Characterization of Kenyan Obsidian Through Analysis of Magnetic Properties
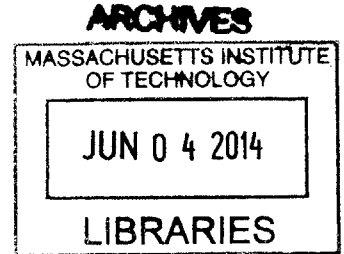
By

Elizabeth A. Krueger

Submitted to the Department of Materials Science and Engineering in
Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Archaeology and Materials
at the
Massachusetts Institute of Technology

June 2014

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Abstract

Obsidian is known to have been used for tool making in Kenya since the Early Stone Age, appearing as early as 974 thousand years ago (Durkee and Brown, in press). Past research has shown that the study of obsidian artifacts, and the determination of their provenance, can be very useful in reconstructing past civilizations and analyzing the spread of technology and trade. A number of different analytical techniques have previously been utilized to characterize obsidian sources for such studies, including magnetic analysis. This thesis reports the results of a preliminary study to explore the potential of utilizing magnetic analysis for the characterization of obsidian sources in Kenya. A total of 192 samples from 23 localities, belonging to 6 broadly defined petrologically distinct source groups, were analyzed using a vibrating sample magnetometer to test saturation magnetization (Ms), remanence magnetization (Mr), and coercivity (Hc). Comparing the ratio of Mr/Ms with Hc allowed clear differentiation among three of the analyzed obsidian sources (Groups 14, 19, and 29 from Merrick and Brown 1984a). The magnetic signatures reveal clues about the microscopic Fe mineral grains present in the samples, suggesting that magnetic characterization also has the potential to provide additional value as a supplementary technique to chemical analysis. Based on these preliminary results, it is proposed that future studies could examine the temperature dependence of the magnetic properties of obsidian to provide more complete characterization of the obsidian sources.

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Introduction

The goal of this thesis project was to explore the possibility of using magnetic properties as a characterization metric for the study of obsidian provenance in Kenya. This research will add to the available database of general knowledge about magnetic obsidian sourcing in various regions worldwide. No previous magnetic obsidian provenance studies have been conducted in eastern Africa (Coleman, 2008). Three major magnetic properties, discussed in more detail later, were analyzed here to determine whether any combination of them showed enough patterning to provide useful characterization metrics for sourcing Kenyan archaeological obsidian artifacts.

Archaeological Provenance

Provenance studies, also known as sourcing studies, are a type of archaeological research where various material sources (stone, metal ores, clays, etc.) in a region are characterized using one or more testing metrics to create a sort of "fingerprint" (Cann and Renfrew, 1964) allowing archaeologists to locate the original material sources of archaeological artifacts. Such studies have been shown to be extremely useful in the study of the human past (Glascock et al., 1998).

Tracing artifacts back to the locations where the material itself originated can provide useful information about how ancient societies functioned. Tracing materials found at artifact production sites can give us a look at production methods, whether people were shaping the material at the source or transporting

the raw material long distances back to the production site. Artifacts found in other contexts can have important implications regarding early human movement and material exchange patterns, as well as potentially hinting at the material's cultural significance (Glascock et al., 1998).

The provenance postulate states that in order to successfully source an artifact, there must be "a demonstrable set of physical, chemical, or mineral characteristics in the raw material source deposits that is retained in the final artifact" (Rapp and Hill, 2006; 222). This condition allows the comparison of the properties of the artifact with those of various source samples so that the artifact can be matched to its source. There are a number of methods that archaeologists have at their disposal with which to do this. The most common methods in use today for the analysis of obsidians involve the testing of their physical and geochemical properties, either alone or in combination, and comparing them to those of the various obsidian sources in the surrounding area (Rapp and Hill, 2006).

Obsidian

Obsidian is a volcanic silicate glass, which occurs in several forms within pyroclastic deposits (flows, welded layers, and lapilli). It exhibits a strong pattern of conchoidal fracture, which makes it an ideal material for the manufacture of sharp-bladed objects such as cutting tools and spear points. Obsidian is often known for its shiny black color, although it also comes in a variety of other color variants (Miller, 2014). Since the obsidian is liquid before the eruption, thorough mixing usually occurs within the magma chamber, and an entire eruptive event will produce obsidian with

approximately identical chemical makeup. This homogeneity can lead to obsidians with such similar chemistry many miles/kilometers apart depending on the size of the flow.

All obsidians contain trace amounts of various minerals in sub-millimeter sized crystal grains. The most common mineral found as micro-inclusions in obsidian is magnetite (Fe_3O_4), which causes obsidian's typical black coloration. Hematite, ilmenite, feldspars, and other minerals are also common (Frahm and Feinberg, 2013). The concentrations, compositions, morphologies, and the size and spatial arrangement of these mineral grains can all affect the magnetic properties of obsidian. Unlike the bulk chemical composition of the obsidian, the magnetic properties of the mineral grains are affected by the local flow conditions under which the obsidian cooled, which can vary across a single flow, causing intra-flow spatial patterning of the magnetic properties of obsidian (Frahm and Feinberg, 2013).

