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# Late Holocene forager-fisher and pastoralist interactions along the Lake Victoria shores, Kenya: Perspectives from portable XRF of obsidian artifacts

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ABSTRACT

The East African Rift system created one of the world's most obsidian-rich landscapes, where this volcanic glass has been used to make tools for nearly two million years. In Kenya alone, there are >80 chemically distinct obsidians along a 800-km north-south transect. Recently Brown et al. (2013) published their Kenyan obsidian database assembled since the 1980s. Specifically, they report elemental data measured by EMPA, ICP-MS, and WDXRF, providing a rich basis for future sourcing studies. Here we report our use of portable XRF (pXRF), calibrated specifically and directly to the database in Brown et al. (2013), to examine interactions between Later Stone Age forager-fishers and pastoralists near Lake Victoria. Regarding our calibration to the WDXRF and EMPA datasets of Brown et al. (2013), the elements of interest have very high correlations ($R^2 = 0.96–0.99$) to our pXRF values, which show, on average, only a 2–5% relative difference from the published values. Use of pXRF data specifically calibrated to the datasets from Brown et al. (2013) greatly expands the impact of their work over three decades to catalog and characterize a multitude of Kenyan obsidians. Our focus here is investigating social contacts and exchange between late Holocene populations that included Kansyore forager-fishers and Elmenteitan pastoralists. Similarities and differences in their obsidian access provide new insights into long-term interactions between foragers and food producers in eastern Africa. We report new sourcing results for obsidian artifacts from six late Holocene rock shelters along the Winam Gulf of Lake Victoria. The patterns in obsidian access are consistent with changing interaction spheres that are relevant to understanding forager-fisher social identities and subsistence strategies during periods of economic and demographic change.



## 1. Introduction

Volcanism of the East African Rift, where the African tectonic plate is splitting in two, created one of the world's most obsidian-rich landscapes, where this volcanic glass has been used, perhaps continuously, to make tools for almost two million years (Leakey, 1971; Clark and Kurashina, 1981; Brandt et al., 1996; Brandt and Weedman, 1997; Piperno et al., 2009). Many dozens of obsidian sources lie between Eritrea in the north and Tanzania in the south. There are, by some tallies (Brown et al., 2013), >80 chemically distinct obsidians in Kenya alone. It is unsurprising, therefore, that archaeologists have long been interested to trace the distribution of obsidians across the region (e.g., Merrick and Brown, 1984a, b; Merrick et al., 1988, 1994; Negash and Shackley, 2006; Coleman et al., 2008; Nash et al., 2011; Ndiema et al., 2011; Ambrose, 2012). Before the successes of chemical obsidian sourcing (Cann and Renfrew, 1964), researchers sought to match obsidian artifacts to these sources using density, refractive index, and similar physical properties (Lucas, 1942, 1947; Leakey, 1945). Surveys of the southern Kenya Rift (Bower et al., 1977) revealed a greater number of obsidians than anticipated, complicating the potential for sourcing research. To conduct obsidian sourcing in Kenya, for example, one must first sample the multitude of obsidian sources that occur along a 800-km stretch between Lake Turkana on the Ethiopian border and Lake Natron on the Tanzanian border (Fig. 1). Alternatively, one could utilize a coherent, published database of Kenyan obsidians – that is, if the measurements of obsidian artifacts are sufficiently compatible with an existing source database.

Recently Brown et al. (2013) published their full Kenyan obsidian source database, assembled since the 1980s (Merrick and Brown,

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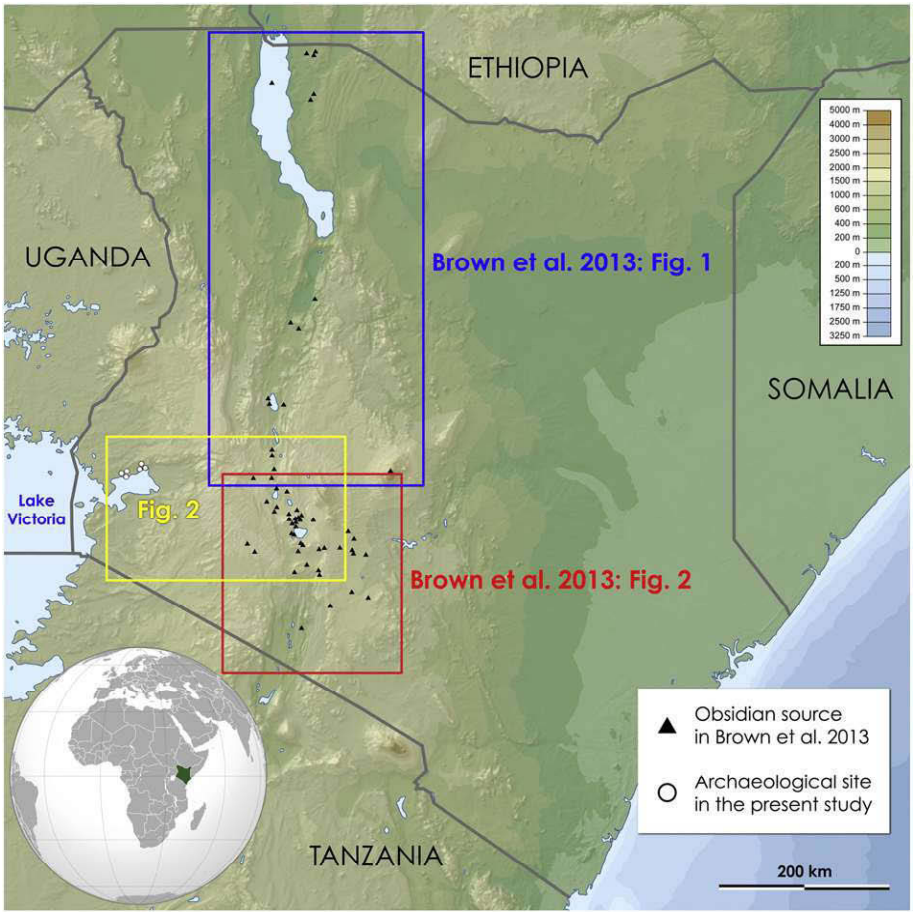


**Fig. 1.** Locations of Kenyan obsidian sources (black triangles) published by Brown et al. (2013) and the six Late/Terminal Kansyore rock shelters excavated by Gabel (1969) along the Lake Victoria shore (white circles). Insets correspond to figures in Brown et al. (2013) (red and blue) and to Fig. 2 here (yellow). Background map source: NASA Shuttle Radar Topography Mission (SRTM3).

1984a). Specifically, they report elemental data for 194 geological obsidian specimens from 90 localities across Kenya. From these specimens, small subsamples were prepared for (i.e., cut, mounted, ground, and polished) and measured by electron microprobe analysis (EMPA), specifically a CAMECA SX-50, using conditions found in Nash (1992). The original EMPA measurements in Merrick and Brown (1984a) were acquired using an ARL-EMX, an instrument from the 1960s that output data onto punch cards. Therefore, their new EMPA data represent a considerable improvement. The same subsamples were measured using inductively coupled plasma mass spectrometry (ICP-MS) with laser ablation, specifically an Agilent 7500ce quadrupole mass spectrometer, using conditions reported in Eggins (2003). Other subsamples were prepared for (crushed and finely powdered) and measured by wavelength-dispersive X-ray fluorescence (WDXRF), specifically a Fisons (now Thermo Scientific) 6400 instrument, using conditions reported in Brown et al. (2006). Consequently, their published database includes EMPA, WDXRF, and ICP-MS data for the same suite of obsidian specimens, providing a rich basis on which other researchers can build archaeological studies involving artifact sourcing.

The last few years have seen the rise and proliferation of portable X-ray fluorescence (pXRF) in obsidian sourcing. Such instruments offer archaeologists a number of advantages over analytical techniques traditionally used for sourcing. First, pXRF is a non-destructive technique, meaning that the artifacts do not need to be polished, powdered, or disposed as radioactive waste. Second, it is rapid, frequently requiring only a minute or two to measure dozens of elements. Third, it can be conducted at a museum, in a field house, or even at an archaeological site. Thus, artifacts can be sourced without concern for the practical, legal, or ethical limitations associated with distant instruments or destructive techniques.

The adoption of pXRF, however, is not without controversy. One concern expressed in the literature (e.g., Shackley, 2012b; Speakman and Shackley, 2013) and at conferences (e.g., Brandt et al., 2013) is that pXRF datasets are not – due to technical limitations or user inexperience – compatible with data from other analytical techniques. However, this is not an issue particular to pXRF. Instead, it is unwise to uncritically integrate datasets from any combination of measuring devices, be they spectrometers or bathroom scales. Recent pXRF instruments indeed have the technical capacity for high accuracy and reproducibility, which are attainable using suitable methods (Frahm, 2014a). Another concern is that pXRF lacks the sensitivity needed to distinguish chemically similar obsidian sources in complex regions (e.g., Shackley, 2011a). Yet pXRF can make subtle source distinctions that once required neutron activation analysis (NAA; Frahm and Feinberg, 2015), exhibiting greater analytical sensitivity than conventional lab-based XRF instruments only a decade ago.

Here we report our use of pXRF, specifically calibrated and compared to the datasets in Brown et al. (2013), to study interactions between Later Stone Age (LSA) foragers and food producers near the eastern shore of Lake Victoria. Regarding our direct calibration to the WDXRF and EMPA datasets from Brown et al. (2013) using matched specimens from their reference collection, the elements of interest for assigning obsidian artifacts to their geological sources (e.g., Zr, Nb, Rb) exhibit very high correlations ($R^2 = 0.96–0.99$) to our pXRF measurements. Once calibrated to the Brown et al. (2013) data, our pXRF measurements exhibit, on average, only a 2–5% relative difference, akin to compatible datasets in other studies using lab-based instruments. In addition, when our new pXRF measurements of geological specimens are plotted with published data, they directly overlap, further

demonstrating that the published values and our pXRF values are directly compatible and suitable for such a study. As with any sourcing work, the strength of the artifact attributions is predicated on the comprehensiveness of the source database. Here we use the database of Brown et al. (2013), but such work is not complete. In Kenya and surrounding regions, our knowledge of obsidian sources and their utilization in the past continues to improve due to ongoing endeavors (e.g., Coleman et al., 2008, 2009; Brandt and Johnson, 2011; Ambrose, 2012; Ambrose et al., 2012a, b; Ferguson, 2012; Slater et al., 2012; Brandt et al., 2013, 2014; Brandt, 2015; Slater and Ambrose, 2015).

Our results suggest that late Holocene fisher-foragers in the Lake Victoria region maintained sophisticated social contacts with mobile herders and sedentary farmers across several centuries. There are outstanding questions concerning the nature of forager-food producer relationships in this region and how such interactions may have been integrated into the long-term resilience of these groups. Addressing such questions is considered an essential – but elusive – step in understanding the spread of African mobile herding, the persistence of forager lifeways into the present, and the sustainability of these lifeways in unpredictable environments with dispersed resources (e.g., Dale and Ashley, 2010; Gifford-Gonzalez, 2016; Marshall et al., 2011; Lane, 2004; Prendergast and Lane, 2010).

Reconstructing the movement and exchange of obsidian artifacts is a promising line of investigation to elucidate the interaction spheres of Holocene foragers, which, in the Lake Victoria region, included groups defined by the use of "Kansyore" ceramics (Dale and Ashley, 2010). Lacking sources of high-quality obsidian in the immediate vicinity, fisher-foragers in the Lake Victoria region relied primarily on local quartz sources. Merrick and Brown (1984b) report that, in "Early Kansyore" (~8000–7000 cal BP) contexts, obsidian is sparse and derives from a variety of sources near Lake Naivasha, including Mt. Eburru, ~200 km to the east (Fig. 2). This lies well beyond the known boundaries of Kansyore material culture. Therefore, small-scale acquisition of distant obsidians likely reflects varied forms of exchange among the diverse foragers occupying the Central Rift Valley and the Loita-Mara plains (Ambrose, 1998). When pastoralists linked to "Elmenteitan" material culture become archaeologically visible near Lake Victoria in the late Holocene, obsidian is more abundant in Kansyore assemblages and originates primarily from Mt. Eburru (Merrick and Brown, 1984a, b). Obsidian in Kansyore assemblages, we propose, reflects changes through time in patterns of cultural interaction and exchange. These patterns are relevant for investigating how Kansyore (and other) forager-fishers manipulated their social identities and economic strategies during known periods of demographic and climatic change.

## 2. Archaeological background

Increased monsoonal rainfall regimes fed an expansive system of lakes and rivers in some portions of Africa during the African Humid Phase after ~8000 BP, encouraging the development of complex fisher-forager traditions (e.g., Kuper and Kröpelin, 2006; Kusimba, 2013; Stojanowski et al., 2014). The nature of the archaeological and behavioral variability among late Holocene foragers in eastern Africa remains poorly understood (Wilshaw, 2016). The Kansyore tradition, one of the better-described archaeological complexes, is identified on the basis of its distinctively decorated ceramics (Dale and Ashley, 2010). Kansyore deposits are most abundant near Lake Victoria, where they occur at open-air riverine sites, lakeshore shell middens, and rock shelters. Kansyore-producing forager-fishers used a quartz-based LSA lithic industry and exploited a broad range of terrestrial and aquatic faunas (e.g., Dale et al., 2004; Prendergast, 2010; Seitsonen, 2010). Their economies were perhaps based on "moderate return" strategies that might have resulted from low residential mobility and a focus on seasonally variable subsistence practices, such as fishing, shellfish acquisition, wild game hunting, and plant and honey collection. Available chronological evidence suggests the existence of "Early" (~8000–7000 BP) and "Late/Terminal" (~3000–1500 BP) phases of the Kansyore tradition, but there is still a notable chronological gap that requires further investigation (Dale and Ashley, 2010; Prendergast et al., 2014). Obsidian source data from Early Kansyore strata at White Rock Point and Luanda (Robertshaw et al., 1983; Merrick and Brown, 1984b) indicate that obsidian is sparse (1.3–7.5% of the lithic assemblages), with 25% of the obsidian originating from Mt. Eburru and the remainder from other sources located near Lake Naivasha. These and other data (Faith et al., 2015) attest to well-established late Pleistocene–Holocene systems of obsidian acquisition in the Lake Victoria region well before the local introduction of pastoralist economies.

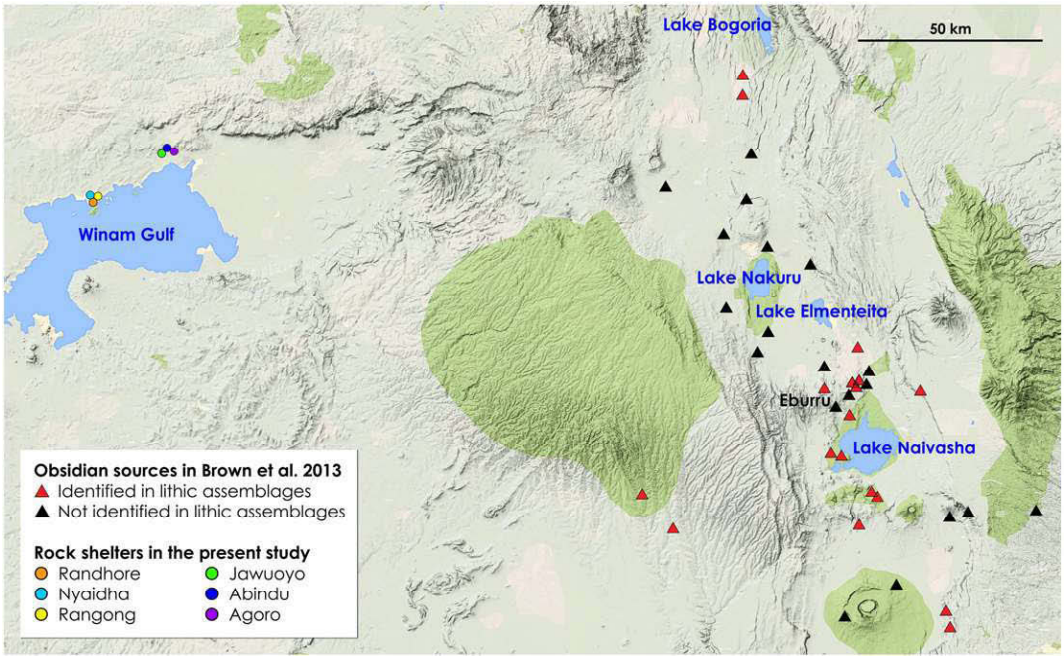


**Fig. 2.** Locations of Kenyan obsidian sources (triangles) in the Naivasha-Nakuru region published by Brown et al. (2013) and the six Late/Terminal Kansyore rock shelters in this study (circles). Obsidians that Brown et al. (2013) reported in archaeological assemblages are denoted by red triangles, while obsidians not identified in assemblages are denoted by black triangles. Background map source: Google Maps.

