hilly uplands to the west and the flat, low-lying coastal zone that extends farther to the east. Geologically elevated areas within this part of the BREA project are characterized as Miocene–Pleistocene sedimentary material and lower floodplain terraces in proximity to the river are Quaternary-aged alluvial material (Wright et al., 1959). The area is ecologically

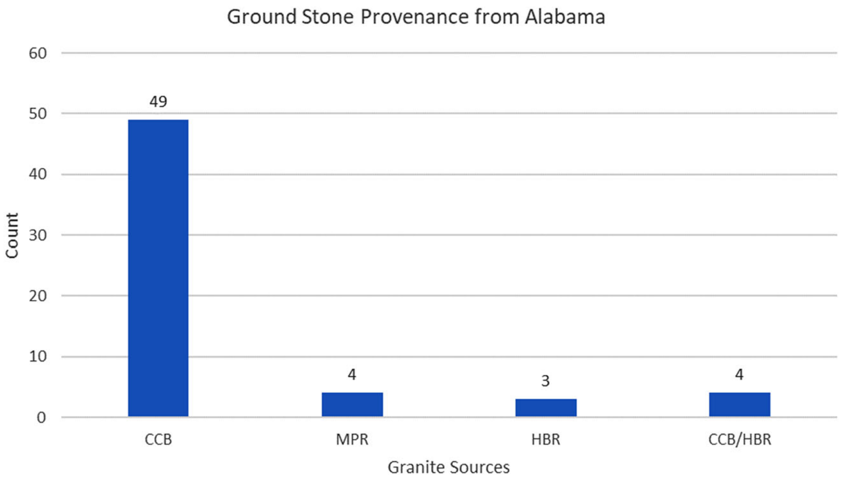

FIGURE 5 Results of pXRF characterization of Alabama granite ground-stone assemblage samples (portable artifacts and construction materials). pXRF, portable X-ray fluorescence. [Color figure can be viewed at wileyonlinelibrary.com]

diverse, with broad-leaf moist forest, scrub forest, and some lowland savanna interspersed with wetland, mangrove, and littoral forest (Cornec, 2010). In the past 10–20 years, large tracts of the area, especially in the middle reaches of the Belize River, have been deforested and converted to agricultural land (e.g., Harrison-Buck, Willis, et al., 2020).

Archaeologists once thought the mid-to-lower reaches of the Belize River to be nearly devoid of ancient Maya settlement, apart from the Saturday Creek and Cocos Bank sites. Chase and Garber (2004, p. 3) wrote that "the lowest part of the Belize River […] runs through savanna and swamp that were not conducive to either large or small Maya settlements. Agriculture was not only difficult in the coastal plain immediately adjacent to the Caribbean but also some 30 km inland, where poor soil conditions prevailed. Only the alluvial soils along rivers that flooded and carried upland soils into these areas could readily support settlement." Ten years of concerted research attention and salvage archaeology efforts by the BREA project have documented ~100 discrete archaeological sites and ~2500 previously undocumented mound structures throughout the project area (Harrison-Buck, 2020; Harrison-Buck, Willis, et al., 2020). Maize agriculture may not have been a viable subsistence practice in parts of this study area; however, other provisioning and extractive practices (e.g., foraging, fishing, aquaculture, salt and pottery production, hardwood extraction) supported widespread settlement.

We focus here on the western section of the BREA study area, where targeted research was conducted between 2011 and 2016. We have not encountered granite as a construction material in the BREA project area, unlike in Alabama. Instead, all granite specimens have taken the form of artifacts, and, notably, we have uncovered no evidence of production or design (e.g., preforms, debitage). Most of the architecture here is of cut limestone block, earthen-core/limestone rubble with limestone facing, or limestone cobble construction (Brouwer Burg et al., 2014, 2016; Harrison-Buck, 2011, 2013, 2015, 2018). We have uncovered only a few limestone stelae fragments in this area of the BREA project. Thus, from an architectural perspective, the BREA sites lie in stark contrast to the granite provisioning and construction practices employed in Alabama.

At the time of Tibbits' fieldwork, a handful of Maya sites spanning the Preclassic through Terminal Classic had been either provisionally or extensively excavated (i.e., Hats Kaab, Hum Chaak, Kaax Tsaabil, Ik'nal, and Ma'xan), yielding 62 granite ground stone tools or tool fragments suitable for XRF analysis in the field laboratory. Surface reconnaissance was also in full swing because of persistent forest clearance and land preparation for intensive agriculture, and five additional granite ground stone tools from this sample were also analyzed. XRF was applied to all available granite ground stone tools in the BREA assemblage as of the summer 2014 field season (*n* = 67; Figure 6). There were roughly similar numbers of manos and metates, all fragmentary, in this assemblage (~45% each), as well as a granite axe head and a few unidentifiable forms (9%; Brouwer Burg et al., 2021; Table 2). One-third of this assemblage was derived from the surface collection, the other two-thirds from excavation.