Obsidian has been the frequent subject of provenance studies in many areas of the world -- including the Near East (Binder et al., 2011), the Mediterranean (Stewart et al., 2003), western North America (Frahm and Feinberg, 2013), Japan (Hall and Kimura, 2002), New Zealand (Sheppard et al., 2011), Mexico (Urrutia-Fucugauchi, 1999), the Andean region of South America (Vásquez et al., 2001), and Kenya (Brown et al., 2013) -- for a number of reasons. First, it was frequently used in artifact manufacture in ancient times around the world practically everywhere it

was available as a natural resource to ancient peoples (Merrick and Brown, 1984a). Second, obsidian-containing localities tend to be very discretized due to the geologic processes that form them (Carmichael, 2014). Obsidian often gets buried under other layers of rock over time, so it is available on the surface only where it has either been freshly laid down by volcanic activity, or where geologic processes such as erosion have brought older layers to the surface (Miller, 2014). The reemergence of old obsidian layers can lead to the existence of a number of discrete obsidian collection localities within a single obsidian flow. Another reason that obsidian is more conducive to provenance studies than some other materials is that the artifact forming processes -- e.g. knapping or flaking -- do not affect obsidian in ways that would affect the properties that are generally used for sourcing materials (Rapp and Hill, 2006). For example: unlike metal ores, which are refined by melting to separate the metal from the unwanted parts of the ore, obsidian artifacts are formed by processes which do not affect the chemistry or magnetic properties of the original material.

One challenging bit of terminology encountered in archaeological provenance studies is the term "obsidian source". Over the history of obsidian provenance studies, different researchers have used varying definitions of an obsidian "source". It seems that each author's definition has generally been defined by the scale of resolution on which the characterization techniques they used can effectively differentiate various obsidians. Many previous authors have used the term "source" to mean one chemically "identical" set of localities, presumed to be from the same

eruptive event or flow due to their chemical similarity (e.g. McDougall et al., 1983; Urrutia-Fucugauchi, 1999; Duttine et al., 2008; etc.). This definition is adopted here, as this is the scale of characterization that is mainly being considered here, and different usages of the term "sources" will be identified by alternative descriptive names to differentiate them. One particular example of a usage of "source" in a more geographically restrictive sense occurs in the recent Frahm and Feinberg paper (2013), where the term "source" refers to the individual quarry localities rather than clusters of quarries showing similar material properties. In this study the term "locality" will be used to discuss the particular quarry from which an artifact originated. In addition, what is referred to in this study as a "source" has been referred to as a "source group" or "petrological group" in previous published research done on these samples (Merrick and Brown, 1984a; Merrick and Brown, 1984b; Merrick, Brown and Nash, 1994; Brown et al., 2013). In this study, "source group" "group" and "source" are used approximately interchangeably.

Evolution of Obsidian Provenance Studies

The development and use of obsidian provenance studies has been a major archaeological success story. Over the roughly fifty years or so that obsidian sourcing has been developing, hundreds of such studies have been conducted (Frahm and Feinberg, 2013). Of the methods that have been tested for sourcing obsidian, chemical analysis techniques – such as spectrometry based methods including optical emission spectrometry (OES) (e.g. Cann and Renfrew, 1964) and more refined inductively coupled plasma mass spectrometry (ICP-MS) (Binder et al., 2011), x-ray fluorescence (XRF) (e.g. Ndiema et al., 2011), electron microprobe

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analysis (EMP) (Brown et al., 2013), and neutron activation analysis (NAA) (Hallam et al., 1976) – have come to be widely used and are considered the most successful, although a number of other metrics have also been used at various times to characterize obsidian sources (e.g. Binder et al., 2011; Duttine et al., 2008; Game in Leakey, 1945). In the case of eastern Africa, alternate sourcing metrics that have been used include refractive index and specific gravity (Game in Leakey, 1945; Walsh and Powys, 1970). Because of its success, chemical composition analysis is the most common obsidian characterization method in use today.

The success of chemical analysis as the leading method of obsidian characterization is in part due to the chemical homogeneity of obsidian within a single flow. Since the obsidian produced from a single eruptive event originated from a single source or chamber of liquid magma, an entire flow will have a homogenous chemical composition. A single volcano can produce multiple eruptive events over its lifetime, each of which will have similar but not identical chemistries because lighter elements tend to become depleted in successive eruptions. In theory, chemical analysis could be used to differentiate among flows from the same volcano if enough elements were analyzed. However, it would be impractical to perform such tests for cost reasons and because at some point the chemical variations may be less than the analytical precision of the measurements. In cases of chemically similar flows from successive eruptions of a single volcano, it is often possible to characterize the individual flows using obsidian dating methods (e.g. Bigazzi et al., 1997) or other supplementary techniques.

In the earlier days of obsidian sourcing, chemical analysis methods – typically OES (Cann and Renfrew, 1964), XRF or NAA -- were costly and more time-consuming than other non-chemical methods that were available at the time. These drawbacks made chemical analysis impractical for sourcing large collections of artifacts. These earlier chemical analytical techniques were generally also destructive of the samples, which is obviously undesirable when it comes to working with scarce archaeological materials. These disadvantages led researchers to search for alternative and perhaps better methods for sourcing obsidian. One of the more commonly studied alternatives to chemical analysis was magnetic testing (McDougall et al., 1983).

The first major magnetic obsidian provenance study was conducted by McDougall (McDougall, 1978; McDougall et al., 1983). The purpose of the study was to examine whether magnetic analysis could be used as an effective alternative to slower and more expensive chemical analysis methods. McDougall and others (1983) analyzed a collection of Mediterranean obsidians consisting of both geological and archaeological samples. Their archaeological samples had already been chemically analyzed by NAA, and they used this previous chemical sourcing data for comparison to test the reliability of their magnetic data (McDougall, 1978). They tested a number of magnetic parameters including natural remanent magnetization, saturation magnetization, and mass susceptibility -- another magnetic property that has been used for previous magnetic studies (e.g. Schmidbauer et al., 1986) but is

not further discussed here. Using a combination of these parameters, they were able

to partially characterize the obsidian sources in the Mediterranean. However,

McDougall and others' magnetic data showed high intra-source variability, making

the precise characterization of sources more difficult (McDougall et al. 1983). Most