**Table 1**
In a "round robin" test conducted by Glascock (1999), eight labs, all experienced in obsidian sourcing, provided ten datasets for two geological specimens: one from Sierra de Pachuca and one from Little Glass Buttes. Additionally, a newer dataset for each specimen is also shown: Glascock (2011) for Sierra de Pachuca and Frahm and Feinberg (2015) for Little Glass Buttes. The mean element concentrations across all labs are shown in the first column, and for each dataset, percent relative difference is calculated relative to the mean values, which can be considered as the best available "true" values (i.e., the values against which accuracy could be judged). The pXRF data in Frahm and Feinberg (2015) for Little Glass Buttes yielded some of the most accurate values (relative difference: 7% mean, 6% trimmed mean), demonstrating that portable instruments can be highly accurate.

| | | Sierra de Pachuca, Hidalgo, Mexico | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Glascock, 2011 | | Glascock, 1999 | | | | | | | | | | | | | | | | | | |
| | Mean | MURR | | MURR | | CNRS Orléans | | | | Rio | | CNRS Grenoble | | | | ANSTO | | Rome | | Ashe Analytics | | NW Obsidian | | Mean |
| | Value | EDXRF | %Diff | NAA | %Diff | NAA | %Diff | LA-ICP-MS | %Diff | AES/MS | %Diff | AES/MS | %Diff | PIXE | %Diff | PIXE/PIGME | %Diff | WDXRF | %Diff | EDXRF | %Diff | EDXRF | %Diff | %Diff |
| Ba | 18 | | | 30 | 51 | 21 | 17 | 9 | 65 | 13 | 31 | 17 | 4 | | | | | | | 20 | 12 | 14 | 23 | 29 |
| Ca | 1052 | | | | | 1160 | 10 | 2362 | 77 | 640 | 49 | 750 | 33 | 769 | 31 | 894 | 16 | 786 | 29 | | | | | 35 |
| Fe | 16,773 | 15,900 | 5 | 15,800 | 6 | 17,200 | 3 | 16,600 | 1 | 16,600 | 1 | 16,200 | 3 | 15,600 | 7 | 18,100 | 8 | 18,900 | 12 | 16,400 | 2 | 17,200 | 3 | 5 |
| Mn | 1064 | 797 | 29 | 1149 | 8 | 990 | 7 | 1048 | 2 | 837 | 24 | 1231 | 15 | 1008 | 5 | 1265 | 17 | 1161 | 9 | 1095 | 3 | 1124 | 5 | 11 |
| Nb | 94 | 84 | 11 | | | 91 | 3 | 116 | 21 | 84 | 11 | 91 | 3 | 97 | 3 | | | 91 | 3 | 91 | 3 | 99 | 5 | 7 |
| Rb | 202 | 189 | 7 | 192 | 5 | 219 | 8 | 203 | 0 | 181 | 11 | 185 | 9 | 211 | 4 | 224 | 10 | 194 | 4 | 200 | 1 | 225 | 11 | 6 |
| Sr | 4 | 10 | 88 | | | | | 2 | 64 | 2 | 64 | 2 | 64 | | | 3 | 25 | 5 | am | 2 | 64 | 5 | 25 | 52 |
| Ti | 1120 | 945 | 17 | | | 1300 | 15 | 1190 | 6 | 1050 | 6 | 1049 | 7 | 1028 | 9 | 1118 | 0 | 1258 | 12 | | | 1141 | 2 | 8 |
| Zn | 224 | 207 | 8 | 191 | 16 | 240 | 7 | 210 | 6 | 206 | 8 | | | 221 | 1 | 292 | 26 | | | 224 | 0 | 224 | 0 | 8 |
| Zr | 985 | 957 | 3 | 888 | 10 | 1020 | 3 | 1058 | 7 | 796 | 21 | 1005 | 2 | 1008 | 2 | 1097 | 11 | 1055 | 7 | 991 | 1 | 965 | 2 | 6 |
| Mean: | | | 21 | | 16 | | 8 | | 25 | | 23 | | 16 | | 8 | | 14 | | 13 | | 11 | | 9 | 17 |
| Trimmed mean: | | | 13 | | 10 | | 7 | | 22 | | 20 | | 11 | | 5 | | 15 | | 11 | | 4 | | 7 | 14 |

| | | Little Glass Buttes, Oregon, United States | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Frahm and Feinberg, 2015 | | Glascock, 1999 | | | | | | | | | | | | | | | | | | |
| | Mean | Minnesota | | MURR | | CNRS Orléans | | | | Rio | | CNRS Grenoble | | | | ANSTO | | Rome | | Ashe Analytics | | NW Obsidian | | Mean |
| | Value | pXRF | %Diff | NAA | %Diff | NAA | %Diff | LA-ICP-MS | %Diff | AES/MS | %Diff | AES/MS | %Diff | PIXE | %Diff | PIXE/PIGME | %Diff | WDXRF | %Diff | EDXRF | %Diff | EDXRF | %Diff | %Diff |
| Ba | 1232 | 1265 | 3 | 1270 | 3 | 1550 | 23 | 1080 | 13 | 843 | 37 | 1237 | 0 | | | | | | | 1270 | 3 | 1338 | 8 | 11 |
| Ca | 5996 | 5878 | 2 | | | 5900 | 2 | 6813 | 13 | 5432 | 10 | 6219 | 4 | 5565 | 7 | 6230 | 4 | 5933 | 1 | | | | | 5 |
| Fe | 6491 | 5939 | 9 | 6200 | 5 | 6500 | 0 | 6840 | 5 | 6100 | 6 | 6500 | 0 | 6070 | 7 | 7020 | 8 | 7900 | 20 | 5730 | 12 | 6600 | 2 | 7 |
| Mn | 323 | 337 | 4 | 327 | 1 | 297 | 8 | 269 | 18 | 303 | 6 | 333 | 3 | 291 | 10 | 357 | 10 | 387 | 18 | 298 | 8 | 349 | 8 | 9 |
| Nb | 8 | 8 | 3 | | | 12 | 37 | 9 | 9 | 8 | 3 | 8 | 3 | | | | | 6 | 32 | 7 | 16 | 8 | 3 | 13 |
| Rb | 99 | 94 | 6 | 95 | 4 | 110 | 10 | 97 | 2 | 95 | 4 | 94 | 6 | 105 | 6 | 109 | 9 | 97 | 2 | 96 | 3 | 101 | 2 | 5 |
| Sr | 73 | 78 | 7 | 78 | 7 | | | 52 | 33 | 66 | 10 | 87 | 18 | 73 | 0 | 81 | 11 | 71 | 3 | 69 | 5 | 73 | 0 | 9 |
| Ti | 655 | 778 | 17 | | | 690 | 5 | 595 | 10 | 600 | 9 | 527 | 22 | 788 | 18 | 691 | 5 | 659 | 1 | | | 570 | 14 | 11 |
| Zn | 38 | 38 | 0 | 31 | 21 | 90 | 81 | 27 | 34 | 29 | 27 | | | 27 | 34 | 36 | 6 | | | 24 | 45 | 41 | 7 | 28 |
| Zr | 102 | 85 | 18 | 118 | 15 | 99 | 3 | 83 | 20 | 106 | 4 | 106 | 4 | 105 | 3 | 107 | 5 | 105 | 3 | 96 | 6 | 109 | 7 | 8 |
| Mean: | | | 7 | | 8 | | 19 | | 16 | | 12 | | 7 | | 11 | | 7 | | 10 | | 12 | | 6 | 11 |
| *Trimmed mean:* | | | 6 | | 7 | | 13 | | 15 | | 10 | | 5 | | 9 | | 7 | | 8 | | 9 | | 5 | 9 |

In the Lake Victoria region south of the Winam Gulf (Figs. 1 and 2), archaeological deposits containing Kansyore ceramics are overlain by assemblages produced by stone-tool-using mobile pastoralists associated with the Elmenteitan tradition (after ~2000 cal. BP) and, subsequently, iron-using farmers with Urewe ceramics (by ~1200 cal. BP). North of the Winam Gulf, Kansyore strata are directly overlain directly by those containing Urewe ceramics at multiple localities (Lane, 2004). There is evidence (albeit from potentially mixed contexts) of domesticated livestock entering Late/Terminal Kansyore economies (Gabel, 1969; Karega-Mũnene, 2002; Lane et al., 2007; Prendergast, 2010), and environmental data (Chritz et al., 2015) establish the suitability of the eastern margins of Lake Victoria for livestock during the late Holocene. These occasional traces of domestic fauna (cattle, sheep, goats) at Late/Terminal Kansyore sites have been interpreted as the outcome of limited contact with immigrating Elmenteitan pastoralist groups, but whether the traces reflect the exchange of individual animals with pastoralists, raiding of pastoralist livestock, or partial integration of herding into a foraging economy remains unclear (Karega-Mũnene, 2002; Lane et al., 2007; Prendergast, 2010).

Elmenteitan sites are identified by their uniform ceramic style and features of lithic technology. The latter includes small (~15–20 mm) microliths and large (~5–10 cm), heavily used blades that were produced by the punch technique and often segmented (Ambrose, 1984). Economies in Elmenteitan sites of the Loita-Mara region (e.g., Ngamuriak and Sambo Ngige) indicate a nearly exclusive reliance on domesticated cattle, sheep, and goat, whereas fish (and wild game) were also exploited at Gogo Falls, closer to lake Victoria (Marshall and Stewart, 1994; Robertshaw, 1988, 1991). Unlike Kansyore sites, where local stone materials predominate, Elmenteitan lithic assemblages are dominated by obsidian, regardless of their distance to the nearest source. Obsidian constitutes 71.4–98.3% of Elmenteitan lithic assemblages from Gogo Falls (~230 km linearly from the Lake Naivasha sources), Sambo Ngige (~170 km), and Ngamuriak (~100 km; Robertshaw, 1988, 1991), and it occurs with similar abundance at other sites (Olopilukunia, ~120 km, Siiriäinen, 1990; Wadh Lang'o, ~170 km, Lane et al., 2007). There is a consensus that the Elmenteitan pattern of obsidian access reflects some variety of regional exchange or distribution network (Ambrose, 2001; Gifford-Gonzalez, 1998; Goldstein, 2014; Robertshaw, 1988). Strikingly, Elmenteitan obsidian artifacts are largely (67%) from Mt. Eburru (Merrick and Brown, 1984a, 1984b; Merrick et al., 1988).

The Mt. Eburru source was used extensively despite the presence of closer sources west of Lake Naivasha (~10–20 km away). Elmenteitan groups did not exploit the nearest sources of similarly high-quality raw material as might be predicted by least-cost principles. Other obsidian sources, particularly those west of Lake Naivasha, seem to have been favored by contemporary but archaeologically distinct populations attributed to the Savanna Pastoral Neolithic (SPN), sites of which are not found on the margins of Lake Victoria. These patterns imply that, among Late Holocene pastoralist groups, there was a form of culturally mediated restrictions to obsidian sources (Ambrose, 2012).

Early Kansyore foragers during the early-mid Holocene apparently used obsidian sparingly, and when they did, it originated from various sources. In contrast, Elmenteitan pastoralists used obsidian in abundance and primarily from a single source (Mt. Eburru). The extent to which obsidian acquisition and use changed during the later Holocene at Late/Terminal Kansyore and other sites provides insights about the nature of differentiation and interaction among populations who made these archaeological complexes. While insufficient in isolation, obsidian sourcing data can complement insights based on stratigraphic, chronological, ceramic, lithic, and faunal datasets. We begin these comparisons by presenting our new chemical source attributions, based on pXRF analyses, for a collection of 78 obsidian artifacts from six late Holocene fisher-forager assemblages, which likely reflect Late/Terminal Kansyore material culture, from the northeastern shores of Lake Victoria.

## 3. Terminology notes: “sources” and “pXRF”

It is worth briefly addressing how an individual obsidian “source” is conceptualized in this paper. The literature includes a plethora of terms to define and distinguish obsidian sources and hierarchies among them (see discussions in Green, 1998; Hughes, 1998; Frahm, 2014b). There are two principal ways in which an obsidian “source” is conceptualized and defined: geographically (i.e., a location on the land) and chemically (i.e., a cluster in chemical data). The difference is whether a source is described by a dot on a map or by a cluster in a plot of chemical data. Ideally, of course, one dot is the same as one cluster, but it is rarely so simple as each outcrop exhibiting a unique chemical composition. There are advocates for both geographical (Harbottle, 1982; Neff, 1998) and chemical (Hughes, 1998; Wilson and Pollard, 2001) definitions of a source, and both have appropriate applications.

Brown et al. (2013) favor the chemical definition of an obsidian source, but they also report named geographical locales, reflecting how obsidian is collected on the landscape. If different locales have obsidian with the same elemental composition (“fingerprint”), Brown et al. (2013) group them together into one chemical source. For example, twelve obsidian specimens from seven locations on Mt. Eburru comprise one source (“Eburru GsJj 50, north slope, hilltop, and steam jets”). Obsidian from these different locations might vary in color, texture, or other physical properties. Chemically, however, the obsidian is identical because its expression in different locations seems to represent one volcanic eruption. In addition, based on our fieldwork, we can identify the Eburru and major Naivasha sources as primary, not secondary, obsidian sources. For example, the GsJj 50 locale is a primary exposure that covers an area ~200 × 20 m, and other Eburru locales are similar. The Naivasha sources are more variable. Some sources are obsidian flows that extend nearly 2000 m, whereas others are exposures ~200–800 $m^2$ in area. Occasionally a source is exposed in only spot or across an entire hillside, leading to a colluvial scatter no more than a few hundred meters in size. Sparse Quaternary rivers cutting through the southern Kenya Rift or draining into Lake Victoria mean that there were few, if any, opportunities for obsidians to be spread across large areas.

Brown et al. (2013) tend to be “splitters” rather than “lumpers” when chemically defining sources. If, for example, two obsidian specimens differ by more than one standard deviation for any of five key elements (i.e., Al, Fe, Ca, Cl, Ti), they defined them as different sources (Brown et al., 2013:3235). Sometimes Brown et al. (2013) defined a source on the basis of only a handful of specimens, occasionally just one or two. This reflects, in part, the challenges of collecting specimens on such an obsidian-rich landscape.

Because we use their data in this paper, we follow the sources as chemically defined by Brown et al. (2013), except when elements we favor (i.e., Zr, Rb, Nb, Sr, Fe, Mn) imply no appreciable difference exists between two sources. Accordingly, the “GsJj 50” locale is not distinguished from other nearby outcrops with obsidian chemically assigned to the “Eburru” source; however, our observations suggest that such distinctions may be possible based on variability in color and texture. Greater specificity might also eventually be possible using quantitative means. In particular, we have sampled the Mt. Eburru obsidian quarries and outcrops with sufficient intensity such that we might be able to quantify spatial differences using rock magnetic characterization (Frahm and Feinberg, 2013a).

It should be stressed that here “pXRF” refers to the handheld instruments about the size, shape, and mass of a cordless drill. Some (e.g., Craig et al., 2007; Liritzis and Zacharias, 2011) consider “pXRF” to include small benchtop instruments that, indeed, have been used to good effect (e.g., Cecil et al., 2007; Liritzis, 2008). Our focus here, however, is the class of ruggedized instruments that can be used equally well in a museum or in the field. It should also be emphasized that pXRF technologies have advanced so much that any performance appraisals more than a few years old are essentially obsolete (e.g., Cesareo et al., 2008; Potts and West, 2008; Williams-Thorpe, 2008; Pessanha et al.,

2009). The X-ray detectors and associated electronics found in a recent pXRF instrument are more sensitive than those in most benchtop models five or ten years ago (Speakman and Shackley, 2013). For example, after a 40-second measurement using our instrument, the detection limit for Sr and Rb was 1–2 ppm for flaked surfaces (i.e., not polished or powdered) of obsidian.

The list of settings where pXRF has been successfully employed in obsidian sourcing has grown markedly in recent years. It has been used, for example, in Eurasia (e.g., Frahm, 2007, 2013, 2014a; Carter, 2009; Jia et al., 2010, 2013; Tykot et al., 2011, 2013; Forster and Grave, 2012; Frahm and Feinberg, 2013b, c; Adler et al., 2014; Frahm et al., 2014a, b, c; Milić, 2014), Oceania (e.g., Golitko et al., 2010, 2012; Sheppard et al., 2010, 2011; Burley et al., 2011; Golitko, 2011; McCoy et al., 2011, 2014; Torrence et al., 2012; Galipaud et al., 2014; Lawrence et al., 2014; Mulrooney et al., 2014), North America (e.g., Millhauser et al., 2011, 2015; Goodale et al., 2012; Mills et al., 2013; Moholy-Nagy et al., 2013; Rodríguez-Alegría et al., 2013; Ebert et al., 2014; Frahm and Feinberg, 2015; Reimer, 2015), and South America (e.g., Craig et al., 2010; Vázquez et al., 2012; Williams et al., 2012; Kellett et al., 2013).

## 4. Dataset compatibility: what is good enough?

Demonstrating compatibility of our pXRF dataset with those of Brown et al. (2013) is crucial to establishing confidence in our findings. To avoid judgmental determinations of data compatibility, we quantitatively compared obsidian datasets reported in the literature, especially when researchers found them in sufficient agreement to use together.

In one example, Glascock (1999) reports the datasets from a "round robin" in which eight laboratories submitted their values for Sierra de Pachuca (Hidalgo, Mexico) and Little Glass Buttes (Oregon, USA) obsidians (Table 1). The labs used varied analytical techniques (e.g., EDXRF, WDXRF, NAA, ICP-MS, PIXE/PIGME) and, in turn, approaches to calibration, increasing the variability among them. The use of pXRF to characterize Little Glass Buttes obsidian yielded values with above-average accuracy relative to the other datasets (i.e., 7% difference relative to the mean values for all datasets, which, on average, had 11% relative difference; Frahm and Feinberg, 2015). Use of obsidian standards characterized with NAA at MURR also means that the pXRF measurements exhibited good agreement (9% relative difference on average) with the MURR dataset (Table 2), while researchers using different calibrations report values with greater disparities (>16% difference on average). When the highest and lowest disparities are ignored, the pXRF data agree with the MURR NAA data almost as well as the MURR EDXRF data do (6% vs. 4% on average, respectively). Glascock (2011) argues that, for elements of interest, MURR "data on obsidian samples measured by XRF can be compared directly to [data] collected by NAA" (191). This suggests a difference ~5% relative, on average, would be sufficient for compatible datasets.

In a second example, Shackley (2012b) contends, regarding EDXRF in three North American obsidian sourcing labs, that "most of the measurements are within 1%" (see also "often only 1%" in Shackley, 2011a:33). Published measurements from these facilities do not support such claims (Table 3). Instead, data for the RGM-1 obsidian standard, averaged over ten publications, vary with an overall mean of 6% relative. The individual datasets can differ overall by 4 to 9% relative averaged across seven trace elements. Only Zr exhibits an average difference of 1% among the datasets, followed by Rb and Fe (3%). Clearly, though, the Berkeley Geoarchaeological XRF Lab had sufficiently consistent data that source values from one analytical session could be compared to artifact data from another. Furthermore, Shackley (2012b) states that these laboratories routinely use each other's data. It is clearly the case that a standard of "within 1%" is both unrealistic and unnecessary.

In summary, a goal of 5% or less relative difference between datasets is achievable and certainly sufficient for compatible values, whereas a relative difference of 10% or less, at least for certain elements, is likely still sufficient for dataset compatibility. We show that our pXRF data attain such agreement with those in Brown et al. (2013). Seeking to attain even higher dataset agreement (e.g., ≤1%) is impractical. As established in Table 3, EDXRF variability is rarely better than 4% relative over time, even with the same instrument in the same laboratory following the same analytical procedures. Furthermore, concentrations of trace elements can vary slightly within an individual obsidian source. In a pioneering study on this subject, Laidley and McKay (1971) sampled Big Obsidian Flow (Newberry Volcano, Oregon, USA) at 30-m intervals across a 1500-m transect. Their WDXRF data revealed that, while statistically insignificant for most elements, elemental concentrations varied by more than the analytical uncertainties. For example, Rb had an uncertainty of 1.4% relative, but it varied by 3.1% relative across the transect. Furthermore, elements such as Fe, Ti, and Ca all varied by 1–2% relative across the flow. Consequently, striving for <1–2% relative difference between datasets is, in most instances, statistical overkill.

## 5. Analytical conditions

Here we report the details of our pXRF instrument, its operation, how the raw data were corrected for various physical effects within specimens, and the factory-set calibration which we "fine tuned" for direct compatibility with the published Brown et al. (2013) values.