The XRF analysis revealed that the bulk of the BREA assemblage was derived from the MPR source (84%), 4% from the HBR source, 3% from the CCB, and 9% of unknown or indeterminate origin (Brouwer Burg et al., 2021; Figure 4; Tibbits, 2016, pp. 145–146). This section of the BREA study area is roughly equidistant (in linear distance) from the MPR and HBR granite sources, while the CCB source is almost double the distance (Brouwer Burg et al., 2021; Figure 6). However, linear distance is not very instructive for approximating movement within a landscape characterized by fluctuating elevations, crisscrossing waterways, and heterogeneous

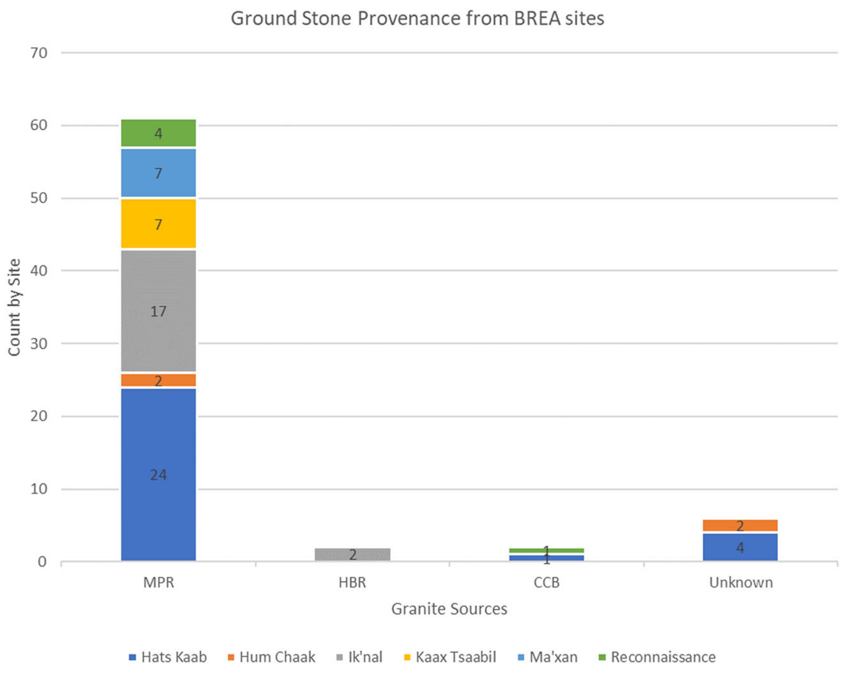

FIGURE 6 Results of pXRF characterization of the BREA granite ground-stone assemblage. BREA, Belize River East Archaeology; pXRF, portable X-ray fluorescence. [Color figure can be viewed at wileyonlinelibrary.com]

land cover. Further, the weight of granite (either in raw or finished form) is such that people would likely prefer to offset some of the cost of transportation with nonhuman modes, such as by boat or canoe. Archaeologists have suggested that the ancient Maya in certain areas preferred water-based transportation to overland routes, especially for the long-distance movement of goods (Drennan, 1984; Graham, 2002, p. 409). Via a combination of waterways and overland portaging, the HBR source is slightly closer in aggregate distance than the MPR source to the BREA study sites discussed here, and the CCB is much farther afield (Brouwer Burg et al., 2021; Figure 4).

We expected a small percentage of CCB granite, but what strikes us as most interesting here is the lack of HBR granite when it is the closest source of granite in linear and overwater travel models. Why were Maya populations in the middle reaches of the Belize River not sourcing granite from the Hummingbird pluton, which is arguably as close as the Mountain Pine source? Was this a result of geographic impediments, locational restrictions, or perhaps more nuanced sociopolitical or ideological factors? We require further XRF testing, analysis, and theorizing about mechanisms of ground stone exchange and meaning to shed light on these questions.

4 | DISCUSSION

As shown here through our experimental methodology, archaeologists can apply field-based XRF to accurately characterize coarse-grained materials like granite in a replicable and nondestructive manner. Further, since this technique can be carried out in the field, it eliminates the need to export heavy artifacts, not to mention the high costs involved. By using multiple data points per whole-rock sample, XRF can produce bulk geochemical signatures indistinguishable from those XRF signatures obtained in the lab on both whole-rock and powdered samples. Over time, the XRF unit can consistently produce accurate and precise results on a suite of elements, including Rb, Sr, and Y, which can differentiate between granite from MPR, HBR, and CCB. Therefore, the results of this sourcing project are considered robust within the confines of the Maya Mountains of Belize.