of the obsidian sources that had been previously identified through chemical

analysis were distinguishable with minimal overlap, but there were a few sources

that had too much overlap to be easily distinguishable. This can be seen in Figure 1.
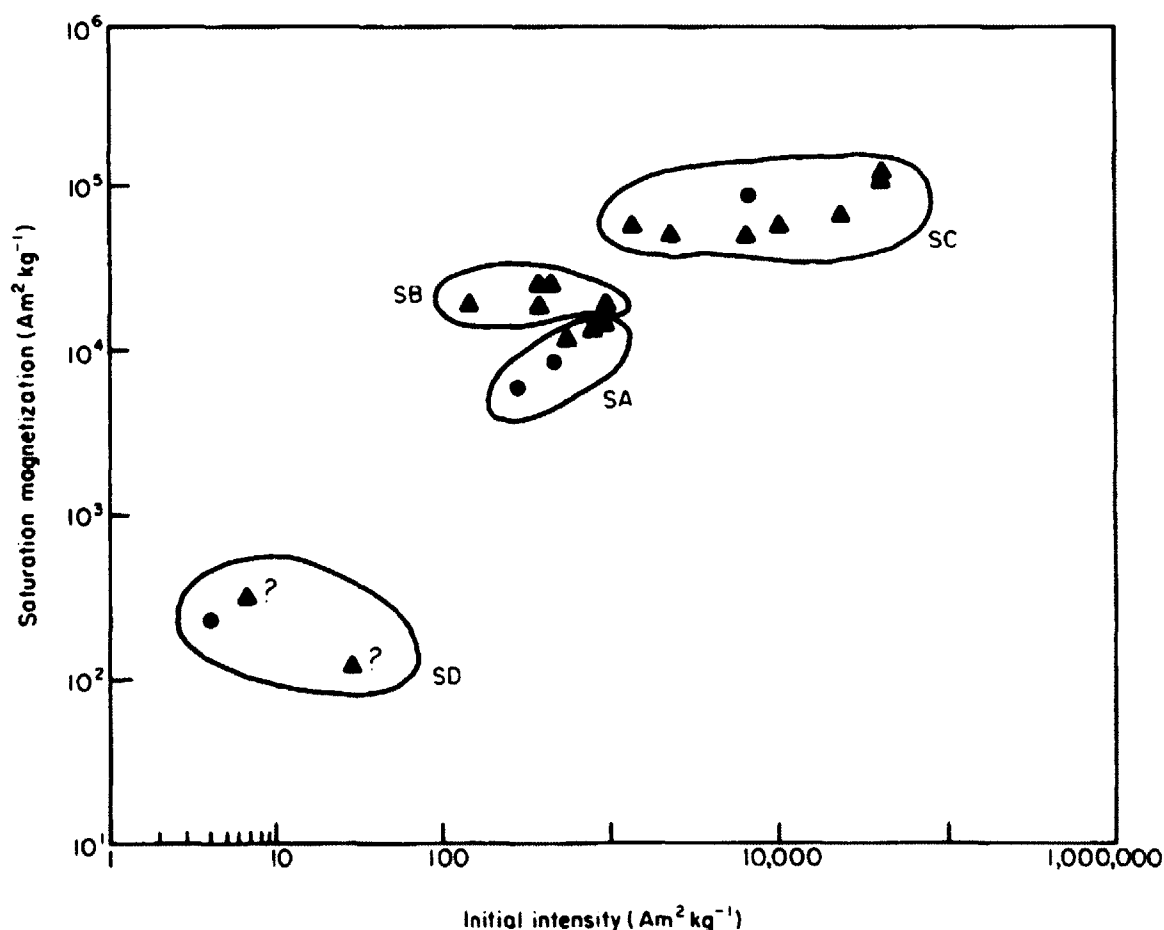
Figure 1. Initial and Saturation magnetization of Sardinian obsidians, from McDougall et al., 1983. Circles represent source samples, and triangles represent archaeological artifacts. SA, SB, SC, and SD are chemically distinct obsidian sub-types. SC and SD can be clearly distinguished, but SA and SB are close enough together that distinguishing between the two using this method would not be feasible.

Since McDougall and others' initial study, several other magnetic obsidian

provenance studies have been conducted in various regions, including Mexico

(Urrutia-Fucugauchi, 1999), and the Near East (Hillis et al., 2010; Frahm and

Feinberg, 2013). These studies have generally yielded mixed results, with most

finding that magnetic analysis could work in specific cases, but that it is still less

reliable than chemical sourcing techniques, and thus not a good substitute. Prior to

the current research, no such magnetic studies had been conducted on Kenyan or

other eastern African samples.

Magnetic properties, unlike chemical composition, are dependent on the

microstructure and molecular organization of the material (Carmichael, 2014).

Since these both depend on the conditions in which the obsidian cooled, the

magnetic properties of obsidian are not always constant across a single flow (Frahm

and Feinberg, 2013). This variation can make it difficult to differentiate between

obsidian flows using magnetic properties in regions with chemically similar

obsidian sources, like those observed in the studies reference above. Since there is

higher intra-source variation in magnetic properties, it is easier for different

sources' magnetic signatures to overlap than for their chemical compositions to do

so.

Despite the mixed success of previous magnetic obsidian provenance studies,

certain characteristics of eastern African obsidians make them a potential target for

better results from magnetic study. The obsidian flows in Kenya are known for

having a much higher range of iron contents than obsidians in most other regions, and given the highly magnetic nature of iron minerals, this wider range may possibly translate to wider inter-source variation, potentially making magnetic sourcing more effective in this region than previous research in other regions has found it to be. Despite improvements in chemical analysis methods, magnetic analysis is still fairly easy and cheap, so if it were useful in discriminating between sources, it might still provide a reasonable alternative to chemical analysis.