**Table 2**
The pXRF data in Frahm and Feinberg (2015) were calibrated, in part, using NAA and EDXRF data from the University of Missouri's Research Reactor (MURR) for a series of matched obsidian specimens. This yields greater compatibility with MURR datasets (i.e., a lower relative difference) than other calibration approaches in other recent publications.

| | Sierra de Pachuca, Mexico | | | Little Glass Buttes, Oregon, United States | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Glascock, 1999 | Glascock, 2011 | | Glascock, 1999 | Frahm and Feinberg, 2015 | | Millhauser et al., 2015 | | Millhauser et al., 2011 | | Scharlotta, 2010 | |
| | MURR | MURR | | MURR | Minnesota | | Field Museum | | Field Museum | | IIRMES | |
| | NAA | EDXRF | %Diff | NAA | pXRF | %Diff | pXRF | %Diff | pXRF | %Diff | LA-TOF-ICP-MS | %Diff |
| Ba | 30 | | | 1270 | 1265 | 0 | 904 | 34 | 776 | 48 | 1173 | 8 |
| Ca | | | | | 5878 | | | | 5134 | | 2652 | |
| Fe | 15,800 | 15,900 | 1 | 6200 | 5939 | 4 | 5713 | 8 | 5408 | 14 | 5353 | 15 |
| Mn | 1149 | 797 | 36 | 327 | 337 | 3 | 272 | 18 | 227 | 36 | 299 | 9 |
| Nb | | 84 | | | 8 | | | | 6 | | | |
| Rb | 192 | 189 | 2 | 95 | 94 | 1 | 100 | 5 | 101 | 6 | 79 | 18 |
| Sr | | 10 | | 78 | 78 | 0 | 73 | 7 | 73 | 7 | 45 | 54 |
| Ti | | 945 | | | 778 | | | | 572 | | 420 | |
| Zn | 191 | 207 | 8 | 31 | 38 | 20 | 26 | 18 | 32 | 3 | 27 | 14 |
| Zr | 888 | 957 | 7 | 118 | 85 | 33 | 93 | 24 | 91 | 26 | 64 | 59 |
| Mean: | | | 11 | | | 9 | | 16 | | 20 | | 25 |
| Trimmed mean: | | | 4 | | | 6 | | 15 | | 18 | | 22 |

**Table 3**
Element values for the powdered obsidian standard RGM-1 (U.S. Geological Survey Glass Mountain rhyolitic obsidian) from laboratories in the United States that offer obsidian sourcing as an analytical service. Shackley (2012b) claims that, for these laboratories, "most of the measurements are within 1%" (also "often only 1%" in Shackley, 2011a:33). However, data from these publications vary with an overall mean of 6% relative. Individual datasets can differ overall, on average, by 4 to 9% relative. Only Zr has an average difference of 1% among the datasets, followed by Rb and Fe (3%).

| | Cited in Shackley, 2012b | | | | | | | Other Berkeley data | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speakman and Shackley, 2013 | | | Skinner and Davis, 1996 | | Hughes, 2007 | | Negash and Shackley, 2006 | | Carter and Shackley, 2007 | |
| | Berkeley | Georgia CAIS | | NW Obsidian | | Geochem Res | | Berkeley | | Berkeley | |
| | Mean | Mean | %Diff | Mean | %Diff | Mean | %Diff | Mean | %Diff | Mean | %Diff |
| Mn | 302 | 321 | 6 | 291 | 4 | 278 | 8 | 308 | 2 | 278 | 8 |
| Fe | 13,116 | 13,075 | <1 | 13,480 | 3 | 13,079 | <1 | 13,988 | 6 | 14,212 | 8 |
| Rb | 151 | 157 | 4 | 152 | 1 | 143 | 5 | 154 | 2 | 153 | 1 |
| Sr | 106 | 104 | 2 | 107 | 1 | 105 | 1 | 113 | 6 | 114 | 7 |
| Y | 25 | 26 | 4 | 24 | 4 | 23 | 8 | 22 | 13 | 23 | 8 |
| Zr | 219 | 223 | 2 | 217 | 1 | 214 | 2 | 224 | 2 | 221 | 1 |
| Nb | 9 | 10 | 11 | 11 | 20 | 8 | 12 | 8 | 12 | 9 | <1 |
| Mean: | | | 4 | | 5 | | 5 | | 6 | | 5 |
| Trimmed: | | | 4 | | 2 | | 5 | | 6 | | 5 |

| | | Other Berkeley data | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Shackley, 2009 | | Craig et al., 2007 | | Dillian et al., 2010 | | Ogburn et al., 2009 | | Doronicheva and Shackley, 2014 | |
| | | Berkeley | | Berkeley | | Berkeley | | Berkeley | | Berkeley | |
| | Overall average %Diff | Mean | %Diff | Mean | %Diff | Mean | %Diff | Mean | %Diff | Value | %Diff |
| Mn | 6 | 292 | 3 | 340 | 12 | 313 | 4 | 322 | 6 | 296 | 2 |
| Fe | 3 | 12,806 | 2 | 13,251 | 1 | 13,299 | 1 | 12,778 | 3 | 13,676 | 4 |
| Rb | 3 | 145 | 4 | 152 | 1 | 148 | 2 | 148 | 2 | 143 | 5 |
| Sr | 4 | 103 | 3 | 112 | 6 | 110 | 4 | 102 | 4 | 104 | 2 |
| Y | 8 | 23 | 8 | 20 | 22 | 22 | 13 | 25 | <1 | 26 | 4 |
| Zr | 1 | 221 | 1 | 223 | 2 | 218 | <1 | 213 | 3 | 220 | <1 |
| Nb | 14 | 7 | 25 | 9 | <1 | 6 | 40 | 10 | 11 | 10 | 11 |
| Mean: | 6 | | 7 | | 6 | | 9 | | 4 | | 4 |
| Trimmed: | 5 | | 4 | | 4 | | 5 | | 4 | | 3 |

**Table 4**
List of 27 obsidian specimens from Brown et al. (2013) analyzed by pXRF for this study. The first twelve specimens were used to calibrate the instrument, while the second batch of fifteen was measured for reproducibility checks.

| Specimen | Merrick & Brown | Brown et al., 2013 | | | | |
|---|---|---|---|---|---|---|
| | Chemical Type | Source/location | Source group/area | Source region | N. Lat. | E. Long. |
| **Calibration standards, n = 12** | | | | | | |
| MER 31 | Type 20 | Hell's Gate #1 | Ol Karia Group, South Naivasha | Naivasha-Nakuru | −0.88 | 36.34 |
| MER 36 | Type 8 | Kisanana | Kisanana and Mugerin | Mt. Kenya/Baringo | 0.03 | 36.06 |
| MER 40 | Type 9 | Kabazi | Kampi ya Moto, Kabazi, Rigo Cave | Mt. Kenya/Baringo | −0.08 | 36.17 |
| MER 42 | Type 11 | Mackinder #2 | Mackinder Valley, Mt. Kenya | Mt. Kenya/Baringo | −0.12 | 37.29 |
| MER 63 | Type 6 | Karau, Lake Baringo Region | Karau, Kampi ya Samaki, Lokoritabim | Mt. Kenya/Baringo | 0.62 | 36.19 |
| MER 65 | Type 6 | Karau, Lake Baringo Region | Karau, Kampi ya Samaki, Lokoritabim | Mt. Kenya/Baringo | 0.62 | 36.19 |
| MER 68 | Type 14 | Gicheru Diatomite Quarry | South Kenya Rift Valley | Southern Kenya | −1.19 | 36.55 |
| MER 71 | Type 32 | Ilkek | Mt. Eburru, West Lake Naivasha | Naivasha-Nakuru | −0.59 | 36.37 |
| MER 74 | Type 35 | Opuru | Mt. Eburru, West Lake Naivasha | Naivasha-Nakuru | −0.59 | 36.25 |
| MER 80 | Type 15 | Magadi East | South Kenya Rift Valley | Southern Kenya | −1.82 | 36.30 |
| MER 82 | Type 20 | Njorowa Gorge South | Ol Karia Group, South Naivasha | Naivasha-Nakuru | −0.96 | 36.31 |
| MER 113 | Type 53 | Kijabe Escarpment Road | – | Southern Kenya | −1.08 | 36.60 |
| **Reproducibility checks, n = 15** | | | | | | |
| MER 34 | Type 22 | Akira Ranch | – | Southern Kenya | −0.99 | 36.31 |
| MER 38 | Type 9 | Kampi ya Moto #2 | Kampi ya Moto, Kabazi, Rigo Cave | Mt. Kenya/Baringo | −0.11 | 35.95 |
| MER 45 | Type 12 | Mangu | – | Southern Kenya | −1.00 | 36.95 |
| MER 69 | Type 14 | Gicheru Diatomite Quarry | South Kenya Rift Valley | Southern Kenya | −1.19 | 36.55 |
| MER 70 | Type 32 | Ilkek | Mt. Eburru, West Lake Naivasha | Naivasha-Nakuru | −0.59 | 36.37 |
| MER 75 | Type 35 | Opuru | Mt. Eburru, West Lake Naivasha | Naivasha-Nakuru | −0.59 | 36.25 |
| MER 76 | Type 27 | Cedar Hill South | Mt. Eburru, West Lake Naivasha | Naivasha-Nakuru | −0.61 | 36.27 |
| MER 83 | Type 20 | Njorowa Gorge South | Ol Karia Group, South Naivasha | Naivasha-Nakuru | −0.96 | 36.31 |
| MER 96 | Type 24 | Kinangop Escarpment | Ol Karia Group, South Naivasha | Naivasha-Nakuru | −0.63 | 36.49 |
| MER 99 | Type 31 | West Naivasha #1 | Mt. Eburru, West Lake Naivasha | Naivasha-Nakuru | −0.69 | 36.31 |
| MER 105 | Type 12 | Chania Dam | – | Southern Kenya | −0.88 | 36.84 |
| MER 112 | Type 53 | Kijabe Escarpment Road | – | Southern Kenya | −1.08 | 36.60 |
| MER 115 | Type 29 | Upper Eburru, North Slope | Mt. Eburru, West Lake Naivasha | Naivasha-Nakuru | −0.62 | 36.25 |
| MER 117 | Type 29 | Upper Eburru, Hilltop | Mt. Eburru, West Lake Naivasha | Naivasha-Nakuru | −0.63 | 36.26 |
| MER 119 | Type 29 | Upper Eburru, Hilltop | Mt. Eburru, West Lake Naivasha | Naivasha-Nakuru | −0.63 | 36.26 |

*5.1. Instrument and settings*

Our analyses used a Thermo Scientific Niton XL3t GOLDD instrument. To generate incident X-rays, it has a miniaturized 50-kV, Ag-anode X-ray tube. The tube's voltage and current vary in combination with different X-ray filters during a measurement to optimally fluoresce different portions of the periodic table. The operating conditions were 40 kV and ≤50 μA with the "main" X-ray filter, 20 kV and ≤100 μA with the "low" filter, and 50 kV and ≤40 μA with the "high" filter. As is the case with many modern XRF instruments (Shackley, 2011a), the instrument adjusts the tube current automatically to attain optimal X-ray count rates. To measure the X-rays emitted by a specimen, this instrument is

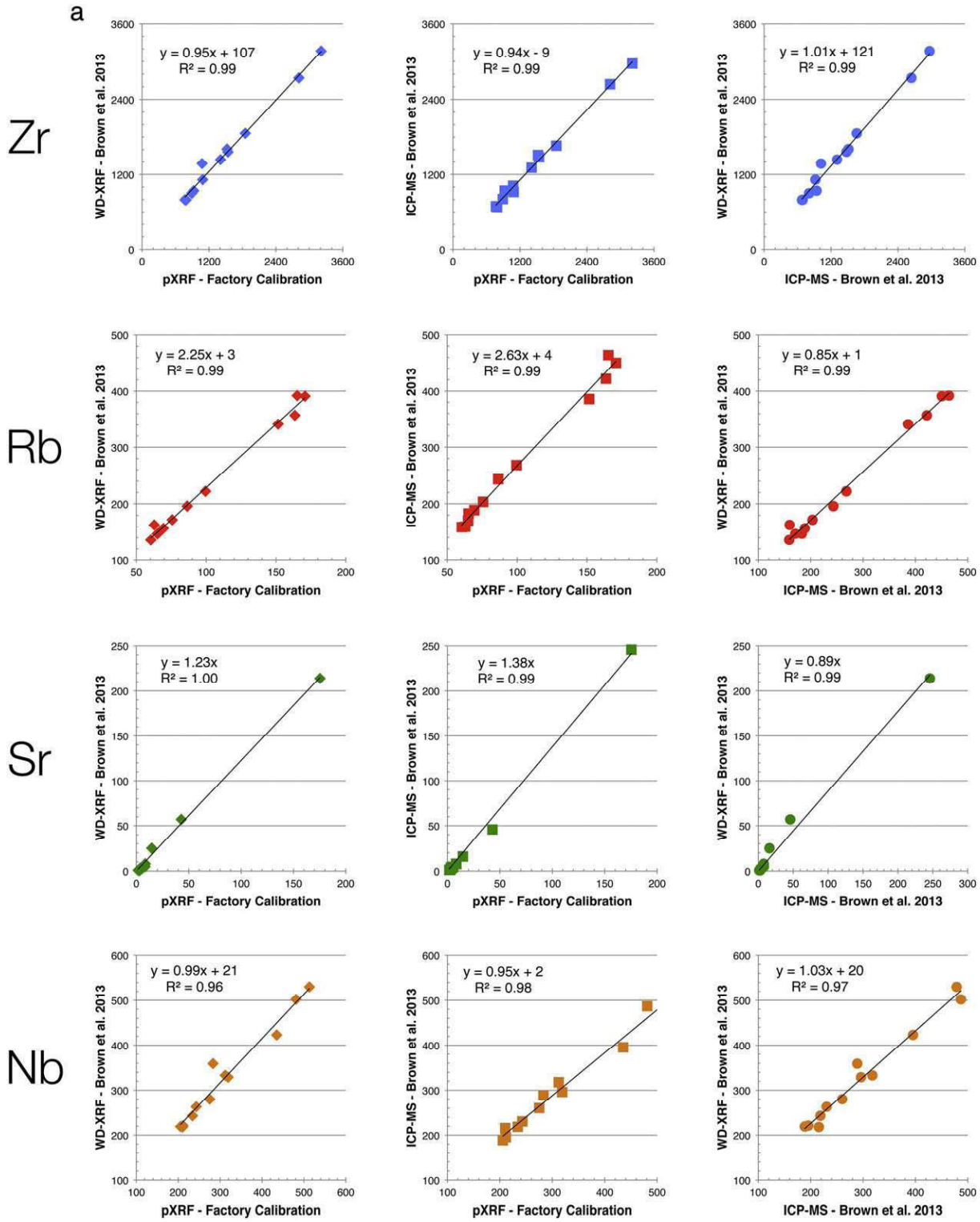


**Fig. 3.** Best-fit lines and correlations (i.e., $R^2$) between our pXRF (with initial factory-set calibration) data and the published datasets from Brown et al. (2013) for a set of twelve matched obsidian specimens (Table 4): pXRF versus WDXRF (diamonds), pXRF versus EMPA (triangles), pXRF versus ICP-MS (squares), and WDXRF and EMPA versus ICP-MS (circles). These equations were used to calibrate our pXRF data to the other datasets. In this case, we calibrated our pXRF data to those from Brown et al. (2013).

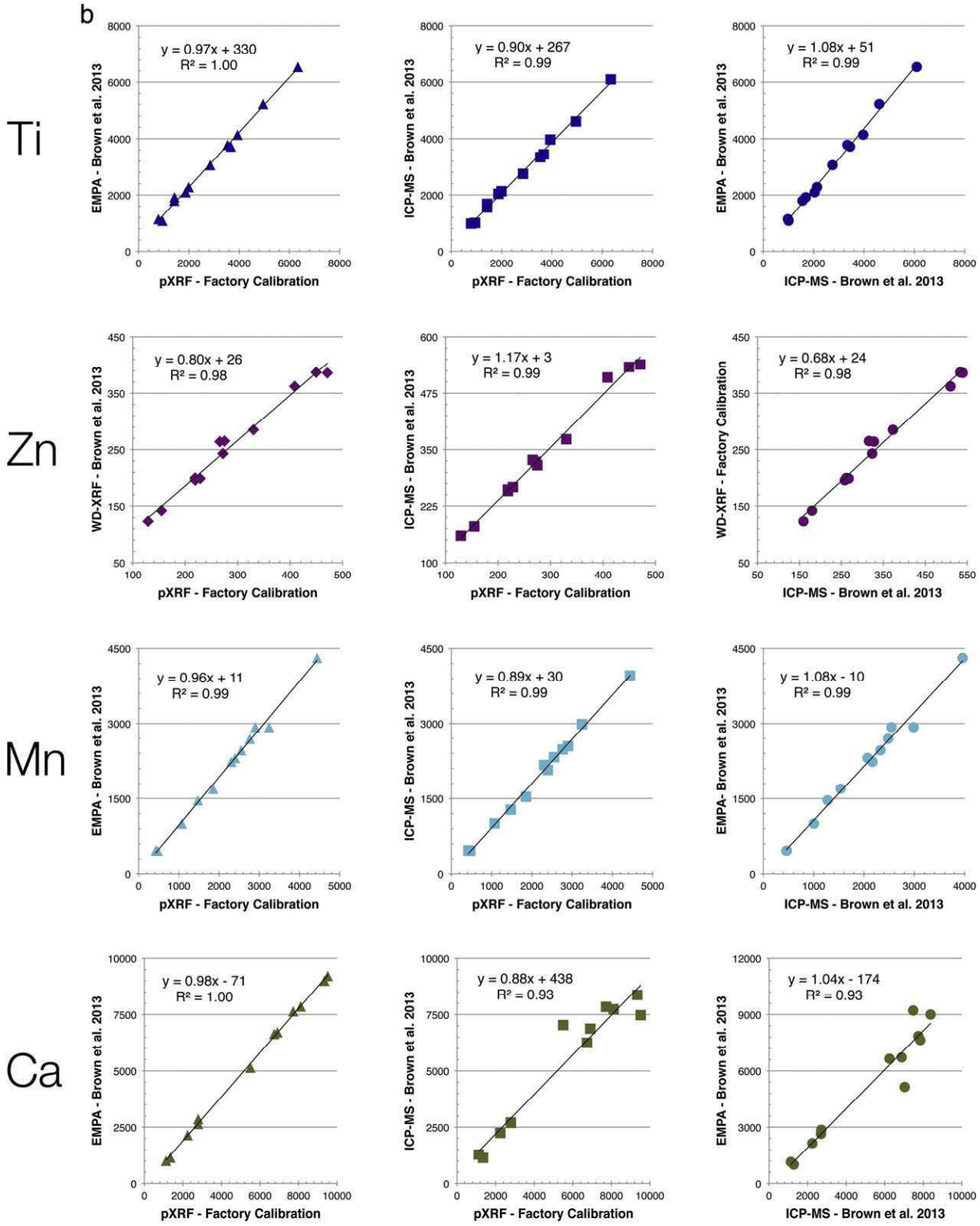


**Fig. 3** (*continued*).

outfitted with a 25-mm$^2$ Si drift detector (SDD) that has an energy resolution ≤155 eV in practice. Ordinarily the X-ray beam is ~8-mm in diameter (~50 mm$^2$), but the instrument is also equipped with a small-spot collimator that can restrict the beam to a ~3-mm diameter (~7 mm$^2$), yielding an analytical area ~85% smaller, well suited for small (<5 mm) artifacts. Measurements with the full-size beam were 120 s (40 s each for three filters), whereas those with the small spot were 90 s (45 s each for two filters). The instrument was mounted in a portable Thermo Scientific SmartStand for the most precise positioning of the geological specimens and artifacts. Although this instrument is equipped to measure >40 elements (including, except for Na, all major elements in obsidians), our focus was a subset of elements well measured both by pXRF and by the techniques used by Brown et al. (2013) since not all techniques have equal sensitivities for all elements.