We have shown through the case studies described above just how fruitful the use of XRF on coarse-grained materials is slated to become. We can now begin unraveling granite provisioning, production, and distribution questions heretofore off-limits. We have demonstrated that proximity was undoubtedly an essential factor guiding ground stone procurement and distribution at both Alabama and the BREA sites. However, it was not the only factor indicated by the geochemical variation found within the granite tool assemblages. The presence of granite tools at both Alabama and the BREA sites suggests interaction between the residents of these areas and the metateros of Pacbitun, a site with an auxiliary mound group that appears to have been a ground stone tool workshop (Powis et al., 2020; Skaggs et al., 2020; Ward, 2013). At the Tzib group, many manos ($n = 78$) and metate ($n = 67$) fragments were found, in addition to some 1500 kg of granite debitage, thought to result from long-term, intensive production. The movement of ground stone tools from MPR and HBR to Alabama or the BREA study area is significant; these tools, especially metates, are large, fragile, and difficult to transport. Their movement may represent a number of interwoven phenomena, from manufacturing practices and exchange relationships, to postmarital residence moves and other types of relocation and beyond.

Additionally, while no granite extraction was taking place in the BREA study area, the Maya of east-central Belize engaged in multiple granite resource development and management activities. In Alabama, granite exploitation appears to be short-lived, but when it occurred was on a relatively grand scale, spanning the manufacture of manos to monumental construction blocks and slabs, evidenced by debitage, preforms, and final products distributed throughout the associated settlement zone. This distribution suggests a household and community-oriented craft industry (Costin, 1991; Feinman & Nicholas, 2000; Hayden, 1987b; Hendon, 1996; Hirth, 2010). Further, extraction methods appear to have varied in Alabama and were different from the granite production and distribution at the Tzib Group and nearby center of Pacbitun. There is little evidence indicating that the Maya of Alabama were creating formal quarries within plutons and actively carving granite pieces from larger units. It is more likely that the ancient Maya at Alabama achieved their granite resource extraction and acquisition goals by taking advantage of the natural breakage of large boulders. Such boulders become disconnected from the larger outcrops through mechanisms such as rockfall and the resulting small boulders/large cobbles can be collected from stream drainages. This latter source was far more accessible and more viable an option for manos, metates, and some construction blocks.

5 | CONCLUSION

Results from the field and lab-based, energy-dispersive handheld XRF application outlined in this paper are comparable to those obtained with traditional lab-based XRF on a suite of elements. While it is challenging to distinguish fully between HBR and CCB granites in certain portions of the plutons, we will increase the clarity of the relationships between these plutons in subsequent work. Importantly, the field-based XRF analyses executed on different materials (whole rock and powdered) returned similar results. This confirms that the multishot XRF method using a handheld unit on whole rock is as fit for purpose as lab-based XRF on powdered samples, especially when we analyze known geologic reference materials to develop secondary corrections. Assessing the limitations of the XRF instrumentation on coarse-grained materials is needed for reproducible data sets. Testing should be conducted to ascertain which elements are most accurately read, abundant in the material to be analyzed, and not impacted by weathering or other factors (i.e., post-depositional anthropogenic activities).

By establishing a baseline number of bulk points for whole rock analysis and outlining a technique for testing geologic reference materials repeatedly, this project assessed what elements were appropriate for sourcing the granites in Belize. We found that five randomly selected data points per sample were sufficient to distinguish between plutons and yielded consistent results with destructive, lab-based XRF methods. The number of randomly selected data points described above is unique to our study context and research questions; XRF applications in other regions on coarse materials will require Monte Carlo Simulation to determine the appropriate number of data points required to yield accurate geochemical readings. We hope that this technique can be applied more widely to granite archaeological samples in various global settings in the future.

Field-based XRF work is unlocking many new avenues of research for archaeologists out of the lab setting and is shedding light on longstanding questions in the discipline. Presently, we can only answer the fundamental question of where the ancient Maya sourced the granites they used to produce ground stone items in Belize. Outstanding questions that we plan to investigate in future work can be parsed into two areas of inquiry. First, we aim to clarify whether XRF and other characterization studies could provide more detailed provenance location for plutons within and beyond Belize. For instance, more research is needed to further examine the distinct geochemical signatures from within each of the three plutons in Belize to fully reconstruct the ancient use and management of the MPR, HBR, and CCB granite sources. Along these same lines, we also plan to expand our investigations to include geochemical testing of granite plutons in Guatemala and Honduras, which is critical to isolate all potential sources that were utilized in the past and to be confident in our source assignments. Second, in conjunction with additional assemblage testing, geospatial modeling, and socioeconomic theory development, we seek to answer the more nuanced questions of granite ground stone resource management, including how the stone was quarried. Were these materials transported before/during/after production, in what directions, and why? What socioeconomic factors drove the distribution of finished ground stone items within the community and the broader region? Now that we have a reliable technique for sourcing granite in the field, our future research goals are to be able to further contribute to questions of granite ground stone timing, tempo, and spatial distribution among the ancient Maya of lowland Mesoamerica.