Kenyan Obsidian

Obsidian provenance study in Kenya began in the 1940s with P.M. Game's study of the refractive index and specific gravity of obsidian artifacts from the Hyrax Hill archaeological site being studied by Mary D. Leakey (1945). The refractive index is a measure of how light bends across the boundary between different materials, and specific gravity compares the density of a sample to the density of a reference substance, usually water, under the same conditions. Game compared the data from these archaeological samples to data from samples from the Njorowa Gorge and Mt. Eburru obsidian sources. From this comparison, he was able to determine that ancient people had been using obsidian from both of these sources (Game in Leakey, M.D. 1945).

Chemical analysis as a method for obsidian provenance was not used in Kenya until the 1970's and 1980's. The first of such studies in the region (Michels et al., 1983; Merrick and Brown, 1984a; Merrick and Brown, 1984b) utilized atomic absorption spectroscopy (AAS), XRF and electron microprobe analysis (EMP) techniques to

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characterize obsidian samples. These techniques proved successful, and they continue to be used to this day. NAA has also been used recently in this region. Coleman and others (2008) showed NAA to have better resolved data clusters than XRF. As of today, more than 80 chemically distinct Kenyan obsidian sources have been characterized, although only about 20 of these are known to have been used archaeologically, and even fewer saw regular use (Brown et al. 2013).

Obsidian artifacts are known to have been in use in Kenya as early as 974,000 years ago (Durkee and Brown, in press). Thereafter, obsidian continued to be used, though uncommonly, throughout the Acheulean period, or the latter half of the Early Stone Age until about 200,000 years ago. Obsidian use in the region picks up in the Middle Stone Age beginning within the last 150,000 years, with the majority of archaeological sites within a radius of about 50 km from a source of obsidian showing use of it. The first appreciable quantities of obsidian (20% or greater) at sites more distant than 50 km from any obsidian sources also start to appear during this period. By the Late Stone Age, almost all sites in the central Rift Valley in Kenya display considerable percentages of obsidian artifacts, suggesting pervasive adoption of obsidian as a tool-making material (Merrick, Brown and Nash, 1994).

The Pastoral Neolithic period began in eastern Africa around 2000 BC. In this period, obsidian starts to appear as the dominant material (>90%) in nearly all archaeological sites within 50 km of an obsidian source. Obsidian also begins to be used very frequently further away from sources during this period, with a number

of sites as far as 100-200 km away showing high frequencies of obsidian (Merrick and Brown, 1984a).

Materials and Methods

Types of Magnetism

The magnetic properties of materials are derived from the atomic magnetic moments of their constituent atoms. Although most people only think of "magnetic" materials as materials that can be permanently magnetized, many materials generate some kind of response to being placed in a magnetic field (Borradaile et al., 1998). Some of the common types of magnetic response are shown in Figure 2, along with relevant examples of materials that produce each kind of response.

Paramagnetic	Ferromagnetic	Antiferromagnetic	Ferrimagnetic
Ex: Aluminum	Ex: Pure Fe metal	Ex: FeO, α-Fe_2O_3	Ex: γ-Fe_2O_3, Fe_3O_4
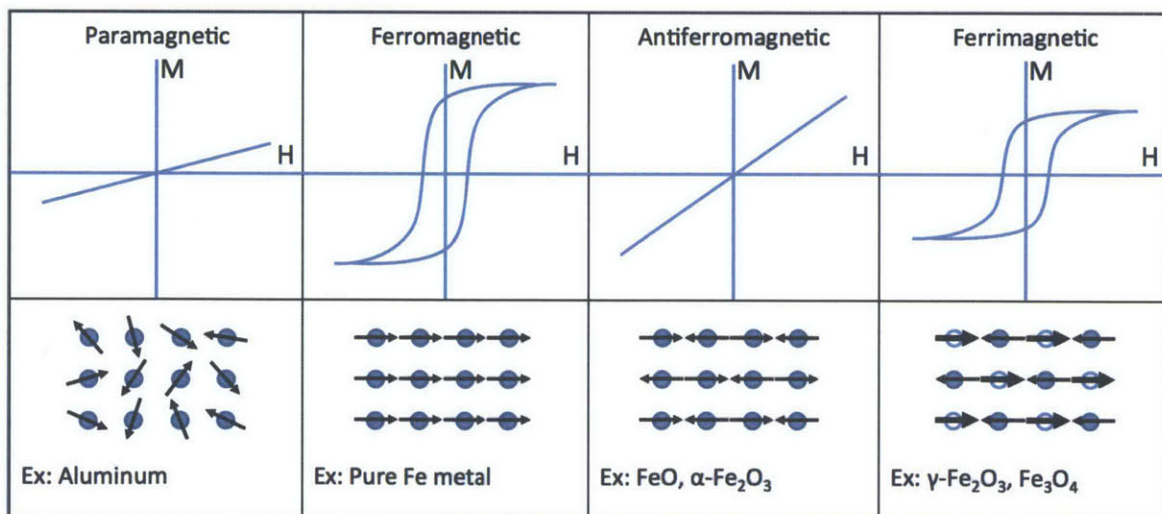
Figure 2. Generic hysteresis loops and diagrams of the atomic basis for various types of magnetic response.

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Paramagnetic

Paramagnetic materials have unpaired electrons, each of which has a fluctuating magnetic dipole moment, but there is no interaction between the electrons of adjacent atoms. The lack of interaction means that the moments are randomly directed, causing a lack of macroscopic magnetization when not under the influence of an external magnetic field. However, when a magnetic field is applied, the moments will rotate to line up with the direction of the applied field. The strength of this response increases linearly with the strength of the field applied, but quickly dissipates when the field is removed (Carmichael, 2014).

Ferromagnetic

Ferromagnetic materials are the type of material that most people associate with the concept of magnetism because ferromagnets can hold a strong permanent magnetic charge. When there is no magnetic field being applied, the exchange interactions between the individual magnetic dipole moments cause them to line up. The combination of all of the atomic moments is strong enough to cause the bulk material to have a macroscopic magnetization (Carmichael, 2014).