### 5.2. Correction scheme

Measured X-rays must be "corrected" for a variety of physical phenomena, including inter-element effects, within a specimen (e.g., X-ray absorption and attenuation, secondary and tertiary X-ray fluorescence, photoelectric emission). There are several approaches to correction: empirical methods (e.g., alpha factors, influence coefficients), normalization to a certain phenomenon (e.g., Compton scattering), or physics-based models (e.g., fundamental parameters). We use the fundamental parameters (FP) approach, which, for each analysis, solves a set of nonlinear equations that describes the relationship between X-ray emission intensities and elemental concentrations in a given specimen. FP correction has been used routinely in select XRF applications since the 1990s (de Boer and Brouwer, 1990). Because FP correction involves more intensive calculations than empirical methods (e.g., influence coefficients date back to the 1950s; Sherman, 1955), the addition of powerful processors to pXRF instruments has allowed its implementation. Heginbotham et al. (2010) conducted an inter-laboratory test based on 12 copper alloys measured by 19 different XRF instruments and methods in 14 laboratories worldwide. The single greatest variable in accuracy was the correction scheme. All of the highest ranked instruments used FP calibrated with standards, whereas instruments with empirical correction approaches ranked lower. Heginbotham et al. (2010: 185) report that "it is very clear that laboratories using fundamental parameters software calibrated with standards… performed consistently more accurately than laboratories using other methods," despite each of the top-performing labs using different models and brands. Our choice of calibration standards, specifically a collection of matched Kenyan obsidian specimens from Brown et al. (2013), is discussed in Section 6.

### 5.3. Initial factory-set calibration

Like all modern pXRF instruments from major manufacturers, the instrument has a factory-set calibration. In fact, it has two "internal" calibrations: one for its "mining" mode and one for its "soils" mode. Both calibrations are intended to be flexible and remain stable for a long time. The "mining" calibration is principally geared toward various applications in mining and geological exploration, while the "soils" calibration is optimized to measure soil contaminants in environmental testing and remediation. These factory-set calibrations are tested for accuracy against a set of certified standard reference materials (SRM), largely from the United States' National Institute of Standards and Technology (NIST). The Thermo engineers assessed the "mining" calibration with six metal and phosphorous ores (e.g., NIST SRMs 25d, 113b, and 694) as well as feldspar (NIST SRM 70a). These factory calibrations can yield accurate values for a few elements in obsidian but inaccurate values for others. Given that these calibrations are intended to be broadly applicable across a wide range of values, it is not surprising that, for the narrow concentration ranges in obsidians, further calibration is needed. Fortunately, it is straightforward to adjust the factory-set calibrations using linear regression, as shown here, thereby forming the basis of our custom calibration specifically tailored to the datasets in Brown et al. (2013).

## 6. Calibration approach

There are two approaches to XRF calibration for obsidian artifact sourcing. The two approaches are conceptually similar, and the only significant difference is the compositional range of the standards. In this study, we used a set of obsidian specimens from Brown et al. (2013) as calibration standards to "fine-tune" our data specifically and directly to theirs. As demonstrated in Section 7, this approach yielded directly compatible datasets.

### 6.1. Two calibration approaches

The first strategy is to create a generalized silicate or volcanic rock calibration based on a collection of certified SRM powders, often principally from the United States Geological Survey (USGS). This calibration approach has been favored at Berkeley's Geoarchaeological XRF Laboratory (e.g., Shackley, 1995, 2005, 2011b) and McMaster's Archaeological XRF Lab (e.g., Carter and Contreras, 2012; Carter et al., 2013), among other XRF labs. Only three of Shackley's (2011b) sixteen standards are obsidians (e.g., USGS RGM-1), and the remaining SRMs fall outside the usual compositional range for rhyolitic obsidians and include basalts, andesites, and other volcanics (e.g., USGS AGV-2 and BHVO-2) as well as metamorphic and sedimentary rocks (e.g., USGS SDC-1 and SCO-1). The result is a calibration that is effective for obsidian but also generally applicable to a broader range of volcanic rocks (e.g., Shackley, 2011b, 2012a). The key advantage is that, other things being equal, analytical facilities that calibrate using similar sets of USGS SRMs should produce data having the greatest possible compatibility with the USGS and, consequently, with each other.

The second approach is to calibrate an XRF instrument using a collection of obsidian specimens that have been characterized using several analytical techniques (often NAA and one or two others). This strategy has been favored by MURR (e.g., Glascock, 2011; Ferguson, 2012; Glascock and Ferguson, 2012) and the lead author (e.g., Frahm and Feinberg, 2013b, c, 2015; Frahm, 2014a; Frahm et al., 2014a, b, c), among others. For example, MURR assembled a set of 40 obsidian specimens from American sources and determined their compositions with NAA and two ICP-MS methods as a means to calibrate XRF instruments. When plotted on a total alkali vs. silica (TAS) plot and classified according to Le Maitre et al. (2002), most of the obsidians are rhyolitic ($n = 35$), four are trachytic, and one is an andesitic basalt. This calibration set reflects the compositions of American obsidians, which are predominantly rhyolite (Hughes and Smith, 1993; Glascock, 1994; Shackley, 2005). Shackley (2011a:34) notes that, when selecting calibration standards, "they should exhibit the entire range of variation expected from the rocks to be analyzed." Thus, for typical rhyolitic obsidians, XRF data calibrated using these standards will maximize reproducibility with respect to MURR's NAA and ICP-MS datasets. Similarly, Frahm (2014a) describes a series of 24 obsidian standards from Southwest Asia (i.e., Armenia, Georgia, and Turkey), all rhyolitic, analyzed by NAA and XRF at MURR and EMPA at Minnesota. The resulting pXRF data exhibit high reproducibility with respect to MURR and Minnesota data for rhyolitic obsidians, from Armenia (e.g., Frahm, 2014a; Frahm et al., 2014b) to the Americas (Frahm and Feinberg, 2015).

### 6.2. Issues with past approaches

A key aspect of this study was attaining the greatest possible compatibility with the Kenyan obsidian sources' compositional data in Brown et al. (2013). Accordingly, it did not make sense, with this goal, to calibrate to SRMs from the USGS and other organizations, nor could we simply calibrate with the standards used to generate these datasets. For instance, calibration for EMPA is commonly different than that for XRF. EMPA calibration ordinarily involves a single standard per element, and typically only the major elements are calibrated on a standard close in composition to the unknowns. Thus, Brown et al. (2013) calibrated for Si, Al, and K with their in-house Mineral Mountain obsidian standard, whereas Zr, Ti, and Fe were calibrated with their oxides: $ZrO_2$, $TiO_2$, and $Fe_2O_3$, respectively. Calibration for ICP-MS used a single standard: NIST SRM #610, a synthetic glass. The WDXRF calibration used three standards: USGS G-2 (granite powder, which is no longer available) for Sr and two in-house standards for the other elements. Furthermore, while their EMPA procedures have undergone extensive accuracy testing (e.g., Jochum et al., 2006: Lab 28; Kuehne et al., 2011: Lab 5), we do not have similar assessments of their WDXRF and ICP-MS data. Brown et al. (2013) did, though, compare the WDXRF and ICP-MS

datasets and establish, for example, that WDXRF consistently measured ~85 ppm of Rb for every 100 ppm measured by ICP-MS, meaning that both sets of Rb values cannot be entirely accurate.

Nor was it appropriate to simply use a set of standards based on rhyolitic obsidians from Southwest Asia (e.g., Frahm, 2014a; Frahm et al., 2014b) or the Americas (e.g., Glascock, 2011; Glascock and Ferguson, 2012). As reported by Brown et al. (2013), Kenyan obsidians span much of the compositional range of igneous rocks from rhyolite to phonolite. Based on the compositional analyses summarized by Brown et al. (2013), two-thirds (66%) of the Kenyan obsidian specimens are rhyolitic. The rest are phonolite (18%) and trachyte (16%), according to a TAS plot. Even the rhyolitic obsidians have elemental concentrations outside typical ranges. For example, of their rhyolitic specimens, half (51%) have $FeO_{total}$ above 7 wt.%, almost two-thirds (62%) have Mn above 1000 ppm, most (92%) have Zr above 1000 ppm, and most (90%) have Nb above 200 ppm. These concentrations are outside typical rhyolitic obsidian variability (e.g., Glascock, 1994; Ferguson, 2012), and Shackley (2011a) emphasizes a need for standards to reflect unknowns' full compositional range. Indeed, Ferguson (2012) mentions issues encountered by MURR (e.g., too low Zr and Nb values) when their custom Americas-based obsidian calibration was applied to Kenyan obsidians.

### 6.3. Matched specimens as standards

To maximize compatibility with the obsidian data in Brown et al. (2013), we used a set of 27 obsidian specimens originally analyzed for their study (Table 4), provided to us by Frank Brown. Therefore, we were able to match their data to ours for the same specimens without any uncertainties regarding different source terminology or other potential sources of variation. Twelve of the specimens were selected for use as calibration standards. They were measured using the instrument's factory-set "mining" calibration (see Section 5.3), our values were compared to those of Brown et al. (2013), and linear regression was used to derive calibration equations (Fig. 3). The other fifteen specimens served as independent "secondary standards" to assess the custom calibrations and to demonstrate how well our calibrated pXRF data can replicate values in Brown et al. (2013). Thus, our standards in this study are specifically tailored not only to the chemical range of Kenyan obsidians but also the measurements of Brown et al. (2013), regardless of their accuracy.

Table 5 shows the WDXRF, ICP-MS, and EMPA data from Brown et al. (2013) for the twelve calibration standards. It also shows our pXRF measurements with the initial factory-set calibration. Fig. 3 shows the linear regression analyses of these datasets. These plots illustrate the correlations between the data from WDXRF and pXRF (diamonds), EMPA and pXRF (triangles), ICP-MS and pXRF (squares), and WDXRF or EMPA and ICP-MS (circles) in Table 5. Note that the correlations between the datasets are often very high (i.e., $R^2$ is often 0.98 or better), which is paramount for their compatibility. In fact, as shown in Fig. 3, the pXRF data are as highly correlated to the datasets in Brown et al. (2013) as the Brown et al. (2013) datasets are to each other. We used the equations of these best-fit lines to calibrate our pXRF data specifically to the measurements of Brown et al. (2013).

## 7. Evaluating compatibility between datasets

Once the calibrations based on twelve obsidian specimens from Brown et al. (2013) were applied to our pXRF measurements, the remaining fifteen specimens from Brown et al. (2013) were used as independent "secondary standards" to check the reproducibility and to demonstrate that our measurements are compatible with theirs. First, we plot the values to find the correlations between datasets as well as the slopes of the best-fit lines. Second, we calculate the percent relative difference between the measurements.

### 7.1. Plotting correlation and slope

Fig. 4 shows the checks for our pXRF data calibrated to their WDXRF and EMPA data. The correlations for these elements are high, particularly Zr ($R^2 = 0.99$), Fe (0.99), Rb (0.98), Ti (0.98), Nb (0.96), and Ca (0.96).

**Table 5**
Brown et al. (2013) values (EMPA, WDXRF, ICP-MS) used for calibration and pXRF values using the initial factory-set calibration.

| | Zr | | | Rb | | | Sr | | | Nb | | | Fe | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WDXRF | ICP-MS | pXRF[a] | WDXRF | ICP-MS | pXRF[a] | WDXRF | ICP-MS | pXRF[a] | WDXRF | ICP-MS | pXRF[a] | EMPA | pXRF[a] |
| MER 31 | 1607 | 1512 | 1523 | 392 | 464 | 165 | 1 | 2 | 3 | 333 | 318 | 312 | 29,400 | 26,543 |
| MER 36 | 1860 | 1661 | 1851 | 222 | 268 | 100 | 25 | 16 | 15 | 502 | 487 | 481 | 70,700 | 69,277 |
| MER 40 | 899 | 806 | 892 | 157 | 189 | 69 | 1 | 1 | 2 | 243 | 218 | 234 | 68,040 | 71,166 |
| MER 42 | 1374 | 1020 | 1077 | 163 | 160 | 63 | 214 | 246 | 175 | 359 | 289 | 283 | 41,720 | 44,034 |
| MER 63 | 795 | 692 | 769 | 147 | 171 | 65 | 3 | 4 | 4 | 219 | 189 | 206 | 57,470 | 57,246 |
| MER 65 | 793 | 680 | 790 | 147 | 183 | 65 | 3 | 3 | 4 | 221 | 195 | 211 | 57,330 | 58,958 |
| MER 68 | 1117 | 921 | 1088 | 196 | 243 | 86 | 57 | 46 | 43 | 263 | 230 | 243 | 23,870 | 24,056 |
| MER 71 | 2740 | 2640 | 2813 | 357 | 422 | 164 | 5 | 8 | 8 | 423 | 395 | 435 | 54,740 | 55,865 |
| MER 74 | 1437 | 1307 | 1407 | 172 | 203 | 76 | 1 | 3 | 3 | 280 | 260 | 275 | 73,500 | 71,149 |
| MER 80 | 940 | 942 | 926 | 136 | 159 | 60 | 3 | 5 | 5 | 218 | 216 | 210 | 65,800 | 64,744 |
| MER 82 | 1562 | 1476 | 1541 | 391 | 450 | 171 | 3 | 4 | 4 | 329 | 296 | 319 | 26,950 | 27,833 |
| MER 113 | 3165 | 2966 | 3211 | 341 | 386 | 152 | 8 | 8 | 9 | 530 | 479 | 513 | 38,850 | 40,501 |

| | Ti | | | Zn | | | Mn | | | Ca | | | K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EMPA | ICP-MS | pXRF[a] | WDXRF | ICP-MS | pXRF[a] | EMPA | ICP-MS | pXRF[a] | EMPA | ICP-MS | pXRF[a] | EMPA | pXRF[a] |
| MER 31 | 1140 | 976 | 785 | 264 | 327 | 266 | 462 | 468 | 425 | 1000 | 1284 | 1123 | 38,263 | 29,641 |
| MER 36 | 2100 | 2040 | 1871 | 387 | 533 | 450 | 4312 | 3958 | 4438 | 6646 | 6247 | 6734 | 37,018 | 28,942 |
| MER 40 | 4140 | 3969 | 3935 | 243 | 323 | 272 | 2926 | 2987 | 3243 | 6717 | 6878 | 6900 | 39,508 | 31,779 |
| MER 42 | 6540 | 6095 | 6334 | 142 | 180 | 155 | 2233 | 2170 | 2303 | 9004 | 8377 | 9337 | 45,484 | 36,878 |
| MER 63 | 3780 | 3340 | 3535 | 196 | 258 | 219 | 2695 | 2480 | 2765 | 7646 | 7843 | 7721 | 45,069 | 34,801 |
| MER 65 | 3720 | 3444 | 3671 | 199 | 267 | 228 | 2926 | 2547 | 2899 | 7861 | 7741 | 8110 | 47,476 | 36,931 |
| MER 68 | 3060 | 2748 | 2849 | 123 | 160 | 129 | 1001 | 1005 | 1076 | 5145 | 7037 | 5500 | 44,820 | 35,288 |
| MER 71 | 1920 | 1688 | 1426 | 386 | 539 | 471 | 1694 | 1534 | 1853 | 2144 | 2244 | 2243 | 38,263 | 30,824 |
| MER 74 | 1800 | 1555 | 1421 | 362 | 510 | 409 | 2310 | 2071 | 2397 | 2858 | 2707 | 2792 | 36,022 | 28,659 |
| MER 80 | 5220 | 4606 | 4951 | 200 | 262 | 219 | 2464 | 2327 | 2551 | 9218 | 7475 | 9513 | 41,915 | 34,574 |
| MER 82 | 1080 | 1002 | 946 | 265 | 316 | 275 | 462 | 458 | 471 | 1143 | 1133 | 1346 | 38,097 | 29,502 |
| MER 113 | 2280 | 2133 | 1992 | 285 | 373 | 330 | 1463 | 1277 | 1475 | 2644 | 2692 | 2787 | 40,172 | 31,876 |

[a] These pXRF values reflect the generic factory-set calibration, not the new calibration based on these obsidian specimens as standards.

Sr has the lowest correlation ($R^2 = 0.89$), but this is partly a result of mostly low concentrations with one high value. The slope ($m$) of these best-fit lines are mostly near 1 (0.97–1.00), with Sr as the exception ($m = 0.94$) for the same reason. The overall mean values are $R^2 = 0.95$ and $m = 0.99$ for these elements.

Fig. 5 shows similar checks for our pXRF values calibrated to the ICP-MS data in Brown et al. (2013). The correlations are again high, including that for Sr ($R^2 = 0.99$), which indicates high reproducibility between our pXRF values and their ICP-MS values. Ca has the lowest correlation ($R^2 = 0.86$) here. With the exception of Sr, the slopes of the best-fit lines are again mostly near 1 ($m = 0.94$–$1.01$), supporting compatibility. The overall mean values for these datasets are $R^2 = 0.95$ and $m = 0.95$, only a slight decrease.

### 7.2. Calculating percent relative difference

Table 6 shows the WDXRF and EMPA data from Brown et al. (2013) alongside our calibrated pXRF data for these fifteen obsidian specimens. The percent differences between the measurements are also shown. Note that, because Sr occurs at such low concentrations in these obsidians, the percent relative difference between the datasets is inflated. Horwitz et al. (1980) demonstrated that, for any analytical technique, uncertainties will increase as the element's concentration decreases. With the exception of Sr, the difference between the pXRF and WDXRF data varies, on average, from 2% (Zr) to 5% (Zn). The relative difference between the pXRF and EMPA data are almost as small, varying from 2% (K) to 7% (Ca and Mn), on average. Therefore, our calibrated pXRF data achieve our goal: 5% or less relative difference with respect to the WDXRF data from Brown et al. (2013), and these differences are only slightly greater (≤7% relative) with respect to the EMPA data.