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REFERENCES

Abramiuk, M. A., & Meurer, W. P. (2006). A preliminary geoarchaeological investigation of ground stone tools in and around the Maya Mountains, Toledo District, Belize. *Latin American Antiquity*, *17*, 335–354. https://doi.org/10.2307/25063056

Adams, J. (1996). *Manual for a technological approach to ground stone analysis*. Center for Desert Archaeology.

Adams, J. (2014). *Ground stone analysis: A technological approach* (2nd ed). University of Utah Press.

Adams, J. L. (1999). Refocusing the role of food-grinding tools as correlates for subsistence strategies in the U.S. Southwest. *American Antiquity*, *64*, 475–498. https://doi.org/10.2307/2694147

Barbera, G., Barone, G., Crupi, V., Longo, F., Majolino, D., Mazzoleni, P., & Venuti, V. (2013). Nondestructive analyses of carbonate rocks: Applications and potentiality for museum materials. *X-Ray Spectrometry*, *42*, 8–15.

Bateson, J. H. (1972). New interpretation of geology of Maya Mountains, British Honduras. *Association of American Petroleum Geologists*, *56*, 956–963.

Bateson, J. H., & Hall., I. H. S. (1977). *Geology of the Maya Mountains, Belize*. HM Stationery Office.

Biskowski, M. (2000). Maize preparation and the Aztec subsistence economy. *Ancient Mesoamerica*, *11*, 293–306.

Brouwer Burg, M., Runggaldier, A., & Harrison-Buck, E. (2014). At the crossroads: Examining the Hats Kaab E-group as a node of trade and communication in the Eastern Belize watershed. *Research Reports in Belizean Archaeology*, *11*, 259–270.

Brouwer Burg, M., Runggaldier, A., & Harrison-Buck, E. (2016). The afterlife of earthen-core buildings: A taphonomic study of threatened and effaced architecture in Central Belize. *Journal of Field Archaeology*, *41*, 17–36.

Brouwer Burg, M., Tibbits, T. L. B., & Harrison-Buck, E. (2021). Advances in geochemical sourcing of granite ground stone: Ancient Maya artifacts from the middle Belize Valley. *Advances in Archaeological Practice*, *9*, 338–353.

Chase, A. F., & Garber, J. F. (2004). The archaeology of the Belize Valley in historical perspective. In J. F. Garber (Ed.), *The ancient Maya of the Belize Valley: Half a century of archaeological research* (pp. 1–14). University Press of Florida.

Clemons, R. E., & Long, L. E. (1971). Petrologic and Rb-Sr isotopic study of the Chiquimula Pluton, Southeastern Guatemala. *Geological Society of America Bulletin*, *82*, 2729–2740.

Conrey, R. M., Goodman-Elgar, M., Bettencourt, N., Seyfarth, A., Van Hoose, A., & Wolff, J. A. (2014). Calibration of a portable X-ray fluorescence spectrometer in the analysis of archaeological samples using influence coefficients. *Geochemistry: Exploration, Environment, Analysis*, *14*, 291–301. https://doi.org/10.1144/geochem2013-198

Cook, S. (1982). *Zapotec stoneworkers: The dynamics of rural simple commodity production in modern Mexican capitalism*. University Press of America.

Cornec, J. H. (2010). *Geology map of Belize*. Geology and Petroleum Office, Ministry of Economic Development and Petroleum.

Costin, C. (1991). Craft specialization: Issues in defining, documenting, and explaining the organization of production. *Journal of Archaeological Method and Theory*, *3*, 1–56.

Craig, N., Speakman, R. J., Popelka-Filcoff, R. S., Glascock, M. D., Robertson, J. D., Shackley, M. S., & Aldenderfer, M. S. (2007). Comparison of XRF and PXRF for analysis of archaeological obsidian from southern Perú. *Journal of Archaeological Science*, *34*, 2012–2024.

Dawe, S. E. (1984). *The geology of the Mountain Pine Ridge area and the relations of the Mountain Pine Ridge granite to Late Paleozoic and Early Mesozoic Geological History of Belize, Central America* [Unpublished master's thesis]. State University of New York.

Delu, A. (2007). The ground Stone tools of Caye Coco, Belize (Occasional Publication Number 12). Institute of Mesoamerican Studies, SUNY.

Dixon, C. G. (1956). *Geology of Southern British Honduras with notes on adjacent areas*. Government Printer.

Drennan, R. D. (1984). Long-distance movement of goods in the Mesoamerican formative and classic. *American Antiquity*, *49*, 27–43.