Antiferromagnetic

Antiferromagnetic materials are similar to ferromagnetic materials in that all of their atomic magnetic moments want to align when there is no applied magnetic field. However, the structure of the material is such that it is favorable for every other atom in the structure to be aligned in the opposite direction, causing the net

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magnetic moment of the bulk material to vanish. Thus, although the atomic moments in an antiferromagnet are aligned, and hence the material is magnetically ordered, it exhibits zero macroscopic magnetization in zero applied field. When an external magnetic field is applied, antiferromagnetic materials act similarly to paramagnetic materials, with the dipole moments rotating towards the same orientation (Carmichael, 2014).

Ferrimagnetic

Ferrimagnetic materials, like antiferromagnetic materials, have adjacent atoms that align in opposite directions. However, the strength of the magnetic moment on adjacent atoms is not equal, so ferrimagnets can still have a non-zero net magnetic moment in the absence of an applied magnetic field (Carmichael, 2014).

The bulk magnetic properties of rocks come from the magnetic properties of the constituent mineral grains (Carmichael, 2014). In general, only a small fraction of these mineral grains are magnetic materials. In obsidian, various iron oxides make up the majority of the magnetic mineral grains. Examples of the most relevant Fe oxide variants are listed in Figure 2, and are typically either antiferromagnetic (FeO, α-Fe_2O_3) or ferrimagnetic (γ-Fe_2O_3, and Fe_3O_4).

The graph in Figure 3 shows a generic example of a hysteresis loop. A hysteresis loop measures the reaction of a material to being put in a magnetic field, plotting the material's induced magnetization (M) in response to an applied field of varying strength (H). The applied field is cycled, first increasing in strength in one direction
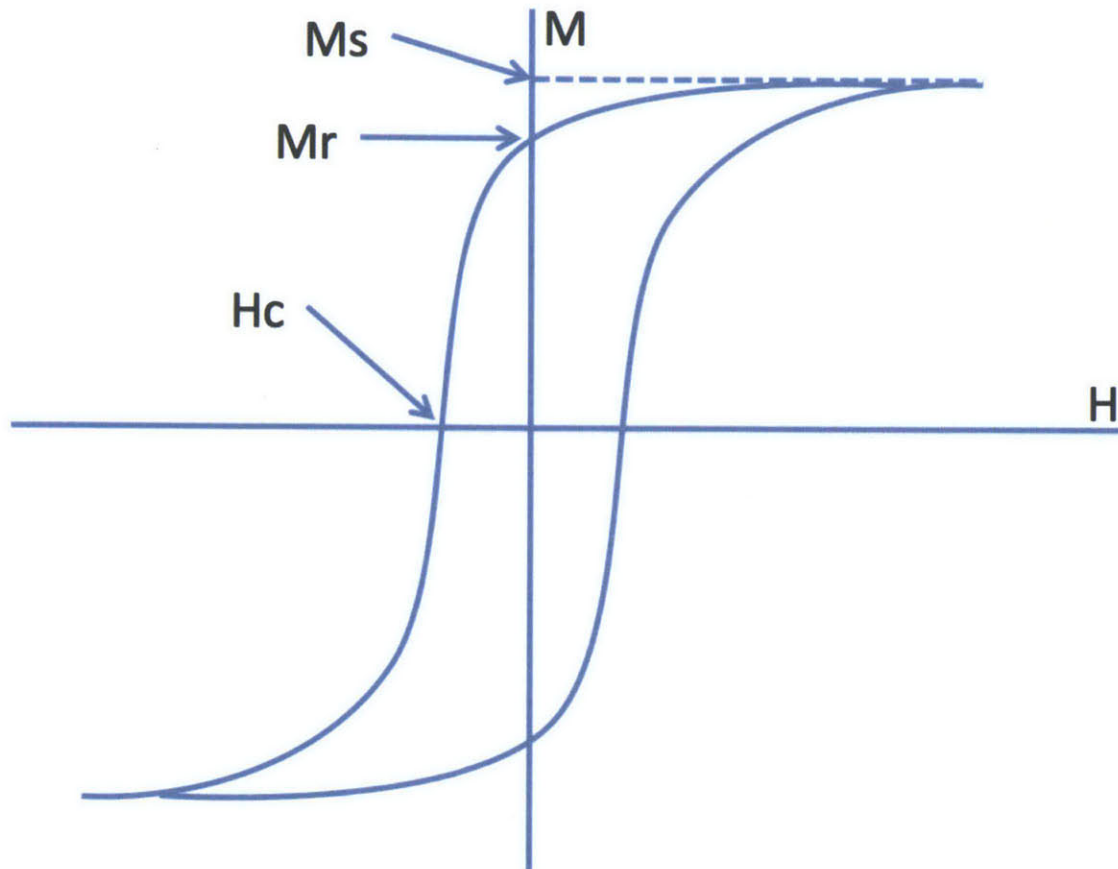
Figure 3. Generic hysteresis loop diagram, measuring applied field (H) against induced magnetic response (M). The points at which saturation magnetization (Ms), remanence magnetization (Mr), and coercivity (Hc) are measured are labeled.

until the sample's magnetization is saturated and the induced magnetization no longer increases, and then returning to zero and increasing in the opposite direction until the sample has reached its saturation magnetization in the other direction before returning to a state of no applied field (Nave, 2014). This cycling yields a somewhat S-shaped loop, although the exact shape of the curve can vary depending on what type of magnetic response the material produces (see Figure 2).

Several magnetic properties can be determined from a hysteresis loop test. The parameters studied here are saturation magnetization (Ms), remanent

magnetization (Mr), and coercivity (Hc). Figure 3 shows where each of these properties appears on a hysteresis loop diagram. Saturation magnetization is the maximum induced magnetization that can be achieved. Remanent magnetization is the strength of the induced magnetization when the applied field drops to zero, showing how strong the magnetization on the sample is when it is no longer in a magnetic field. Coercivity is the strength of the applied magnetic field required to reduce the sample's induced magnetization to zero, measuring how strong a magnetic field is required to demagnetize the sample (Nave, 2014).