Table 7 shows the ICP-MS data from Brown et al. (2013) alongside our pXRF data with the corresponding calibration. The relative differences between the measurements are also listed (again Sr has an inflated relative difference due to its low concentrations). With the exceptions of Sr, the difference between the pXRF and ICP-MS values varies, on average, from 5% (Nb, Rb, Zn, and Ti) to 7–8% (Zr and Mn)

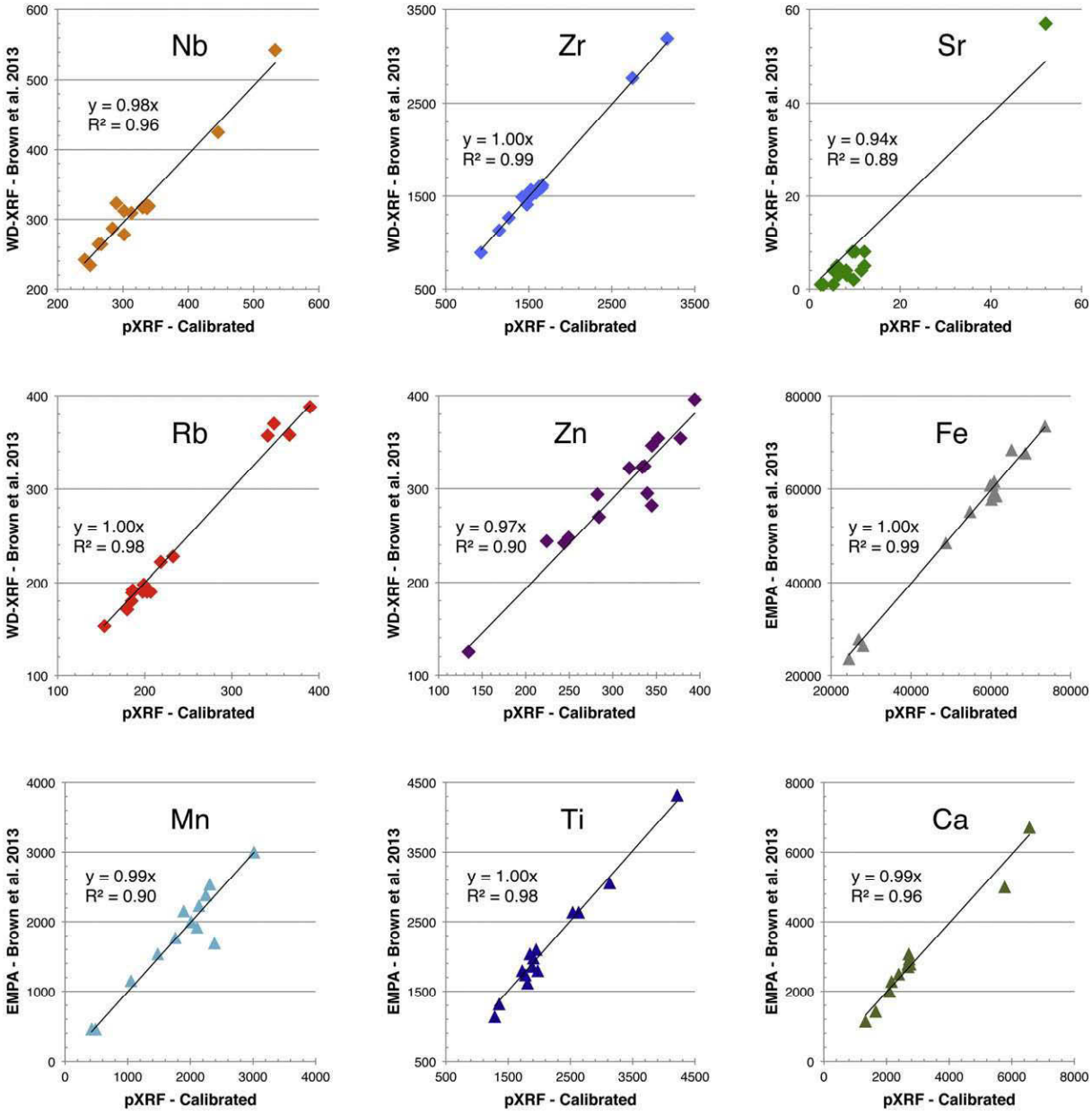


**Fig. 4.** Best-fit lines and correlations between our pXRF (with our adjusted calibrations from Fig. 3) data and the published WDXRF and EMPA datasets from Brown et al. (2013) for a series of fifteen matched obsidian specimens used as reproducibility checks (Table 4): pXRF versus WDXRF (diamonds) and pXRF versus EMPA (triangles).

to 20% (Ca). While not as excellent as the agreement between the pXRF and WDXRF datasets (2–5%), most elements still exhibit good agreement (5–8% relative) between the pXRF and ICP-MS datasets.

### 7.3. Summary

Our pXRF values, when calibrated to the WDXRF and EMPA data from Brown et al. (2013), exhibit high compatibility with those datasets. When plotted, their correlations are high (on average, $R^2 = 0.95$), and the best-fit slopes nearly equal 1 (on average, $m = 0.99$) for the elements of interest. Additionally, the percent relative differences are small: 2–5% with respect to the WDXRF data and 2–7% with respect to the EMPA data. There should be little lingering doubt these datasets can be reliably and validly used together. As a result, we can now use pXRF in combination with the Brown et al. (2013) database as a means to conduct rapid and field-based source identifications of Kenyan obsidian artifacts. This calibration approach is entirely generalizable, not specific to our particular pXRF instrument, model, or brand. Specimens from a range of Kenyan obsidian sources (with known compositions that span the anticipated chemical range) can be used to similarly calibrate any XRF instrument, regardless of whether it is portable or laboratory-based.

## 8. Study area: six Winam Gulf rock shelters

We analyzed 78 obsidian artifacts from the Randhore, Rangong, Nyaidha, Jawuoyo, Agoro, and Abindu rock shelters along the northern margins of the Winam Gulf in Kenya (Fig. 2). The sites were originally excavated and reported by Gabel (1969), and portions of these six artifact assemblages are housed at the Gabel Museum of Archaeology at Boston University, USA. We sourced the full collection of obsidian artifacts currently housed in Boston at the Gabel Museum. Our results augment those of Merrick and Brown (1984b), who reported the source attributions of 52 obsidian artifacts from Jawuoyo stored at the National Museums of Kenya in Nairobi. Each rock shelter formed beneath a large Precambrian granitic tor with sediments formed by anthropogenic,

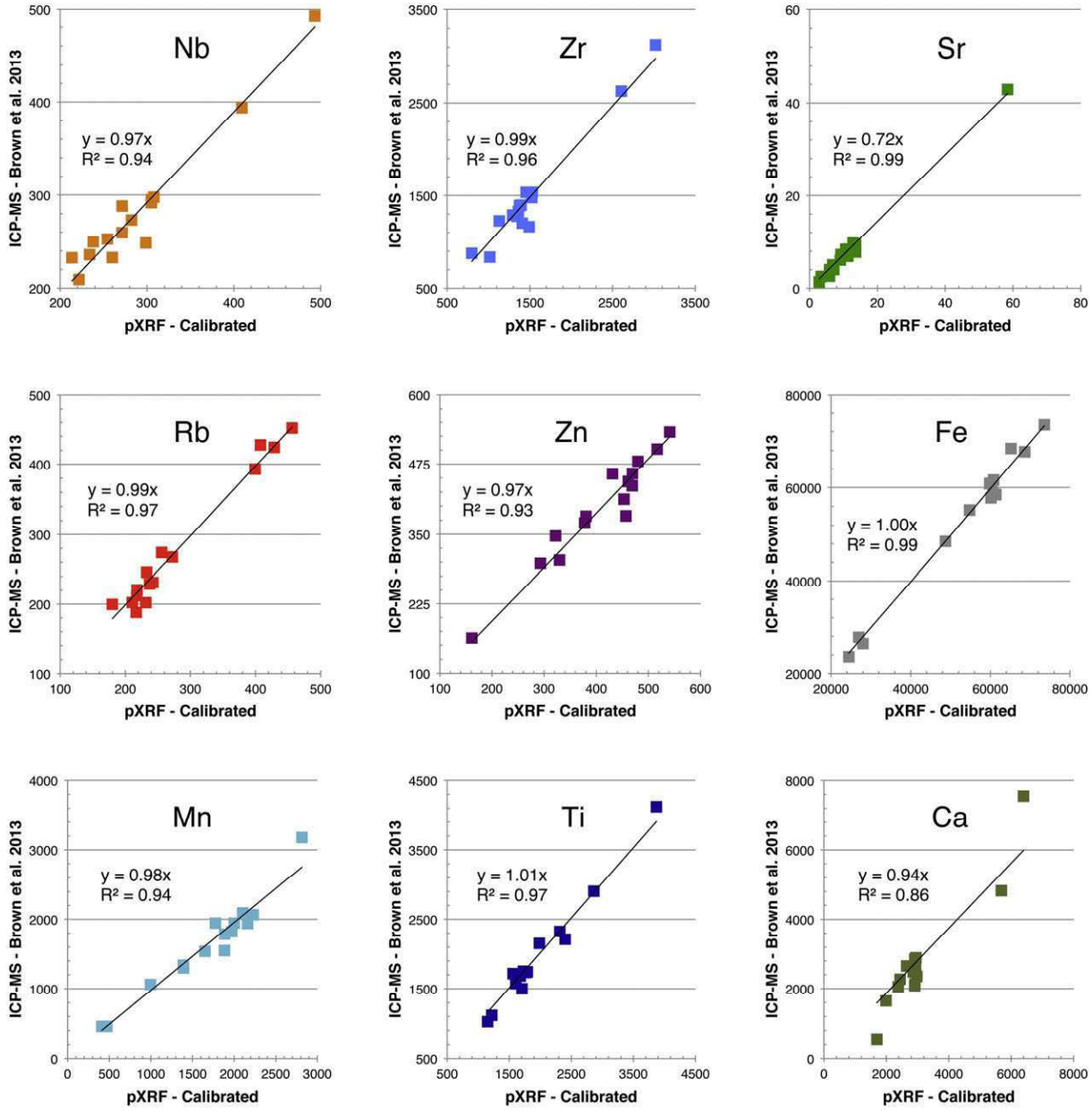


**Fig. 5.** Best-fit lines and correlations between our pXRF (with our adjusted calibrations from Fig. 3) data and the published ICP-MS datasets from Brown et al. (2013) for a series of fifteen matched obsidian specimens used as reproducibility checks (Table 4).

**Table 6**
Comparison of WDXRF/EMPA data from Brown et al. (2013) to fully calibrated pXRF data for matched obsidian specimens not included in the calibration's linear regression analysis.

| | Nb | | | Zr | | | Sr | | | Rb | | | Zn | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WDXRF | pXRF (cal) | %Diff | WDXRF | pXRF (cal) | %Diff | WDXRF | pXRF (cal) | %Diff* | WDXRF | pXRF (cal) | %Diff | WDXRF | pXRF (cal) | %Diff |
| MER 34 | 312 | 302 ± 15 | 3 | 1489 | 1422 ± 63 | 5 | 8 | 10 ± 3 | 23 | 370 | 348 ± 18 | 6 | 244 | 224 ± 14 | 8 |
| MER 38 | 242 | 241 ± 8 | 0 | 890 | 923 ± 31 | 4 | 1 | 3 ± 1 | 86 | 153 | 154 ± 4 | 0 | 242 | 244 ± 8 | 1 |
| MER 45 | 287 | 284 ± 12 | 1 | 1565 | 1525 ± 54 | 3 | 5 | 6 ± 1 | 20 | 189 | 186 ± 7 | 2 | 346 | 345 ± 14 | 0 |
| MER 69 | 264 | 263 ± 2 | 1 | 1129 | 1142 ± 5 | 1 | 57 | 52 ± 1 | 9 | 198 | 199 ± 1 | 0 | 125 | 134 ± 4 | 7 |
| MER 70 | 425 | 445 ± 7 | 5 | 2770 | 2749 ± 46 | 1 | 2 | 10 ± 1 | 132 | 358 | 366 ± 8 | 2 | 396 | 394 ± 14 | 1 |
| MER 75 | 278 | 302 ± 2 | 8 | 1407 | 1476 ± 1 | 5 | 1 | 5 ± 1 | 136 | 171 | 180 ± 2 | 5 | 354 | 377 ± 6 | 6 |
| MER 76 | 309 | 313 ± 4 | 1 | 1526 | 1491 ± 13 | 2 | 4 | 8 ± 1 | 68 | 192 | 186 ± 2 | 3 | 354 | 352 ± 5 | 1 |
| MER 83 | 319 | 340 ± 5 | 6 | 1535 | 1586 ± 24 | 3 | 3 | 6 ± 1 | 72 | 388 | 390 ± 4 | 0 | 248 | 249 ± 6 | 1 |
| MER 96 | 234 | 250 ± 6 | 7 | 1483 | 1505 ± 42 | 1 | 1 | 3 ± 1 | 102 | 228 | 232 ± 8 | 2 | 294 | 282 ± 16 | 4 |
| MER 99 | 264 | 267 ± 6 | 1 | 1266 | 1259 ± 21 | 1 | 3 | 8 ± 1 | 93 | 222 | 218 ± 4 | 2 | 322 | 319 ± 10 | 1 |
| MER 105 | 323 | 290 ± 8 | 11 | 1516 | 1540 ± 47 | 2 | 4 | 5 ± 1 | 28 | 180 | 185 ± 8 | 3 | 323 | 334 ± 9 | 3 |
| MER 112 | 543 | 533 ± 18 | 2 | 3193 | 3167 ± 102 | 1 | 8 | 10 ± 1 | 17 | 357 | 341 ± 14 | 5 | 270 | 284 ± 14 | 5 |
| MER 115 | 320 | 337 ± 8 | 5 | 1613 | 1662 ± 30 | 3 | 4 | 11 ± 1 | 96 | 190 | 207 ± 8 | 8 | 282 | 345 ± 2 | 20 |
| MER 117 | 316 | 337 ± 5 | 6 | 1589 | 1656 ± 20 | 4 | 5 | 12 ± 1 | 83 | 190 | 203 ± 2 | 6 | 295 | 340 ± 7 | 14 |
| MER 119 | 317 | 330 ± 3 | 4 | 1598 | 1623 ± 12 | 2 | 8 | 12 ± 1 | 41 | 190 | 198 ± 2 | 4 | 324 | 336 ± 11 | 4 |
| Mean | | | 4 | | | 2 | | | 67 | | | 3 | | | 5 |

| | Fe | | | Mn | | | Ti | | | Ca | | | K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EMPA | pXRF (cal) | %Diff | EMPA | pXRF (cal) | %Diff | EMPA | pXRF (cal) | %Diff | EMPA | pXRF (cal) | %Diff | EMPA | pXRF (cal) | %Diff |
| MER 34 | 27,790 | 26,959 ± 1906 | 3 | 462 | 424 ± 51 | 9 | 1320 | 1355 ± 72 | 3 | 1429 | 1657 ± 184 | 15 | 38,678 | 36,792 ± 1999 | 5 |
| MER 38 | 67,690 | 68,651 ± 1766 | 1 | 3003 | 3015 ± 97 | 0 | 4320 | 4215 ± 207 | 2 | 6717 | 6566 ± 299 | 2 | 39,010 | 38,949 ± 1422 | 0 |
| MER 45 | 60,830 | 59,820 ± 2499 | 2 | 2387 | 2247 ± 137 | 6 | 2640 | 2537 ± 66 | 4 | 2930 | 2727 ± 163 | 7 | 38,014 | 36,736 ± 1081 | 3 |
| MER 69 | 23,590 | 24,461 ± 529 | 4 | 1155 | 1053 ± 17 | 9 | 3060 | 3130 ± 66 | 2 | 5002 | 5774 ± 625 | 14 | 45,069 | 44,741 ± 133 | 1 |
| MER 70 | 55,230 | 54,478 ± 1181 | 1 | 1771 | 1759 ± 64 | 1 | 1800 | 1726 ± 32 | 4 | 2001 | 2095 ± 83 | 5 | 38,180 | 38,887 ± 607 | 2 |
| MER 75 | 73,500 | 73,566 ± 935 | 0 | 1694 | 2385 ± 28 | 34 | 1740 | 1775 ± 74 | 2 | 2715 | 2683 ± 23 | 1 | 36,271 | 37,350 ± 81 | 3 |
| MER 76 | 68,390 | 65,203 ± 1524 | 5 | 2233 | 2136 ± 61 | 4 | 2040 | 1851 ± 71 | 10 | 2787 | 2702 ± 134 | 3 | 36,354 | 36,741 ± 826 | 1 |
| MER 83 | 26,390 | 28,000 ± 655 | 6 | 462 | 486 ± 41 | 5 | 1140 | 1284 ± 6 | 12 | 1143 | 1331 ± 83 | 15 | 38,097 | 38,096 ± 780 | 0 |
| MER 96 | 48,510 | 48,745 ± 1968 | 0 | 1540 | 1479 ± 64 | 4 | 1800 | 1974 ± 36 | 9 | 2287 | 2161 ± 51 | 6 | 37,765 | 37,402 ± 977 | 1 |
| MER 99 | 61,600 | 60,838 ± 1003 | 1 | 2156 | 1895 ± 41 | 13 | 1620 | 1811 ± 47 | 11 | 2501 | 2392 ± 58 | 4 | 37,350 | 37,406 ± 294 | 0 |
| MER 105 | 60,900 | 60,357 ± 2201 | 1 | 2541 | 2311 ± 111 | 9 | 2640 | 2630 ± 93 | 0 | 3073 | 2711 ± 211 | 12 | 38,014 | 36,977 ± 1718 | 3 |
| MER 112 | | 39,668 ± 1802 | | | 1481 ± 84 | | | 2181 ± 108 | | | 2628 ± 86 | | | 39,895 ± 1630 | |
| MER 115 | 58,520 | 61,374 ± 1505 | 5 | 1925 | 2107 ± 125 | 9 | 1980 | 1905 ± 11 | 4 | 2787 | 2683 ± 50 | 4 | 37,765 | 37,907 ± 803 | 0 |
| MER 117 | 58,940 | 60,609 ± 689 | 3 | 2002 | 2015 ± 33 | 1 | 2100 | 1951 ± 31 | 7 | 2787 | 2758 ± 92 | 1 | 38,180 | 39,026 ± 554 | 2 |
| MER 119 | 57,820 | 60,160 ± 84 | 4 | 2002 | 2011 ± 28 | 0 | 1860 | 1882 ± 17 | 1 | 2715 | 2688 ± 73 | 1 | 37,599 | 37,143 ± 58 | 1 |
| Mean | | | 3 | | | 7 | | | 5 | | | 7 | | | 2 |

* Note that the percent difference for Sr is inflated due to its low concentrations in the obsidians. Horwitz et al. (1980) describe how, for any analytical technique, measurement uncertainties increase as concentrations decrease.