Dunham, P., Murray, R. C., Brooks, W. E., Reynolds, R. P., Cookro, T. H., & Jacobs, J. F. (1995). *Field report of the 1995 season of the Maya Mountains Archaeological Project (MMAP)*. Report submitted to the Department of Archaeology, Forest Department, Office of Geology and Petroleum, Belize Audubon Society, Belmopan, Belize; The National Geographic Society.

Feinman, G. M., & Nicholas, L. M. (2000). High-intensity household-scale production in ancient Mesoamerica. In G. M. Feinman, & L. Manzanilla (Eds.), *Cultural evolution: Contemporary viewpoints* (pp. 119–142). Springer. https://doi.org/10.1007/978-1-4615-4173-8_5

Forster, N., & Grave, P. (2013). Effects of elevated levels of lead in ceramics on provenancing studies using non-destructive PXRF: A case study in Byzantine Cypriot glazed ceramics. *X-Ray Spectrometry*, *42*, 480–486.

Frahm, E. (2012). Non-destructive sourcing of Bronze Age near eastern obsidian artefacts: Redeveloping and reassessing electron microprobe analysis for obsidian sourcing. *Archaeometry*, *54*(4), 623–642.

Frahm, E. (2013a). Is obsidian sourcing about geochemistry or archaeology? A reply to Speakman and Shackley. *Journal of Archaeological Science*, *40*(2), 1444–1448.

Frahm, E. (2013b). Validity of "off-the-shelf" handheld portable XRF for sourcing Near Eastern obsidian chip debris. *Journal of Archaeological Science*, *40*(2), 1080–1092. https://doi.org/10.1016/j.jas.2012.06.038

Frahm, E. (2014). Characterizing obsidian sources with portable XRF: Accuracy, reproducibility, and field relationships in a case study from Armenia. *Journal of Archaeological Science*, *49*, 105–125. https://doi.org/10.1016/j.jas.2014.05.003

Frahm, E., & Doonan, R. C. P. (2013). The technological versus methodological revolution of portable XRF in archaeology. *Journal of Archaeological Science*, *40*, 1425–1434.

García Barrios, A. (2017). The social context of food at Calakmul, Campeche, Mexico: Images painted on the pyramid of Chiik Nahb'. In M. Paxton, & L. Staines Cicero (Eds.), *Constructing power and place in Mesoamerica: Pre-Hispanic paintings from three regions* (pp. 171–190). University of New Mexico Press.

Gauthier, G., & Burke, A. L. (2011). The effects of surface weathering on the geochemical analysis of archaeological lithic samples using non-destructive polarized energy dispersive XRF. *Geoarchaeology*, *26*(2), 269–291. https://doi.org/10.1002/gea.20346

Gill, R. (Ed.). (1997). *Modern analytical geochemistry: An introduction to quantitative chemical analysis for earth, environmental, and materials scientists*. Routledge, Taylor & Francis Group.

Goodale, N., Bailey, D. G., Jones, G. T., Prescott, C., Scholz, E., Stagliano, N., & Lewis, C. (2012). pXRF: A study of inter-instrument performance. *Journal of Archaeological Science*, *39*, 875–883.

Graham, E. (1987). Resource diversity in Belize and its implications for models of lowland trade. *American Antiquity*, *52*, 753–767. https://doi.org/10.2307/281383

Graham, E. (1994). The highlands of the lowlands: Environment and archaeology in the Stann Creek District, Belize Central America. Monographs in World Archaeology, 19. Prehistory Press & Royal Ontario Museum.

Graham, E. (2002). Perspectives on economy and theory. In M. A. Masson, & D. A. Freidel (Eds.), *Ancient Maya political economies* (pp. 398–418). AltaMira Press.

Grave, P., Attenbrow, V., Sutherland, L., Pogson, R., & Forster, N. (2012). Non-destructive pXRF of mafic stone tools. *Journal of Archaeological Science*, *39*, 1674–1686.

Greenough, J. D., Mallory-Greenough, L. M., & Baker, J. (2004). Orthopyroxene, augite, and plagioclase compositions in dacite: Application to bedrock sourcing of lithic artefacts in southern British Columbia. *Canadian Journal of Earth Sciences*, *41*, 711–723.

Guthrie, J. M., & Ferguson, J. R. (2012). *XRF technical overview*. Archaeometry Laboratory University of Missouri Research Reactor. Retrieved July 13, 2022, from: https://archaeometry.missouri.edu/xrf_technical.html

Harrison-Buck, E. (Ed.). (2011). *Surveying the crossroads in the middle Belize Valley: A report of the 2011 Belize River East Archaeology Project* (Occasional Paper No. 5). University of New Hampshire, Durham. Report submitted to the Belize Institute of Archaeology. Retrieved December 23, 2021, from: https://brea-project.org/reports/