Magnetic analysis measures properties of the sub-millimeter-scale magnetic mineral grains in the obsidian. In the process of cooling, obsidian undergoes a range of temperatures and viscosities, as well as deformation and oxidation, all of which affect the size and composition of the mineral grains present in the obsidian (Miller, 2014). These variables can differ widely within a single obsidian flow, causing variation in magnetic properties across the flow. This interpretation sees support in previous studies that show large variability in magnetic properties across a given flow (Urrutia-Fucugauchi, 1999; Frahm and Feinberg, 2013).

Since the magnetic properties of obsidian depend on the chemical phase and microstructure of the Fe oxide grains, these properties can potentially be used to discriminate between obsidians formed under different conditions. Determining the forms of Fe present could provide an additional discriminant for magnetic characterization, whether used as an alternate or supplementary method to

chemical analysis. Such methods can provide information that even very precise chemical analysis cannot. For example, the two main forms of Fe_2O_3 that are present in obsidian (α-Fe_2O_3 and γ-Fe_2O_3) would be indistinguishable from chemical tests due to the fact that both forms have identical chemical composition. However, α-Fe_2O_3 is antiferromagnetic, while γ-Fe_2O_3 is ferrimagnetic, so the two should show very different magnetic responses, allowing discrimination between them (Carmichael, 2014). While the tests performed here cannot completely determine the forms of Fe oxides present in the samples, comparing the weight-normalized Ms to the weight percent of Fe in the obsidian sample can give some information on the fraction of Fe in various forms, discussed further in the Results section.

Samples and Sample Preparation

This study analyzed specimens from the obsidian collection from Harry Merrick and Francis Brown's chemical composition sourcing work in eastern Africa (Merrick and Brown, 1984a; Brown et al., 2013). A map of the localities from which the specimens were originally collected is shown in Figure 4. Figure 5 gives a closer view of the central area of the previous map to more clearly show the closely clustered localities in that area. Detailed chemical composition information for all of the samples analyzed here is available in Brown et al., 2013. This data set was compared with the magnetic data acquired in this study to determine whether magnetic testing could be used as an alternative or accessory technique to supplement archaeologists' current ability to distinguish among Kenyan obsidian sources.

The available Merrick and Brown sample collection included specimens from 23 of the geochemically distinct source groups in Kenya recognized in Merrick and Brown, 1984a. Sixteen of these groups are known to have been used archaeologically, with only 5-6 of these seeing frequent usage. Of this collection, a total of 192 samples from 26 different pieces of obsidian were analyzed. These pieces were collected from 23 different localities assigned to 6 different petrological
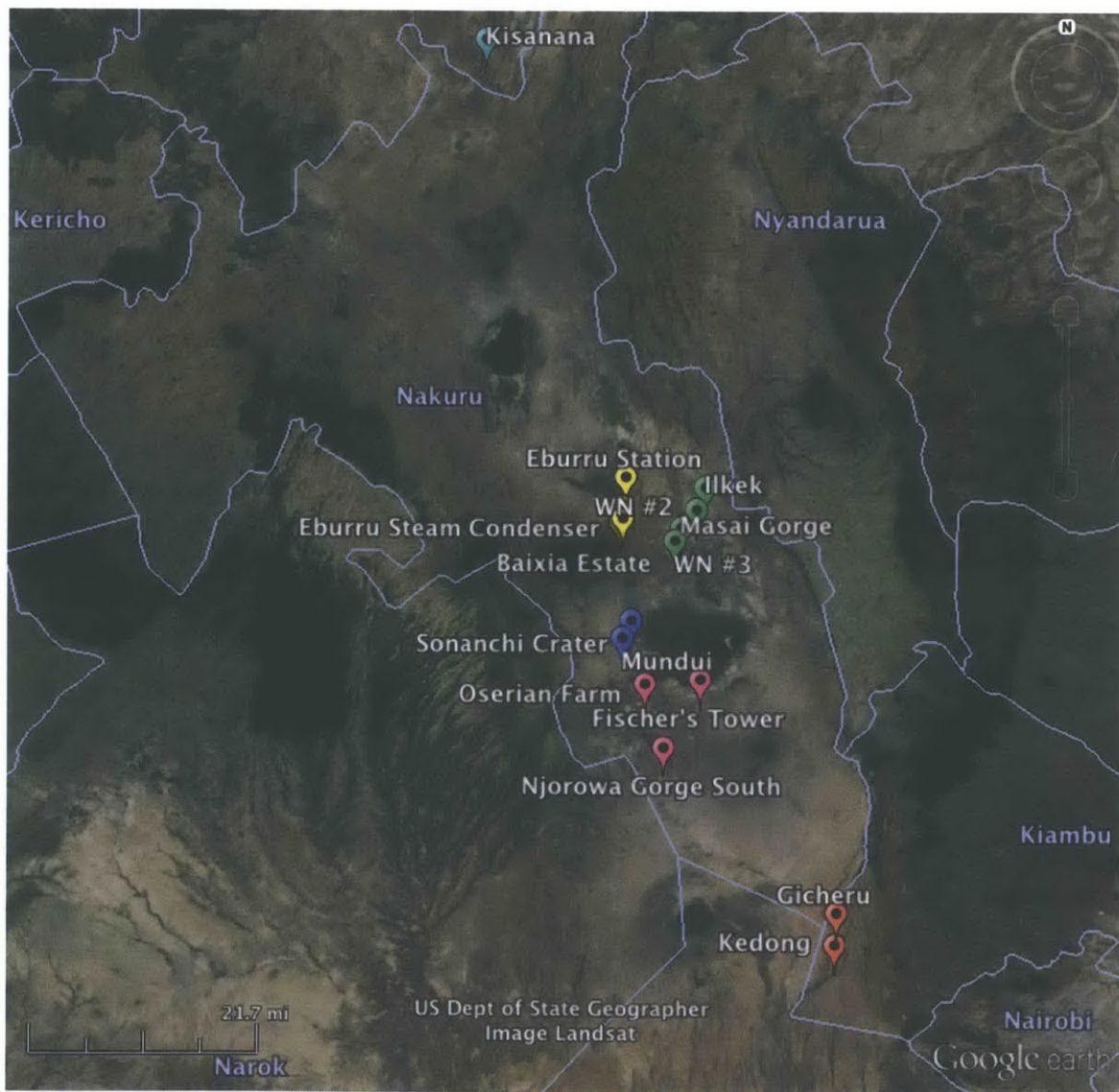
Figure 4. Map of all source localities. Symbol color indicates the petrological group of the locality (Merrick and Brown, 1984a). Pink: Group 20, Red: 14, Yellow: 29, Green: 32, Blue: 8, Purple: 19.