**Table 7**
Comparison of ICP-MS data from Brown et al. (2013) to fully calibrated pXRF data for Merrick obsidian specimens not included in the calibration's linear regression analysis.

| | Nb | | | Zr | | | Sr | | | Rb | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ICP-MS | pXRF (cal) | %Diff | ICP-MS | pXRF (cal) | %Diff | ICP-MS | pXRF (cal) | %Diff* | ICP-MS | pXRF (cal) | %Diff |
| MER 34 | 288 | 271 ± 14 | 6 | 1290 | 1292 ± 62 | 0 | 7 | 11 ± 4 | 49 | 428 | 408 ± 21 | 5 |
| MER 38 | 233 | 213 ± 7 | 9 | 875 | 799 ± 31 | 9 | 1 | 3 ± 1 | 71 | 200 | 180 ± 5 | 10 |
| MER 45 | 253 | 254 ± 11 | 1 | 1396 | 1394 ± 53 | 0 | 5 | 7 ± 1 | 31 | 212 | 217 ± 8 | 3 |
| MER 69 | 236 | 234 ± 2 | 1 | 835 | 1015 ± 5 | 19 | 43 | 58 ± 1 | 31 | 246 | 233 ± 1 | 5 |
| MER 70 | 394 | 409 ± 7 | 4 | 2628 | 2605 ± 45 | 1 | 8 | 11 ± 1 | 29 | 424 | 429 ± 10 | 1 |
| MER 75 | 260 | 271 ± 2 | 4 | 1275 | 1346 ± 1 | 5 | 3 | 6 ± 1 | 77 | 202 | 211 ± 2 | 4 |
| MER 76 | 273 | 282 ± 4 | 3 | 1328 | 1361 ± 13 | 2 | 6 | 9 ± 1 | 40 | 221 | 218 ± 3 | 1 |
| MER 83 | 298 | 308 ± 5 | 3 | 1533 | 1454 ± 24 | 5 | 4 | 7 ± 1 | 56 | 452 | 456 ± 4 | 1 |
| MER 96 | 209 | 222 ± 6 | 6 | 1390 | 1374 ± 42 | 1 | 3 | 3 ± 1 | 31 | 268 | 272 ± 9 | 2 |
| MER 99 | 250 | 238 ± 6 | 5 | 1226 | 1131 ± 20 | 8 | 7 | 9 ± 1 | 24 | 274 | 256 ± 5 | 7 |
| MER 105 | 233 | 260 ± 7 | 11 | 1201 | 1408 ± 47 | 16 | 4 | 6 ± 1 | 39 | 188 | 217 ± 9 | 14 |
| MER 112 | 493 | 493 ± 17 | 0 | 3125 | 3019 ± 101 | 3 | 8 | 11 ± 1 | 24 | 393 | 399 ± 16 | 2 |
| MER 115 | 295 | 305 ± 8 | 3 | 1533 | 1530 ± 30 | 0 | 10 | 13 ± 1 | 28 | 231 | 242 ± 9 | 5 |
| MER 117 | 292 | 305 ± 5 | 4 | 1478 | 1523 ± 20 | 3 | 9 | 14 ± 1 | 37 | 229 | 237 ± 2 | 4 |
| MER 119 | 248 | 299 ± 3 | 18 | 1163 | 1491 ± 12 | 25 | 8 | 14 ± 1 | 54 | 202 | 231 ± 2 | 14 |
| Mean | | | 5 | | | 7 | | | 41 | | | 5 |

| | Zn | | | Mn | | | Ti | | | Ca | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ICP-MS | pXRF (cal) | %Diff | ICP-MS | pXRF (cal) | %Diff | ICP-MS | pXRF (cal) | %Diff | ICP-MS | pXRF (cal) | %Diff |
| MER 34 | 298 | 293 ± 20 | 2 | 458 | 413 ± 47 | 10 | 1116 | 1218 ± 66 | 9 | 1648 | 1989 ± 166 | 19 |
| MER 38 | 347 | 322 ± 11 | 7 | 3177 | 2815 ± 90 | 12 | 4122 | 3872 ± 192 | 6 | 7551 | 6397 ± 269 | 17 |
| MER 45 | 458 | 469 ± 21 | 3 | 2093 | 2103 ± 127 | 0 | 2324 | 2315 ± 61 | 0 | 2892 | 2950 ± 146 | 2 |
| MER 69 | 163 | 162 ± 5 | 1 | 1063 | 996 ± 16 | 6 | 2904 | 2865 ± 61 | 1 | 4828 | 5687 ± 561 | 16 |
| MER 70 | 532 | 541 ± 21 | 2 | 1539 | 1650 ± 60 | 7 | 1717 | 1562 ± 30 | 9 | 2055 | 2383 ± 75 | 15 |
| MER 75 | 502 | 517 ± 8 | 3 | 2064 | 2231 ± 26 | 8 | 1574 | 1607 ± 69 | 2 | 2852 | 2911 ± 20 | 2 |
| MER 76 | 480 | 480 ± 8 | 0 | 1946 | 2000 ± 56 | 3 | 1683 | 1679 ± 66 | 0 | 2748 | 2928 ± 120 | 6 |
| MER 83 | 304 | 330 ± 8 | 8 | 459 | 471 ± 38 | 3 | 1025 | 1152 ± 6 | 12 | 546 | 1697 ± 74 | 103 |
| MER 96 | 370 | 378 ± 24 | 2 | 1338 | 1391 ± 59 | 4 | 1744 | 1792 ± 34 | 3 | 2275 | 2442 ± 46 | 7 |
| MER 99 | 457 | 431 ± 14 | 6 | 1947 | 1776 ± 38 | 9 | 1710 | 1642 ± 44 | 4 | 2654 | 2649 ± 52 | 0 |
| MER 105 | 412 | 453 ± 13 | 9 | 1940 | 2162 ± 103 | 11 | 2213 | 2401 ± 86 | 8 | 2641 | 2936 ± 189 | 11 |
| MER 112 | 382 | 380 ± 20 | 0 | 1300 | 1392 ± 78 | 7 | 2152 | 1984 ± 100 | 8 | 2488 | 2861 ± 77 | 14 |
| MER 115 | 436 | 469 ± 3 | 7 | 1823 | 1973 ± 116 | 8 | 1751 | 1728 ± 10 | 1 | 2083 | 2911 ± 45 | 33 |
| MER 117 | 444 | 462 ± 11 | 4 | 1787 | 1887 ± 31 | 5 | 1735 | 1771 ± 28 | 2 | 2356 | 2978 ± 83 | 23 |
| MER 119 | 383 | 457 ± 17 | 18 | 1548 | 1884 ± 26 | 20 | 1499 | 1707 ± 16 | 13 | 2142 | 2916 ± 65 | 31 |
| Mean | | | 5 | | | 8 | | | 5 | | | 20 |

* Percent difference for Sr is inflated due to its low concentrations. Horwitz et al. (1980) describe how, for any analytical technique, measurement uncertainties increase as concentration decreases.

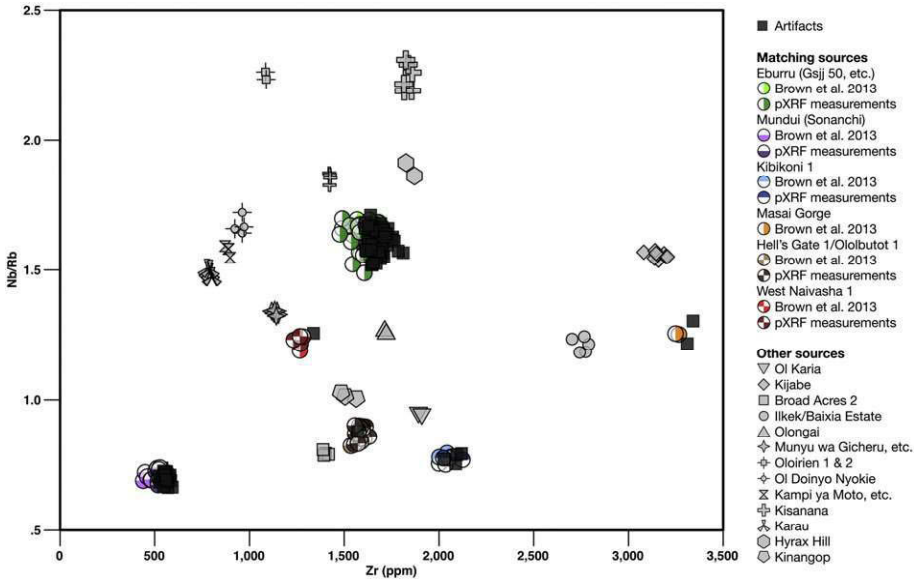


**Fig. 6.** Scatterplot of Zr versus Nb/Rb for the artifacts (black squares), their six matching geological sources (colorful circles), and select other obsidian sources reported by Brown et al. (2013) without matching artifacts (various grey symbols). For the identified sources, the published WDXRF data from Brown et al. (2013) are the lighter shades (e.g., light green for Eburru), while our calibrated pXRF data on geological specimens (when available) are the darker shades (e.g., dark green for Eburru). These measurements are available in Table 8.

**Table 8**
Our pXRF measurements of the 78 obsidian artifacts and their matching geological specimens as well as matching published WDXRF/EMPA data from Brown et al. (2013).

| Source | Site | Specimen/Artifact | Zr (ppm) | Nb (ppm) | Rb (ppm) | Nb/Rb | Sr (ppm) | Fe (ppm) | Mn (ppm) | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| Eburu GsJj 50, N slope, etc. | | *WDXRF/EMPA data from Brown et al. 2013* | | | | | | | | |
| | | MER 100 | 1620 | 325 | 197 | 1.6 | 7 | 58380 | 2079 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 114 | 1646 | 327 | 208 | 1.6 | 12 | 59080 | 1925 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 115 | 1613 | 320 | 190 | 1.7 | 4 | 58520 | 1925 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 116 | 1647 | 322 | 196 | 1.6 | 5 | 58590 | 2079 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 117 | 1589 | 316 | 190 | 1.7 | 5 | 58940 | 2002 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 118 | 1623 | 319 | 196 | 1.6 | 9 | 57960 | 2002 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 119 | 1598 | 317 | 190 | 1.7 | 8 | 57820 | 2002 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 13 | 1641 | 329 | 198 | 1.7 | 1 | 59920 | 2002 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 25 | 1568 | 322 | 190 | 1.7 | 7 | 60760 | 1925 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 26 | 1582 | 315 | 188 | 1.7 | 8 | 60060 | 2079 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 72 | 1679 | 327 | 205 | 1.6 | 9 | 58660 | 2002 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 73 | 1637 | 325 | 196 | 1.7 | 8 | 58450 | 2079 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | *pXRF of Brown et al. 2013 geological reference specimens* | | | | | | | | |
| | | MER 115 | 1651 | 330 | 198 | 1.7 | 11 | 58839 | 2097 | |
| | | MER 115 | 1644 | 329 | 202 | 1.6 | 11 | 58887 | 2011 | |
| | | MER 115 | 1699 | 344 | 212 | 1.6 | 12 | 61360 | 2255 | |
| | | MER 117 | 1680 | 336 | 199 | 1.7 | 13 | 58908 | 2039 | |
| | | MER 117 | 1669 | 339 | 202 | 1.7 | 13 | 59858 | 1994 | |
| | | MER 117 | 1632 | 326 | 200 | 1.6 | 11 | 58331 | 1993 | |
| | | MER 119 | 1631 | 330 | 197 | 1.7 | 13 | 58618 | 2032 | |
| | | MER 119 | 1634 | 329 | 194 | 1.7 | 12 | 58521 | 2049 | |
| | | MER 119 | 1613 | 324 | 194 | 1.7 | 11 | 58459 | 1994 | |
| | | *pXRF of other geological reference specimens* | | | | | | | | |
| | | ke01mr1a | 1630 | 337 | 211 | 1.6 | 7 | 73876 | 2161 | Sampling locus KEB16 in Ren et al. 2006 |
| | | ke01mr1a | 1522 | 312 | 190 | 1.6 | 10 | 64609 | 2109 | Sampling locus KEB16 in Ren et al. 2006 |
| | | ke01mr1a | 1587 | 328 | 210 | 1.6 | 9 | 76817 | 2279 | Sampling locus KEB16 in Ren et al. 2006 |
| | | ke01mr1b | 1489 | 307 | 185 | 1.7 | 10 | 61606 | 2034 | Sampling locus KEB16 in Ren et al. 2006 |
| | | ke01mr1c | 1544 | 313 | 206 | 1.5 | 11 | 70623 | 2155 | Sampling locus KEB16 in Ren et al. 2006 |
| | | ke01mr1c | 1579 | 327 | 209 | 1.6 | 9 | 71154 | 2235 | Sampling locus KEB16 in Ren et al. 2006 |
| | | ke01mr1c | 1490 | 306 | 180 | 1.7 | 12 | 61920 | 2102 | Sampling locus KEB16 in Ren et al. 2006 |
| | | ke02mr1a | 1547 | 317 | 194 | 1.6 | 8 | 62071 | 2159 | Sampling locus KEB17 in Ren et al. 2006 |
| | | ke02mr1a | 1606 | 326 | 219 | 1.5 | 9 | 72182 | 2157 | Sampling locus KEB17 in Ren et al. 2006 |
| | | ke02mr1c | 1629 | 343 | 211 | 1.6 | 9 | 72292 | 2175 | Sampling locus KEB17 in Ren et al. 2006 |
| | | ke02mr1c | 1600 | 330 | 211 | 1.6 | 8 | 71825 | 2155 | Sampling locus KEB17 in Ren et al. 2006 |
| | | ke02mr1c | 1531 | 315 | 188 | 1.7 | 8 | 60760 | 2111 | Sampling locus KEB17 in Ren et al. 2006 |
| | | ke.2009.1 | 1536 | 316 | 196 | 1.6 | 9 | 64540 | 2407 | Sampling locus KEB16 in Ren et al. 2006 |
| | | ke.2009.1 | 1476 | 303 | 185 | 1.6 | 10 | 61868 | 2195 | Sampling locus KEB16 in Ren et al. 2006 |
| | | ke.2009.2 | 1574 | 323 | 194 | 1.7 | 9 | 64191 | 2290 | Sampling locus KEB17 in Ren et al. 2006 |
| | | ke.2009.2 | 1582 | 321 | 195 | 1.6 | 10 | 64048 | 2391 | Sampling locus KEB17 in Ren et al. 2006 |
| | | *pXRF of archaeological artifacts* | | | | | | | | |
| | Abindu | abindu ab10 11 | 1670 | 336 | 204 | 1.6 | 13 | 58708 | 1952 | |
| | | abindu ab10 5 | 1693 | 337 | 211 | 1.6 | 13 | 61255 | 1931 | |
| | | abindu ab11 064 10 | 1666 | 339 | 211 | 1.6 | 11 | 65695 | 1885 | |
| | | abindu ab11 15 | 1633 | 336 | 215 | 1.6 | 12 | 61859 | 1820 | |
| | | abindu ab3 12 | 1677 | 343 | 219 | 1.6 | 11 | 65250 | 1961 | |
| | | abindu ab6 6 | 1695 | 338 | 205 | 1.6 | 13 | 60194 | 1890 | |
| | | abindu ab9 13 | 1700 | 342 | 218 | 1.6 | 11 | 64141 | 1911 | |
| | Agoro | agoro ag44! 3 | 1679 | 337 | 216 | 1.6 | 11 | 65470 | 1982 | |
| | Jawuoyo | jawuoyo ja21 13 | 1697 | 341 | 207 | 1.6 | 13 | 61320 | 1988 | |
| | | jawuoyo ja26 5 | 1659 | 333 | 200 | 1.7 | 10 | 58839 | 1845 | |
| | | jawuoyo ja4 1 | 1664 | 332 | 202 | 1.6 | 11 | 58988 | 1960 | |
| | | jawuoyo ja4 3 | 1752 | 352 | 216 | 1.6 | 14 | 62642 | 1981 | |
| | | jawuoyo ja43 16 a4300 | 1725 | 347 | 217 | 1.6 | 14 | 60644 | 1783 | |
| | | jawuoyo ja49 12 | 1668 | 338 | 216 | 1.6 | 11 | 61572 | 1720 | |
| | | jawuoyo ja67! 15 | 1749 | 355 | 219 | 1.6 | 14 | 63897 | 1981 | |
| | | jawuoyo ja8 4 | 1594 | 327 | 204 | 1.6 | 8 | 71468 | 1986 | |
| | Randhore | randhore rd2 2 | 1610 | 324 | 192 | 1.7 | 12 | 54185 | 1928 | |
| | | randhore rd2 5 | 1807 | 356 | 227 | 1.6 | 14 | 65958 | 2123 | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | randhore rd2 7 | 1705 | 349 | 224 | 1.6 | 12 | 67060 | 2042 | |
| | | randhore rd2? 12 | 1654 | 338 | 216 | 1.6 | 11 | 64145 | 1770 | |
| | | randhore rd2? 13 | 1707 | 344 | 208 | 1.7 | 12 | 60415 | 2000 | |
| | | randhore rd20? 16 | 1641 | 329 | 216 | 1.5 | 12 | 65139 | 1861 | |
| | | randhore rd3 3 | 1659 | 343 | 215 | 1.6 | 13 | 65460 | 1898 | |
| | | randhore rd3 6 | 1687 | 338 | 218 | 1.5 | 11 | 62038 | 1853 | |
| | | randhore rd3 9 | 1761 | 353 | 219 | 1.6 | 14 | 62542 | 1995 | |
| | | randhore rd4 1 | 1615 | 333 | 211 | 1.6 | 14 | 63288 | 1974 | |
| | Rangong | rangong rg10 1 | 1689 | 343 | 220 | 1.6 | 15 | 62045 | 1758 | |
| | | rangong rg10 4 | 1629 | 329 | 198 | 1.7 | 11 | 57772 | 1959 | |
| | | rangong rg10? 3 | 1621 | 327 | 202 | 1.6 | 18 | 56686 | 1811 | |
| | | rangong rg2 9 | 1690 | 337 | 200 | 1.7 | 13 | 59789 | 1909 | |
| | | rangong rg25 2 a5296 | 1657 | 333 | 200 | 1.7 | 12 | 58541 | 1892 | |
| | | rangong rg27 17 | 1696 | 340 | 204 | 1.7 | 12 | 59823 | 1955 | |
| | | rangong rg3 5 | 1669 | 334 | 203 | 1.6 | 12 | 58134 | 1977 | |
| | | rangong rg4 13 | 1660 | 337 | 204 | 1.7 | 14 | 58802 | 2009 | |
| | | rangong rg6 11 | 1623 | 332 | 211 | 1.6 | 11 | 62141 | 1805 | |
| | | rangong rg8 20 | 1661 | 341 | 215 | 1.6 | 12 | 60957 | 1733 | |
| | | rangong rg8 7 | 1681 | 345 | 219 | 1.6 | 12 | 62052 | 1789 | |
| | | rangong rg9 16 | 1650 | 328 | 215 | 1.5 | 13 | 63293 | 1727 | |
| | | rangong rg9 22 | 1641 | 340 | 212 | 1.6 | 11 | 61431 | 1904 | |
| | | rangong rg9 24 | 1610 | 328 | 208 | 1.6 | 14 | 64258 | 1978 | |
| | | rangong rg9 8 | 1637 | 334 | 211 | 1.6 | 14 | 63107 | 1789 | |
| Hell's Gate 1/Ololbutot 1 | | *WDXRF/EMPA data from Brown et al. 2013* | | | | | | | | |
| | | K80-399W | 1598 | 343 | 395 | 0.9 | 1 | 29400 | 462 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 29 | 1577 | 331 | 394 | 0.8 | 1 | 27440 | 539 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 31 | 1607 | 333 | 392 | 0.8 | 1 | 29400 | 462 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 82 | 1562 | 329 | 391 | 0.8 | 3 | 26950 | 462 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 83 | 1535 | 319 | 388 | 0.8 | 3 | 26390 | 462 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | *pXRF of Brown et al. 2013 geological reference specimens* | | | | | | | | |
| | | MER 31 | 1613 | 340 | 379 | 0.9 | 3 | 26284 | 502 | |
| | | MER 31 | 1599 | 338 | 376 | 0.9 | 4 | 27304 | 390 | |
| | | MER 31 | 1632 | 345 | 403 | 0.9 | 3 | 29327 | 491 | |
| | | MER 31 | 1580 | 333 | 369 | 0.9 | 3 | 26266 | 485 | |
| | | MER 31 | 1596 | 336 | 379 | 0.9 | 2 | 27323 | 451 | |
| | | MER 82 | 1571 | 338 | 401 | 0.8 | 4 | 30402 | 344 | |
| | | MER 82 | 1553 | 332 | 402 | 0.8 | 5 | 30560 | 472 | |
| | | MER 82 | 1584 | 343 | 404 | 0.8 | 4 | 29755 | 474 | |
| | | MER 82 | 1558 | 329 | 378 | 0.9 | 4 | 27044 | 470 | |
| | | MER 82 | 1576 | 332 | 377 | 0.9 | 5 | 27184 | 523 | |
| | | *pXRF of archaeological artifacts* | | | | | | | | |
| | Rangong | rangong rg5 19 | 1570 | 334 | 380 | 0.9 | 2 | 26976 | 352 | |
| Kibikoni 1 | | *WDXRF/EMPA data from Brown et al. 2013* | | | | | | | | |
| | | CMN 24 | 2000 | 302 | 400 | 0.8 | 1 | 26740 | 462 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 11 | 2043 | 327 | 412 | 0.8 | 1 | 25270 | 385 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 12 | 2066 | 327 | 419 | 0.8 | 1 | 26950 | 385 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 14 | 2002 | 313 | 402 | 0.8 | 1 | 26390 | 385 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 30 | 2034 | 314 | 418 | 0.8 | 1 | 25760 | 385 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 50 | 2051 | 318 | 410 | 0.8 | 1 | 26880 | 385 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | *pXRF of other geological reference specimens* | | | | | | | | |
| | | ke.2009.9 | 2124 | 343 | 445 | 0.8 | 3 | 29467 | 312 | |
| | | ke.2009.9 | 2022 | 332 | 428 | 0.8 | 2 | 28397 | 301 | |
| | | *pXRF of archaeological artifacts* | | | | | | | | |
| | Rangong | rangong rg10 15 | 2091 | 334 | 422 | 0.8 | 2 | 27973 | 261 | |
| | | rangong rg29 6 | 2116 | 343 | 431 | 0.8 | 2 | 27408 | 297 | |
| Masai Gorge Rockshelter | | *WDXRF/EMPA data from Brown et al. 2013* | | | | | | | | |
| | | MER 90 | 3267 | 502 | 401 | 1.3 | 4 | 57330 | 1848 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 91 | 3248 | 505 | 402 | 1.3 | 4 | 56490 | 1771 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | *pXRF of archaeological artifacts* | | | | | | | | |
| | Abindu | abindu ab10 063 2 | 3337 | 536 | 411 | 1.3 | 12 | 55058 | 1923 | |
| | | abindu ab10 2 | 3307 | 539 | 442 | 1.2 | 12 | 60016 | 1729 | |
| Mundui (Sonanchi) | | *WDXRF/EMPA data from Brown et al. 2013* | | | | | | | | |