Harrison-Buck, E. (Ed.). (2013). *Archaeology in the middle Belize Valley: A report of the 2012 Belize River East Archaeology Project* (Occasional Paper No. 6). University of New Hampshire, Durham. Report submitted to the Belize Institute of Archaeology. Retrieved December 23, 2021, from: https://brea-project.org/reports/

Harrison-Buck, E. (Ed.). (2015). *Investigations of the Belize River East Archaeology Project: A report of the 2014 and 2015 Field Seasons* (Occasional Paper No. 7, Vols. 1–2). University of New Hampshire, Durham. Report submitted to the Belize Institute of Archaeology. Retrieved December 23, 2021, from: https://brea-project.org/reports/

Harrison-Buck, E. (Ed.). (2018). *Investigations of the Belize River East Archaeology Project: A report of the 2016 and 2017 Field Seasons* (Occasional Paper No. 8). University of New Hampshire, Durham. Report submitted to the Belize Institute of Archaeology. Retrieved December 23, 2021, from: https://brea-project.org/reports/

Harrison-Buck, E. (Ed.). (2020). *Investigations of the Belize River East Archaeology Project: A report of the 2018 and 2019 Field Seasons* (Occasional Paper No. 9). University of New Hampshire, Durham. Report submitted to the Belize Institute of Archaeology. Retrieved December 23, 2021, from: https://brea-project.org/reports/

Harrison-Buck, E., Willis, M. D., Walker, C. P., Murata, S., & Brouwer Burg, M. (2020). From urban core to vacant terrain: Defining the heterotopia of Maya monumental landscapes at the crossroads of the middle Belize River Valley. In B. A., Houk, B. Arroyo, & G. Terry (Eds.), *Approaches to monumental landscapes of the ancient Maya* (pp. 85–108). University of Florida Press.

Hayden, B. (Ed.). (1987a). *Lithic studies among the contemporary highland Maya*. University of Arizona Press.

Hayden, B. (1987b). Traditional metate manufacturing in Guatemala using chipped stone tools. In B. Hayden (Ed.), *Lithic studies among the contemporary highland Maya* (pp. 8–119). University of Arizona Press.

Hayden, B. (1987c). Past to present uses of stone tools in the Maya highlands. In B. Hayden (Ed.), *Lithic studies among the contemporary highland Maya* (pp. 160–234). University of Arizona Press.

Hendon, J. A. (1996). Archaeological approaches to the organization of domestic labor: Household practice and domestic relations. *Annual*

Review of Anthropology, *25*(1), 45–61. https://doi.org/10.1146/annurev.anthro.25.1.45

Hermes, O. D., & Ritchie, D. (1997). Nondestructive trace element analysis of archaeological felsite by energy-dispersive X-ray fluorescence spectroscopy. *Geoarchaeology*, *12*(1), 31–40. https://doi.org/10.1002/(SICI)1520-6548(199701)12:1<31::AID-GEA2>3.0.CO;2-A

Hirth, K. G. (2010). *Housework: Craft production and domestic economy in ancient Mesoamerica*. John Wiley & Sons.

Innov-X Systems, Inc. (2010). *User Manual, Delta*^{TM} *Family: Handheld XRF Analyzers*.

Jackson, T. A., Duke, M. J. M., Scott, P. W., Smith, F., & Wilkinson, F. C. F. (1995). Petrology and inferred tectonic setting of the Mountain Pine Ridge Granitoids, Maya Mountains, Belize. *International Geology Review*, *37*, 26–38.

Jochum, K. P., Nohl, U., Herwig, K., Lammel, E., Stoll, B., & Hofmann, A. W. (2005). GeoReM: A new geochemical database for reference materials and isotopic standards. *Geostandards and Geoanalytical Research*, *29*, 333–338.

Jordan, J. M., Peuramaki-Brown, M. M., Chiac, S., Saqui, A., & Tzib, F. (2021). It's what's inside that counts: Developing a paste group typology in Belize. *Journal of Archaeological Science: Reports*, *37*, 103019. https://doi.org/10.1016/j.jasrep.2021.103019

Lundblad, S. P., Mills, P. R., & Hon, K. (2007). Analysing archaeological basalt using non-destructive energy-dispersive X-ray fluorescence (EDXRF): Effects of post-depositional chemical weathering and sample size on analytical precision. *Archaeometry*, *50*, 1–11. https://doi.org/10.1111/j.1475-4754.2007.00345.x

MacKinnon, J. J., Olson, J. M., & May, E. M. (1993). "Megalithic" Maya architectural features at the site of Chacben Kax, Alabama, Stann Creek District, Belize, CA. *Mexicon*, *15*(1), 1–4.

Martens, U., Weber, B., & Valencia, V. A. (2010). U/Pb geochronology of Devonian and older Paleozoic beds in the southeastern Maya block, Central America: Its affinity with peri-Gondwanan terranes. *Geological Society of America Bulletin*, *122*(5-6), 815–829.