groups (Groups 8, 14, 19, 20, 29, and 32) as recognized by Merrick and Brown

(1984a). Only obsidian source groups that have been observed to have been used

for artifact manufacture in the past were selected for analysis in this study. The first

four groups analyzed (8, 14, 19, and 29) were selected to represent a wide range of

Fe contents, as measured by Brown and others (2013). The other analyzed groups

(20, and 32) were chosen for their known use as common obsidian sources in

Figure 5. Closer view of source localities map showing group 29 and 32 localities (Merrick and Brown, 1984a), which were too close together for easy differentiation on the larger map.

prehistoric times. A list of samples, their petrological groups and locations, Fe

contents, and all collected analytical data are given in Appendix A: Table 1.

To prepare the samples for testing, small chips were flaked off of the specimens with

a small copper rod. The chips were then further ground down by hand with the
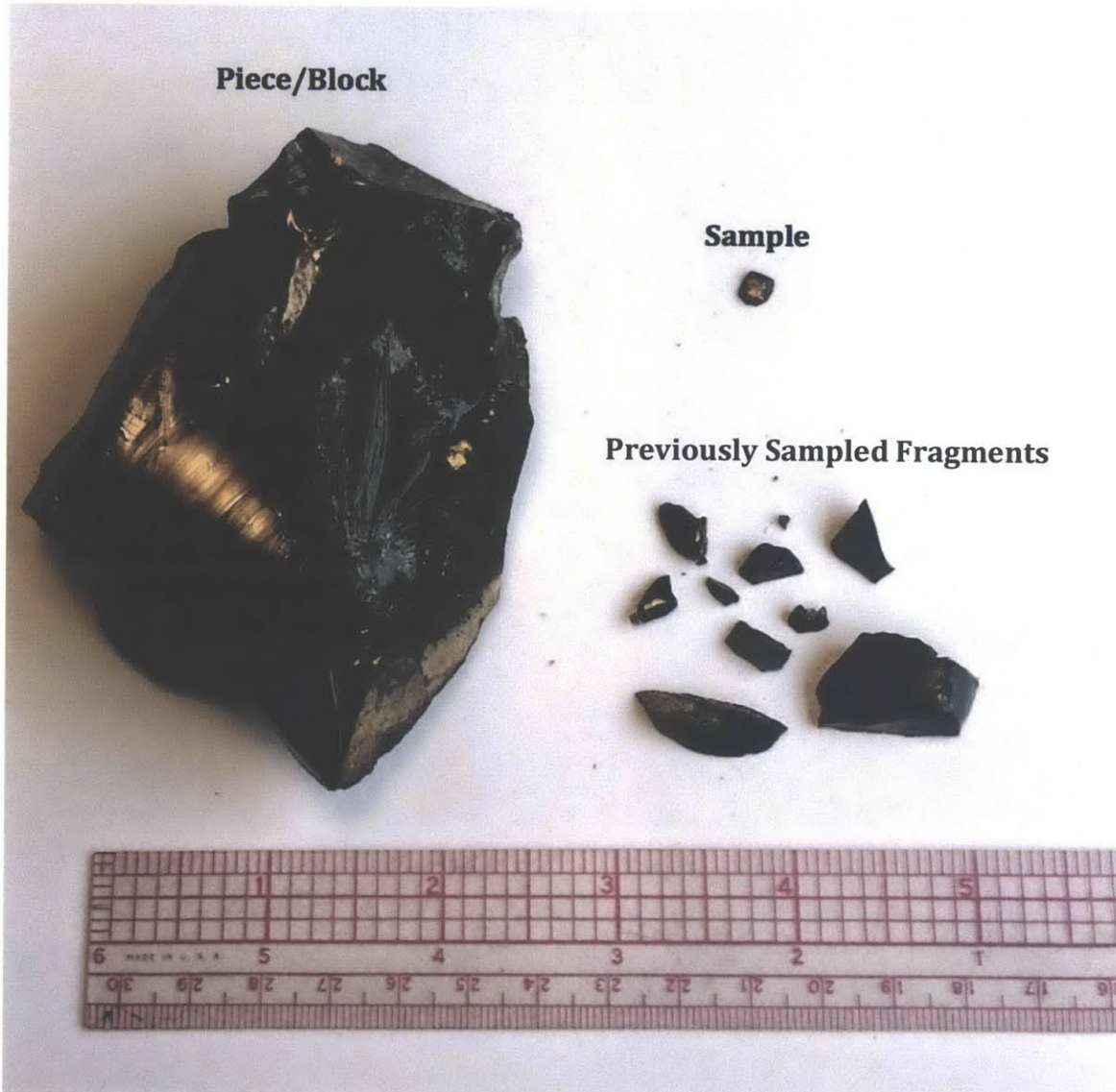
Figure 6. Photograph of an obsidian specimen, shows examples of how large pieces/blocks and samples are. The photographed material makes up a single specimen, although some specimens contain multiple pieces/blocks. Ruler for scale.