*(continued on next page)*

**Table 8** (*continued*)

| Source | Site | Specimen/Artifact | Zr (ppm) | Nb (ppm) | Rb (ppm) | Nb/Rb | Sr (ppm) | Fe (ppm) | Mn (ppm) | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 002 (Plc1) | 439 | 200 | 290 | 0.7 | 6 | 14070 | 308 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | 210b (Plc1) | 450 | 207 | 287 | 0.7 | | 14350 | 231 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | CMN 12 | 461 | 188 | 267 | 0.7 | 3 | 13720 | 308 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 7 | 478 | 191 | 276 | 0.7 | 8 | 14210 | 308 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | MER 8 | 482 | 193 | 278 | 0.7 | 5 | 13650 | 385 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | *pXRF of other geological reference specimens* | | | | | | | | |
| | | ke04mr1a | 520 | 194 | 281 | 0.7 | 4 | 15368 | | Sampling locus KO5 in Ren et al. 2006 |
| | | ke04mr1a | 526 | 195 | 269 | 0.7 | 5 | 14077 | | Sampling locus KO5 in Ren et al. 2006 |
| | | ke04mr1b | 528 | 197 | 286 | 0.7 | 3 | 15637 | | Sampling locus KO5 in Ren et al. 2006 |
| | | ke04mr1b | 527 | 193 | 265 | 0.7 | 5 | 13679 | | Sampling locus KO5 in Ren et al. 2006 |
| | | ke04mr1c | 532 | 204 | 298 | 0.7 | 4 | 15828 | | Sampling locus KO5 in Ren et al. 2006 |
| | | ke04mr1c | 532 | 195 | 286 | 0.7 | 4 | 15317 | | Sampling locus KO5 in Ren et al. 2006 |
| | | ke.2009.4 | 528 | 195 | 263 | 0.7 | 5 | 14085 | 295 | Sampling locus KO5 in Ren et al. 2006 |
| | | ke.2009.4 | 513 | 192 | 262 | 0.7 | 5 | 13537 | 288 | Sampling locus KO5 in Ren et al. 2006 |
| | | ke.2009.8 | 526 | 192 | 259 | 0.7 | 4 | 13744 | 221 | |
| | | ke.2009.8 | 522 | 193 | 263 | 0.7 | 4 | 13683 | 200 | |
| | | ke.2009.8 | 515 | 188 | 274 | 0.7 | 4 | 14970 | 185 | |
| | | ke.2009.8 | 517 | 191 | 284 | 0.7 | 5 | 15283 | 368 | |
| | | ke.2009.8 | 525 | 194 | 279 | 0.7 | 4 | 15386 | 282 | |
| | | *pXRF of archaeological artifacts* | | | | | | | | |
| | Abindu | abindu ab? 4 | 561 | 196 | 273 | 0.7 | 5 | 14908 | 98 | |
| | | abindu ab11 9 | 547 | 191 | 264 | 0.7 | 4 | 13949 | 160 | |
| | | abindu ab12 1 | 552 | 195 | 283 | 0.7 | 4 | 15867 | 187 | |
| | | abindu ab17 7 | 532 | 184 | 255 | 0.7 | 8 | 15299 | | |
| | | abindu ab7 8 | 560 | 199 | 274 | 0.7 | 5 | 14859 | | |
| | | abindu ab9 023 14 | 535 | 192 | 259 | 0.7 | 4 | 13385 | | |
| | Agoro | agoro ag26 2 a5299 | 510 | 183 | 252 | 0.7 | 2 | 13313 | 226 | |
| | | agoro ag29? 1 | 580 | 204 | 294 | 0.7 | 5 | 15831 | 107 | |
| | Jawuoyo | jawuoyo ja26 11 a4276 | 564 | 199 | 283 | 0.7 | 6 | 13408 | | |
| | | jawuoyo ja37 8 | 555 | 195 | 268 | 0.7 | 5 | 14642 | 156 | |
| | | jawuoyo ja43 14 | 535 | 195 | 273 | 0.7 | 3 | 14168 | | |
| | | jawuoyo ja6 2 | 575 | 201 | 287 | 0.7 | 5 | 15891 | 124 | |
| | | jawuoyo ja60 10 a4299 | 517 | 186 | 254 | 0.7 | 4 | 12020 | | |
| | | jawuoyo ja60 7 | 589 | 210 | 314 | 0.7 | 7 | 17607 | 143 | |
| | | jawuoyo ja8 6 | 548 | 193 | 265 | 0.7 | 5 | 13962 | | |
| | | jawuoyo ja9 9 | 577 | 201 | 281 | 0.7 | 5 | 15582 | 119 | |
| | Nyaidha | nyaidha ny3 1 | 543 | 194 | 284 | 0.7 | 7 | 17799 | | |
| | Randhore | randhore rd16 4 | 542 | 194 | 281 | 0.7 | 4 | 15114 | | |
| | | randhore rd2 14 | 564 | 204 | 295 | 0.7 | 4 | 15943 | | |
| | | randhore rd2 15 | 560 | 205 | 286 | 0.7 | 5 | 15384 | | |
| | | randhore rd2 17 | 554 | 200 | 279 | 0.7 | 8 | 15887 | | |
| | | randhore rd3 18 | 550 | 202 | 294 | 0.7 | 3 | 15019 | | |
| | | randhore rd4 10 | 567 | 200 | 280 | 0.7 | 10 | 16494 | 160 | |
| | | randhore rd4 11 | 537 | 202 | 289 | 0.7 | 4 | 15692 | | |
| | | randhore rd63? 8 | 553 | 196 | 288 | 0.7 | 5 | 15997 | | |
| | Rangong | rangong rg10 21 | 550 | 199 | 275 | 0.7 | 6 | 14668 | | |
| | | rangong rg23 18 | 544 | 201 | 277 | 0.7 | 7 | 14978 | 118 | |
| | | rangong rg25 14 | 554 | 198 | 278 | 0.7 | 5 | 15058 | 173 | |
| | | rangong rg6 12 | 565 | 205 | 299 | 0.7 | 6 | 15954 | | |
| | | rangong rg9 10 | 551 | 201 | 279 | 0.7 | 5 | 14626 | 107 | |
| | | rangong rg9 23 | 555 | 205 | 295 | 0.7 | 6 | 15848 | | |
| West Naivasha 1 | | *WDXRF/EMPA data from Brown et al. 2013* | | | | | | | | |
| | | MER 99 | 1266 | 264 | 222 | 1.2 | 3 | 61600 | 2156 | Brown et al. 2013 - Table 3, Naivasha-Nakuru |
| | | *pXRF of Brown et al. 2013 geological reference specimens* | | | | | | | | |
| | | MER 99 | 1269 | 264 | 217 | 1.2 | 8 | 60347 | 1966 | |
| | | MER 99 | 1282 | 272 | 218 | 1.2 | 8 | 59396 | 1906 | |
| | | MER 99 | 1266 | 269 | 216 | 1.2 | 8 | 58949 | 1903 | |
| | | *pXRF of archaeological artifacts* | | | | | | | | |
| | Abindu | abindu ab9 024 3 | 1335 | 284 | 226 | 1.3 | 8 | 61808 | 1954 | |

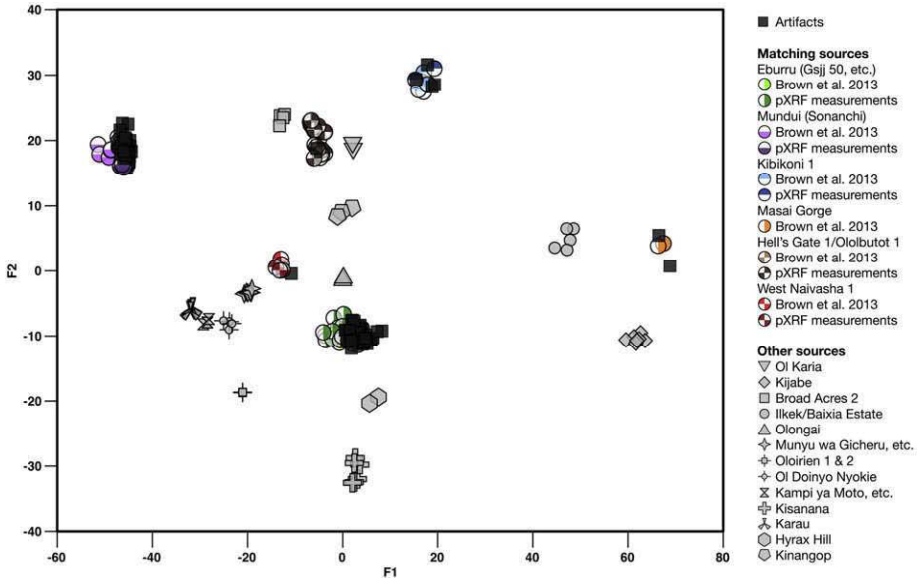


**Fig. 7.** Discriminant functions were derived with source as the grouping variable and Zr, Rb, Nb, and Sr as predicting variables. The resulting scatterplot shows the artifacts (black squares), their six matching geological sources (colorful circles), and select other obsidian sources reported by Brown et al. (2013) without matching artifacts (various grey symbols). Like Fig. 6, the published WDXRF data from Brown et al. (2013) are the lighter shades (e.g., light green for Eburru), while our calibrated pXRF data on geological specimens (when available) are the darker shades (e.g., dark green for Eburru).

sheetwash, and bedrock dissolution processes. They were excavated to depths of 0.75–3.0 m, and their deposits exhibited few stratigraphic distinctions and contained evidence for post-depositional disturbance (Gabel, 1969). Radiocarbon dates on charcoal run in the mid-1960s suggest ages of ~1.2–2.4 ka for the deposits (Gabel, 1969), but given that these samples consisted of aggregated pieces of charcoal tested more than four decades ago, these results should be treated with caution.

Gabel (1969) reported recent ceramics from each of the six rock shelters. Many of the ceramic styles that he described are consistent with what we now know to be Kansyore (ceramic LSA) wares (at Rangong and Abindu) and Urewe (Iron Age agropastoralist) wares (at Nyaidha) (Lane, 2004), although the Kansyore identification is questioned by some (Dale and Ashley, 2010). None of the ceramics are clearly Elmenteitan or SPN styles. Each of the sites contains LSA lithic assemblages dominated by lithic artifacts made of locally available quartz, quartzite, and volcanic rocks. Although Kansyore sites are typically defined on the basis of ceramics, the rock shelters excavated by Gabel have been incorporated into recent discussions of Kansyore lithic variability within the Lake Victoria basin on the basis of techno-typological similarities (Seitsonen, 2010). Like other Kansyore sites (Robertshaw, 1991), obsidian artifacts are persistently present in low quantities ($n$ = 28–157, 0.26–0.98%) at the Winam Gulf rock shelters (Gabel, 1969; see SOM Table A). Our lithic artifact sample includes unretouched debitage as well as tools such as backed microliths. The fauna from the rock shelters considered here, as reported by Gabel (1969), are dominated by wild taxa (reduncine and alcelaphine bovids, bushpig,

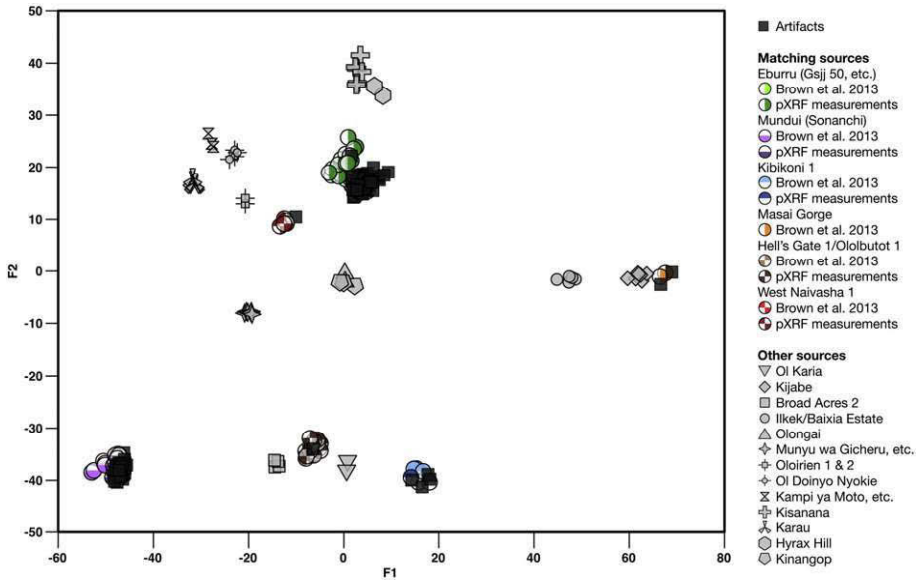


**Fig. 8.** Discriminant functions were derived with source as the grouping variable and Zr, Rb, Nb, Sr, Mn, and Fe as predicting variables. The resulting scatterplot shows the artifacts (black squares), their six matching geological sources (colorful circles), and select other obsidian sources reported by Brown et al. (2013) without matching artifacts (various grey symbols). Like Fig. 6, the published WDXRF data from Brown et al. (2013) are the lighter shades (e.g., light green for Eburru), while our calibrated pXRF data on geological specimens (when available) are the darker shades (e.g., dark green for Eburru).

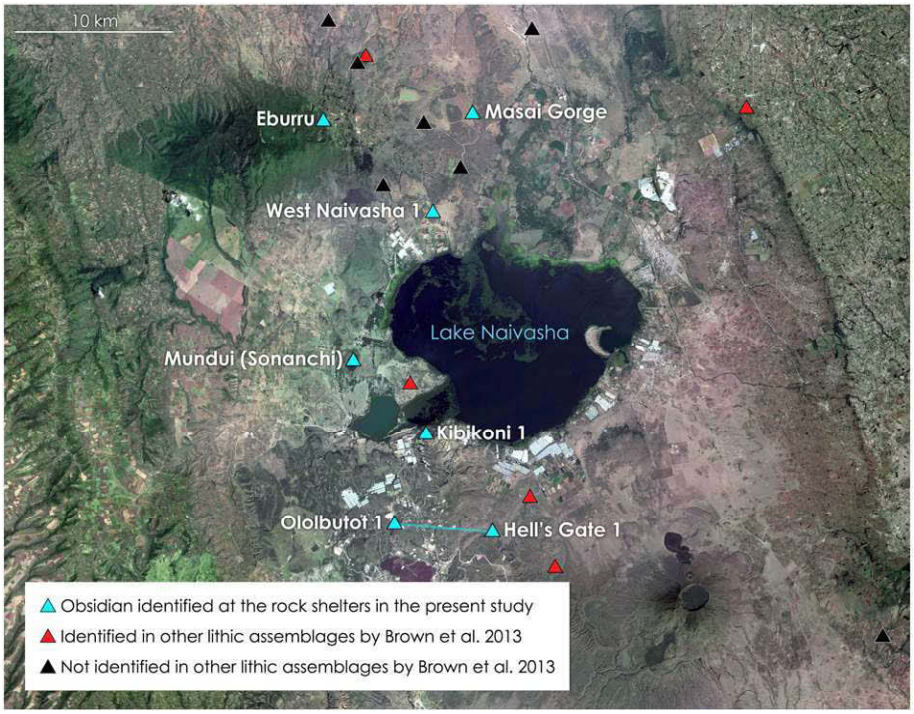


**Fig. 9.** Obsidian sources around Lake Naivasha that we identified at the six rock shelters in our study (cyan triangles with labels), identified by Brown et al. (2013) at other sites (red triangles), and not identified by Brown et al. (2013) at other sites (black triangles). The line between Hell's Gate 1 and Ololbutot 1 reflects that, in our view, these two obsidian sources in Brown et al. (2013) are chemically indistinguishable based on the available data (i.e., just two obsidian specimens define Hell's Gate 1). Background map: satellite image courtesy of the DigitalGlobe Foundation (© DigitalGlobe, Inc., All Rights Reserved).