Menne, J., Holzheid, A., & Heilmann, C. (2020). Multi-scale measurements of Neolithic ceramics–A methodological comparison of portable energy-dispersive XRF, wavelength-dispersive XRF, and micro-computer tomography. *Minerals*, *10*(931), 931.

Mitchell, D., Grave, P., Maccheroni, M., & Gelman, E. (2012). Geochemical characterisation of north Asian glazed stonewares: A comparative analysis of NAA, ICP-OES and non-destructive pXRF. *Journal of Archaeological Science*, *39*, 2921–2933.

Nazaroff, A. J., Prufer, K. M., & Drake, B. L. (2010). Assessing the applicability of portable X-ray fluorescence spectrometry for obsidian provenance research in the Maya lowlands. *Journal of Archaeological Science*, *37*, 885–895.

Nelson, M. C., & Lippmeier, H. (1993). Grinding-tool design as conditioned by land-use pattern. *American Antiquity*, *58*, 286–305.

Odell, G. H. (2000). Stone tool research at the end of the millennium: Procurement and technology. *Journal of Archaeological Research*, *8*, 269–331.

Palumbo, S., Golitko, M., Christensen, S., & Tietzer, G. (2015). Basalt source characterization in the highlands of Western Panama using portable X-ray fluorescence (pXRF) analysis. *Journal of Archaeological Science: Reports*, *2*, 61–68.

Peregrine, P. (1991). Some political aspects of craft specialization. *World Archaeology*, *23*, 1–11.

Peuramaki-Brown, M. M. (2017). Revisiting the ancient Maya of Alabama, Belize: Description, recent research, and future directions. *Mexicon*, *39*, 64–72.

Powis, T. G., Skaggs, S. & Micheletti, G. J. (Eds.). (2020). An archaeological reconstruction of ancient Maya life at Pacbitun, Belize. BAR International Series 2970. British Archaeological Reports.

Peuramaki-Brown, M. M., & Morton, S. G. (2019a). Maya monumental 'boom': Rapid development, hybrid architecture, and 'pretentiousness' in the fabrication of place at Alabama, East-Central Belize. *Journal of Field Archaeology*, *44*, 283–293.

Peuramaki-Brown, M. M., & Morton, S. G. (2019b). Archaeological Reconnaissance at the pearce sites of the Cockscomb Basin, Stann Creek District. Research Reports in Belizean. *Research Reports in Belizean* Archaeology, *16*, 283–293.

Peuramaki-Brown, M. M., & Morton, S. G. (2021). People, animals, protected places, and archaeology: A complex collaboration in Belize. In R.-H. Andersson, B. Cothran, & S. Kekki (Eds.), *Bridging cultural concepts of nature: Indigenous people and protected spaces of nature* (pp. 97–137). Helsinki University Press. https://doi.org/10.33134/AHEAD-1-4

Peuramaki-Brown, M. M., Morton, S. G., & Jordan., J. M. (2020). Maya archaeology of the Stann Creek District, Belize: Early explorations to recent research. *Research Reports in Belizean Archaeology*, *17*, 221–235.

Peuramaki-Brown, M. M., Morton, S. G., Tibbits, T. L. B., & Green, L. (2017). Phase I Reconnaissance (2014-2015) at Alabama: A summary of SCRAP investigations in East-Central Belize. *Research Reports in Belizean Archaeology*, *14*, 299–309.

Piercey, S. J., & Devine, M. C. (2014). Analysis of powdered reference materials and known samples with a benchtop, field portable X-ray fluorescence (pXRF) spectrometer: Evaluation of performance and potential applications for exploration lithogeochemistry. *Geochemistry: Exploration*, *Environment*, *Analysis*, *14*, 139. https://doi.org/10.1144/geochem2013-199

Potter, J. (2018). 2018 geological survey: The cockscomb granites of Alabama. In M. M. Peuramaki-Brown & S. G. Morton (Eds.), *The Stann Creek Regional Archaeology Project: Report of the Fourth (2018) Field Season* (p. 117). Unpublished technical report submitted to the Institute of Archaeology, Belmopan, Belize. Retrieved March 23, 2022, from: https://scraparchaeology.com/publications/

Ratschbacher, L., Franz, L., Min, M., Bachmann, R., Martens, U., Stanek, K., Stubner, K., Nelson, B., Herrmann, U., Weber, B., Lopez-Martinez, M., Jonckheere, R., Sperner, B., Tichomirowa, M., Mcwilliams, M., Gordon, M., Meschede, M., & Bock, P. (2009). *The North American-Caribbean Plate boundary in Mexico-Guatemala-Honduras* (pp. 219–293). Geological Society, Special Publications, 328.

Rice, P. M. (2009). On classic Maya political economies. *Journal of Anthropological Archaeology*, *28*, 70–84.