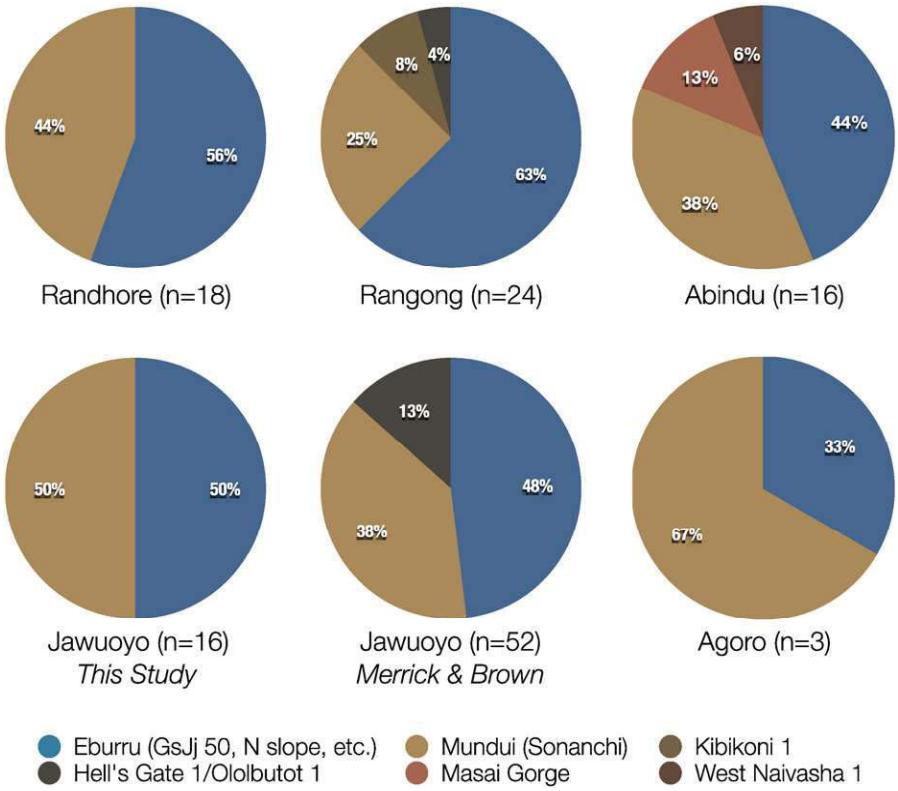


**Fig. 10.** Source identifications of obsidian artifacts (from Table 9) for five of the six rock shelters (leaving out Nyaidha, $n = 1$), including the Jawuoyo results from Merrick and Brown (1984b).

warthog, zebra). There are also freshwater molluscs, fish (lungfish, tilapia, catfish), and traces of domesticated animals (cattle, sheep or goat, possibly cat).

Although imperfect, evidence from the lithic, ceramic, and faunal assemblages (i.e., limited evidence for domesticates) and the available radiocarbon dates from these six rock shelters indicate the presence of late Holocene populations of foragers north of Winam Gulf. Their assemblages are at least broadly aligned with the "Late/Terminal Kansyore" of Dale and Ashley (2010), although the extent to which similarity in ceramic styles tracks other social variables at Kansyore sites remains poorly understood (Ashley and Grillo, 2015). We recognize this complexity as well as the limits of our current data, but we group our results from Randhore, Rangong, Nyaidha, Jawuoyo, Agoro, and Abindu shelters with other known "Late/Terminal Kansyore" sites to increase the total sample of chemically sourced obsidian artifacts made by late Holocene foragers in the Lake Victoria region from 88 to 166, more than doubling the number of sites from three to eight.

Obsidian artifacts in these lithic assemblages are principally bipolar pieces/debris, geometric crescents, and backed and retouched blade fragments. With almost no cores or core trimming elements and very little evidence of production debris, the assemblages are consistent with expectations for down- the-line acquisition of small blades and tools near the end of the reduction sequence, rather than the exchange of large cores or nodules. Details regarding the types, dimensions, and identifications of the artifacts are found in SOM Table B.

## 9. Obsidian source identifications

We made the artifacts' source assignments on three bases, which yielded the same results each time. As reported in Section 7, our calibrated pXRF values are highly correlated to the WDXRF data of Brown et al. (2013) for Zr, Rb, and Nb ($R^2 = 0.96–0.99$; Fig. 3a), and their relative differences are also very low (2–4% relative; Table 6). Therefore, first, we used these three elements. The simplest way to show three elements in two dimensions is using a ratio, and Fig. 6 shows a scatterplot of Zr versus Nb/Rb. Note that, for five of the six identified sources, we plot not only the WDXRF data of Brown et al. (2013) but also our calibrated pXRF measurements for geological specimens from the same sources. These specimens offered an extra check on our ability to reproduce the data in Brown et al. (2013). The published and our newly measured data tend to directly overlap in the scatterplot, demonstrating how well our measurements duplicate those from Brown et al. (2013). The data for this plot and the following ones are available in Table 8.

Second, we derived discriminant functions based on four trace elements – Zr, Rb, Nb, and Sr – to minimize within-source variance and maximize between-source variance. The artifact data were then plotted

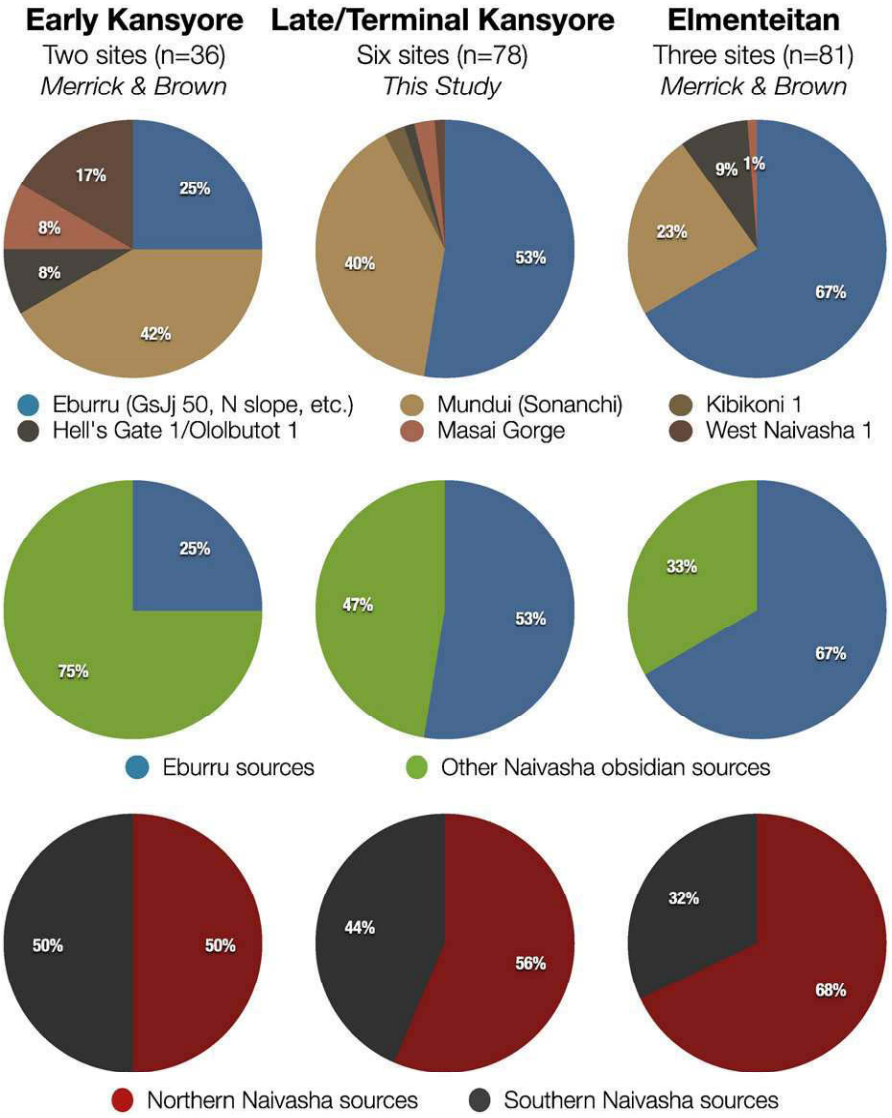


**Fig. 11.** Trends in obsidian source use for Early Kansyore (Merrick and Brown, 1984a, b), Late/Terminal Kansyore, and Elmenteitan (Merrick and Brown, 1984a, b) contexts.

**Table 9**
Summary of our obsidian source identifications by rock shelter and the earlier Jawuoyo results from Merrick and Brown (1984b).

| | This study | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Eburru | | Mundui (Sonanchi) | | Kibikoni 1 | | Hell's Gate 1/Ololbutot 1 | | Masai Gorge | | West Naivasha 1 | | |
| Sites | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | Sum |
| Abindu | 7 | 44% | 6 | 38% | | | | | 2 | 13% | 1 | 6% | 16 |
| Agoro | 1 | 33% | 2 | 67% | | | | | | | | | 3 |
| Jawuoyo | 8 | 50% | 8 | 50% | | | | | | | | | 16 |
| Nyaidha | | | 1 | 100% | | | | | | | | | 1 |
| Randhore | 10 | 56% | 8 | 44% | | | | | | | | | 18 |
| Rangong | 15 | 63% | 6 | 25% | 2 | 8% | 1 | 4% | | | | | 24 |
| Total | 41 | 53% | 31 | 40% | 2 | 3% | 1 | 1% | 2 | 3% | 1 | 1% | 78 |
| | Merrick & Brown | | | | | | | | | | | | |
| Jawuoyo | 25 | 48% | 20 | 38% | | | 7 | 13% | | | | | 52 |

with the derived functions, and Fig. 7 shows the outcome: the same source assignments as Fig. 6, and our new measurements directly overlap with the published values from Brown et al. (2013).

Third, we derived discriminant functions based on six elements: Zr, Rb, Nb, and Sr with the addition of Fe and Mn, both of which Brown et al. (2013) measured using EMPA. Fe is one of the elements favored by Brown et al. (2013) for source identification. Our pXRF measurements are highly correlated to their EMPA data for Fe ($R^2 = 0.99$; Fig. 3), and the relative differences are very low (3% on average; Table 6). Fig. 8 shows the outcome: the same source assignments as Figs. 6 and 7, and our pXRF measurements overlap with the published values from Brown et al. (2013).

Thus, our source identifications remain stable, and our measurements overlap with those of Brown et al. (2013) whether we simply use a scatterplot based on Zr, Nb, and Rb or multivariate statistical methods based on six well-measured elements.

## 10. Interpretation

Data from Randhore, Rangong, Nyaidha, Jawuoyo, Agoro, and Abindu rock shelters exhibit approximately equal representation of obsidians from Mt. Eburru (53%) and other sources near Lake Naivasha (Figs. 9–11; Table 9). These sources are 200 km at a minimum distance from Lake Victoria and closer to ~300–350 km if one assumes movement around, rather than across, the Mau Escarpment. There is no evidence for a Late/Terminal Kansyore presence in the Central Rift Valley, which by ~2 ka was occupied by Elmenteitan and SPN pastoralists. Given apparent control of key obsidian sources by pastoralist groups within the Rift Valley and on Mt. Eburru, and the widespread dispersal of this material at pastoral sites across much of present-day Kenya and northern Tanzania, we interpret the acquisition of obsidian at late Holocene forager sites through the lens of contact and exchange. Differences in obsidian acquisition may reflect changes to regional forager interaction networks through time.

**Table 10**
Comparing Z-scores and p values by period for Eburru versus other Naivasha obsidian sources. All differences are statistically significant when p = 0.10; however, the Late/Terminal Kansyore versus Elmenteitan difference is not significant when p = 0.05.

| | | Early Kansyore | Late/Terminal Kansyore | Elmenteitan |
|---|---|---|---|---|
| Early Kansyore | Z-score: | – | −2.757 | −4.173 |
| | p value: | | 0.006 | 0.000 |
| Late/Terminal Kansyore | Z-score: | 2.757 | – | −1.813 |
| | p value: | 0.006 | | 0.070 |
| Early Kansyore | Z-score: | 4.173 | 1.813 | – |
| | p value: | 0.000 | 0.070 | |

The increase in obsidian from Mt. Eburru at late Holocene sites that include Late/Terminal Kansyore ones relative to previously published data from Early Kansyore ones (Fig. 11) is strong evidence for direct interaction between Kansyore-producing forager-fishers and Elmenteitan-producing herders who migrated into the region by ~2000 cal. BP. By this time, Elmenteitan occupations had come to replace and overlay Eburran V forager levels in caves and rock shelters around Eburru (Ambrose, 1985, 1998). Much of the obsidian originating from the upper Mt. Eburru sources likely originated from the GsJj50 quarry, where recent excavations have yielded dense quarrying and workshop deposits, contemporary with the Late/Terminal Kansyore, with exclusively Elmenteitan ceramics and tools (Goldstein and Munyiri, in press). There is a lack of evidence for comparable forager activity on Mt. Eburru at this time, yet large amounts of Eburru obsidian arrived at Elmenteitan sites in the Lake Victoria basin, such as Wadh Lang'o and Gogo Falls. Social interaction with Elmenteitan pastoralist communities is the most likely explanation for how Late Kansyore and other communities of foragers acquired obsidians from these sources.

Obsidian acquisition from multiple Lake Naivasha sources occurred both prior to and during the appearance of pastoralism in the Lake Victoria region. The proportion of Mt. Eburru obsidian is lowest at Early Kansyore assemblages (25%) and highest in Elmenteitan (67%) assemblages (Fig. 11). Late/Terminal Kansyore sites (53%) are intermediate. These diachronic differences are statistically significant (Table 10). When the sources are divided into those north and south of Lake Naivasha (Figs. 9 & 11), obsidian artifacts from sources north of Lake Naivasha are least abundant at Early Kansyore assemblages (50%), most common at Elmenteitan ones (68%), with Late/Terminal Kansyore assemblages showing an intermediate value (56%). The number of sources represented in Late/Terminal Kansyore assemblages ($n = 6$) is greater than that in either Early Kansyore ($n = 5$) or Elmenteitan ($n = 4$) assemblages. The significance of these general trends is necessarily tempered by our small sample sizes, but the persistent use of obsidians from the Central Rift by groups in the Lake Victoria basin throughout much of the Holocene is apparent.

We have suggested that Eburru obsidian was obtained through Elmenteitan groups. How, then, did Kansyore groups acquire obsidians from the Naivasha sources? Continuity in Lake Naivasha sources through time could reflect ongoing forager networks extending from the Rift Valley, around (or over) the Mau Escarpment, and into the Nyanza region. Our understanding of the distribution and diversity in LSA foragers remains poorly understood, leaving significant potential for such networks to have persisted through the spread of food production (Wilshaw, 2016). Alternatively, SPN-producing herders were heavily exploiting Naivasha sources. The nearest known SPN sites to Lake Victoria are ~90–100 km to the southeast in the Lemek Valley (Robertshaw et al., 1990). Considering the co-occupation of Elmenteitan

and SPN groups across southwestern Kenya, it is possible there was also an as-of-yet undetected significant SPN presence closer to the Kansyore world (as appears to be the case in northern Tanzania where, at sites such as Mumba, Kansyore strata are overlain by SPN layers). Considerably more archaeological and sourcing studies are needed to test these hypotheses, which, at present, remain speculative. Nevertheless, our sourcing results support hypotheses that the Late/Terminal Kansyore fisher-foragers were engaged in a complex set of social relationships (Karega-Mũnene, 2002; Dale, 2007; Prendergast, 2008).

We suggest that the expanded access to diverse obsidians during the Late/Terminal Kansyore reflects one dimension of the broader Kansyore resilience strategy through the Holocene. If the obsidian sourcing pattern did result from interactions with a diverse range of other pastoralists and foragers, it would hint at a social flexibility that mirrors the apparent flexibility in Kansyore subsistence, settlement patterns, and ceramic production (Dale et al., 2004; Prendergast and Lane, 2010; Lane, 2004). Ethno-historically African foragers and herders have often entered into mutualistic relationships wherein the foragers are viewed as specialists in the acquisition of important subsistence supplements such as fish and honey (Berntsen, 1976; Turton, 1986; Blackburn, 2006), producers of poisons and medicines, and practitioners of magic (Kenny, 1981; Kratz, 1993; Grillo, 2014). Transfer or mimesis of material culture often accompanies these economic arrangements, with hunter-gatherers exhibiting a high degree of agency in what pastoralist materials they incorporate and the meanings of those materials in their own cultural sphere (Klumpp and Kratz, 1993). Our results provide preliminary support for a similar model existing in the past, wherein Kansyore or other fisher-foragers were able to absorb new challenges and opportunities presented by the arrival of herders while maintaining the essential structures of a foraging economy.

Pursuing evidence for forager-pastoralist interactions is of crucial importance in understanding both the trajectories of early food production in Eastern Africa and those strategies that allowed foraging to persist as a viable strategy through Holocene climatic changes (Marshall and Hildebrand, 2002; Dale et al., 2004; Gifford-Gonzalez, 1998, 2000, 2016; Marshall et al., 2011; Prendergast, 2011; Prendergast and Mutundu, 2009). In many areas, foragers and food producers alike had to survive in drought-prone, highly unpredictable environments where resources are spatially and temporally disparate. The complex social systems that likely arose among economically and socially diverse communities during the late Holocene may be better understood as mutually beneficial forms of risk mitigation and resilience (Lane, 2004; Prendergast and Mutundu, 2009; Marshall et al., 2011; Chritz et al., 2015). Our data offer supporting evidence that such relationships existed in the Lake Victoria region. This study demonstrates that obsidian sourcing has great potential to test these ideas and to develop a more comprehensive understanding of material access, exchange systems, and interaction spheres. We hope that future studies will take advantage of this opportunity to investigate such questions, which underlie key debates in studies of foragers and food production both regionally and globally.

## 11. Concluding remarks

Regarding our calibration to and use of the WDXRF and EMPA datasets from Brown et al. (2013), elements of interest exhibit very high correlations ($R^2 = 0.96–0.99$) to our pXRF data. Once calibrated to Brown et al. (2013), our pXRF data exhibit, on average, only 2–5% relative differences, equal to or better than compatible datasets from lab-based instruments. When our pXRF data of geological specimens are plotted alongside published values from Brown et al. (2013), they directly overlap, further demonstrating compatibility. Accordingly, we can reliably and validly use pXRF in conjunction with the Brown et al. (2013) database to conduct rapid, field-based source identifications of Kenyan obsidian artifacts. Such work will be strengthened as our knowledge of Kenyan obsidian sources continues to improve via ongoing source characterization projects (e.g., Coleman et al., 2008, 2009; Ambrose, 2012; Ambrose et al., 2012a, b; Slater et al., 2012; Slater and Ambrose, 2015).

Archaeologically this research elucidates interactions between LSA forager-fishers and pastoralists near Lake Victoria. Specifically, the extent to which obsidian acquisition in late Holocene forager contexts that includes Late/Terminal Kansyore assemblages reflects the Early Kansyore and/or Elmenteitan patterns can elucidate links between fisher-forager and pastoral populations. Thus, we present new source attributions for 78 obsidian artifacts from six contemporaneous late Holocene rock shelters along the Winam Gulf. Obsidian is scarce (0.3–1.0%) in these lithic assemblages, and our results reveal approximately equal representation of obsidian from Mt. Eburru (53%) and other sources near Lake Naivasha. Without evidence for a Kansyore presence so far east of our studied site sample, we interpret their obsidian acquisition as a reflection of intergroup contact and exchange. Interaction with Elmenteitan herders or other pastoralists is the most likely explanation for how Late/Terminal Kansyore groups acquired obsidian from the identified sources, involving culturally mediated access to this material.

The obsidian sourcing results we report here hint that the Late/Terminal Kansyore and other late Holocene fisher-foragers were engaged in a complex set of social relationships with neighboring pastoralist and farming communities. This line of evidence supports the idea that these fisher-forager communities interacted with herding groups for long periods of time but without being assimilated into food-producing lifeways. Expanded access to diverse obsidians might reflect the broader Kansyore resilience strategy in an unpredictable and drought-prone environment, and their interactions with economically and socially diverse communities hint at mutually beneficial forms of risk mitigation and resilience. Obsidian sourcing holds great potential for testing such ideas and developing a better understanding of Kansyore resource access and social spheres. The analytical tools and source databases now exist to investigate such questions, which underlie outstanding debates in studies of foragers and food production.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jasrep.2017.01.001.

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