Ross, P. S., Bourke, A., & Fresia, B. (2014). Improving lithological discrimination in exploration drill-cores using portable X-ray fluorescence measurements: (2) Applications to the Zn-Cu Matagami Mining Camp, Canada. *Geochemistry: Exploration*, *Environment*, *Analysis*, *16*, 2014–2326.

Rowan, Y. M. & Ebeling, J. R. (Eds.). (2008). *New approaches to old stones: Recent studies of ground stone artifacts*. Equinox Publishing Ltd.

Searcy, M. (2011). *Life-giving stone: Ethnoarchaeology of Maya metates*. University of Arizona Press.

Shipley, W. E. (1978). *Geology, petrology, and geochemistry of the Mountain Pine Ridge Batholith, Belize, Central America* [Unpublished master's thesis]. Colorado School of Mines.

Shipley, W. E., III, & Graham, E. (1987). Petrographic analysis and preliminary source identification of selected stone artifacts from the Maya sites of Seibal and Uaxactun, Guatemala. *Journal of Archaeological Science*, *14*, 367–383.

Skaggs, S., Micheletti, G. J., Lawrence, M., Cartagena, N., & Powis, T. G. (2020). Identification of an ancient Maya groundstone production site in the periphery of Pacbitun, Belize. In T. G. Powis, S. Skaggs, & G. J. Micheletti (Eds.), *An archaeological reconstruction of ancient Maya life at Pacbitun, Belize*. BAR International Series 2970 (pp. 159–173). British Archaeological Reports.

Solari, L., A. Gomez-Tuena, F. O. -G., Ortega-Gutierrez, F., & Ortega-Obregon, C. (2011). The Chuacus metamorphic complex, Central

Guatemala: Geochronological and geochemical constraints on its Paleozoic-Mesozoic evolution, *Geologica Acta*, *9*, 329–350.

Speakman, R. J., & Shackley, S. M. (2013). Silo science and portable XRF in archaeology: A response to Frahm. *Journal of Archaeological Science*, *40*(2), 1435–1443. https://doi.org/10.1016/j.jas.2012.09.033

Spink, M. (1982). *Metates as socioeconomic indicators during the classic period at Copan, Honduras* [PhD dissertation]. Department of Anthropology, Pennsylvania State University, University Park.

Stuart, D. (2014). A possible sign for metate. *Blog: Maya decipherment—Ideas on ancient Maya writing and iconography*. Retrieved December 10, 2021, from: http://decipherment.wordpress.com/2014/02/04/a-possible-sign-for-metate/

Tibbits, T. L. B. (2016). Geochemical sourcing of granite ground stone tools from Belize [Unpublished doctoral dissertation]. University of Iowa.

Tibbits, T. L. B. (2020). Geochemical sourcing of granite artefacts. In T. G. Powis, S. Skaggs, & G. J. Micheletti (Eds.), *An archaeological reconstruction of ancient maya life at Pacbitun, Belize* (pp. 175–184). BAR International Series 2790. British Archaeological Reports.

Turuk, J. (2006). *More grist for the mill: An analysis of the grinding stones recovered from the ancient Maya Site of Minanha, Belize* [Unpublished master's thesis)]. Trent University, Peterborough.

Ward, D. T. (2013). Investigations of a Ground Stone Tool Workshop at Pacbitun, Belize [Unpublished master's thesis]. Georgia State University.

Weber, B., Scherer, E. E., Martens, U. K., & Mezger, K. (2012). Where did the lower Paleozoic Rocks of Yucatan come from? A U-Pb, Lu-Hf, and Sm-Nd isotope study. *Chemical Geology*, *312–313*, 1–17.

Wells, E. C. (2006). Recent trends in theorizing prehispanic Mesoamerican economies. *Journal of Archaeological Research*, *14*, 265–312.

Weyer, S., Anbar, A., Gerdes, A., Gordon, G., Algeo, T. J., & Boyle, E. A. (2008). Natural fractionation of 238U/235U. *Geochimica et Cosmochimica Acta*, *72*, 345–359.

Williams-Thorpe, O., Aldiss, D., Rigby, I., & Thorpe, R. (1999). Geochemical provenancing of igneous glacial erratics from Southern Britain, and implications for prehistoric stone implement distributions. *Geoarchaeology*, *14*, 209–246.

Williams-Thorpe, O., Potts, J. P., & Webb, P. C. (1999). Field-portable non-destructive analysis of lithic archaeological samples by X-ray fluorescence instrumentation using a Mercury iodide detector: Compariosn with wavelength-dispersive XRF and a case study in British stone axe provenancing. *Journal of Archaeological Science*, *26*(2), 215–237.

Wright, A. C. S., Romney, D. H., Arbuckle, R. H., & Vial, V. E. (1959). Land in British Honduras. Colonial Research Publication No. 24. Her Majesty's Stationery Office [The National Archives].

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