same copper rod to the point where they were approximately the same size (see Figure 6 for scale). Some variation was to be expected considering the fact that the samples were sized by hand and the similarity between sample sizes was determined by a rough visual estimate. All samples' sizes were compared to the first sample created to establish a consistent approximate size. Although this method does not provide a perfectly consistent sample size, this technique is similar to that used for sample preparation in the recent magnetic obsidian sourcing study by Frahm and Feinberg (2013; sample preparation discussed in Frahm, 2010), one of only two papers located that went into detail about their sample preparation methods. The other paper was the McDougall et al. (1983) paper, which used a different enough magnetometer setup that their sample preparation procedure is not relevant here. Despite the slight sample size variation, initial tests of several samples from the same obsidian specimen suggest that size does not noticeably affect the relevant magnetic parameters once they have been weight-normalized, as was expected.

Most of the specimens available for sampling were single pieces of obsidian, along with some small fragments that had resulted from previous sampling of the pieces (see Figure 6). A few of the potential samples consisted of multiple main pieces, which were collected at the same location and thus considered part of the same petrological group for sampling purposes. In such cases, this study considered each of the larger pieces as a separate "block" to avoid the possibility of unexplained bimodality in the case that the two blocks had significantly different properties.

Analysis Methods

Hysteresis loop data can be collected on a vibrating sample magnetometer (VSM). As shown in Figure 7, a VSM consists of several magnetic coils and a sample holder that is vibrated between them. The field coils create a magnetic field around the sample, which induces a magnetic moment in the sample. The sample is vibrated up and down, which rapidly changes the magnetic flux felt by the pickup coils. The changing magnetic flux causes a voltage difference across the pickup coils which is directly related to the strength of the induced magnetic moment on the sample. The voltage difference can thus be measured and from that the induced magnetic moment can be calculated.
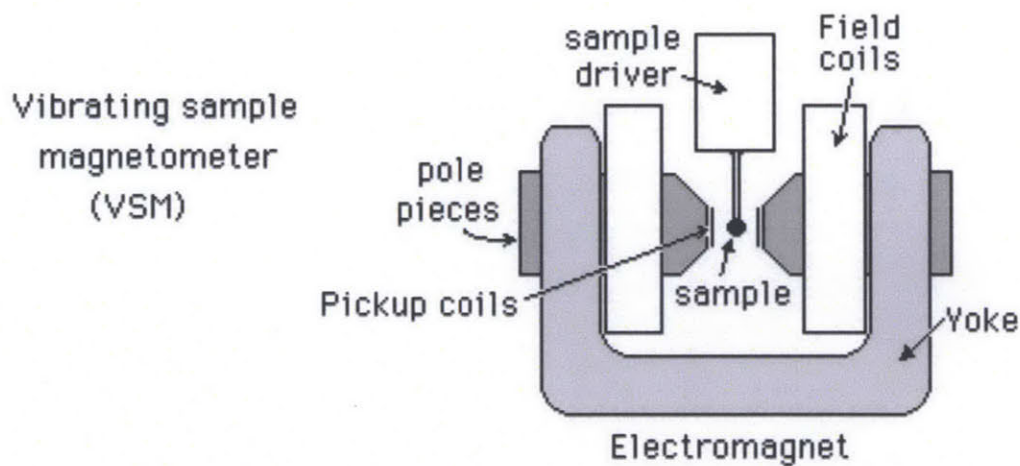
Figure 7. Vibrating sample magnetometer schematic diagram. From MIT 3.014 lab handout "Work Derived from Magnetic Hysteresis Curves", Fall 2008.

The samples in this study were analyzed using a Digital Measurement Systems VSM maintained by the MIT Department of Material Science and Engineering in the undergraduate teaching lab. The applied and induced magnetic fields were measured to create a hysteresis loop, from which the Ms, Mr, and Hc were calculated. These parameters were measured on both sides of the hysteresis loop

and then averaged to minimize possible orientation effects or machine calibration errors. All of the tests were performed at room temperature.

Data analysis was performed using a combination of Microsoft Excel and Mathematica. The final plots were generated using Excel. The magnetic properties mentioned above were analyzed to determine whether any of them, alone or in combination, could be used as an alternate or supplementary method for differentiating between Kenyan obsidian sources. The potential for characterization was analyzed both between sources and, for the few sources with samples from multiple localities, between localities within the same source.

In addition to the above data comparison, an approximation of the forms of Fe present in the samples was also calculated. For the purposes of these calculations, it was assumed that the magnetic moment from non-Fe sources is negligible. This allowed the use the Ms measurements to gain some insight into the mineral forms of Fe present in the obsidian, something that cannot be obtained from chemical analysis alone. By adjusting the chemical analysis data from Brown et al.'s (2013) work -- which lists the Fe content of the samples in weight percent Fe_2O_3 -- such that it is in weight percent Fe, the ratio of measured Ms to weight percent Fe can be compared to literature values for the Ms per weight percent Fe of solid samples of various mineral forms of Fe (O'Handley, 2000). This comparison provides an approximation of what forms of Fe are present in the samples. The results from all of these calculations are shown in the Results section.

Results

The magnetic analyses yielded hysteresis loop data both as a series of data points and as visual output. Two representative examples of the hysteresis loop behavior observed are shown in Figure 8 and Figure 9. Figure 8 shows the visual output from one of the samples from the Baixia Estate locality, while Figure 9 shows one from the Sonanchi Crater locality. The Baixia Estate sample shows what is likely either paramagnetic or antiferromagnetic behavior. In this case, it is more likely that the behavior is due to an antiferromagnetic response because none of the relevant Fe
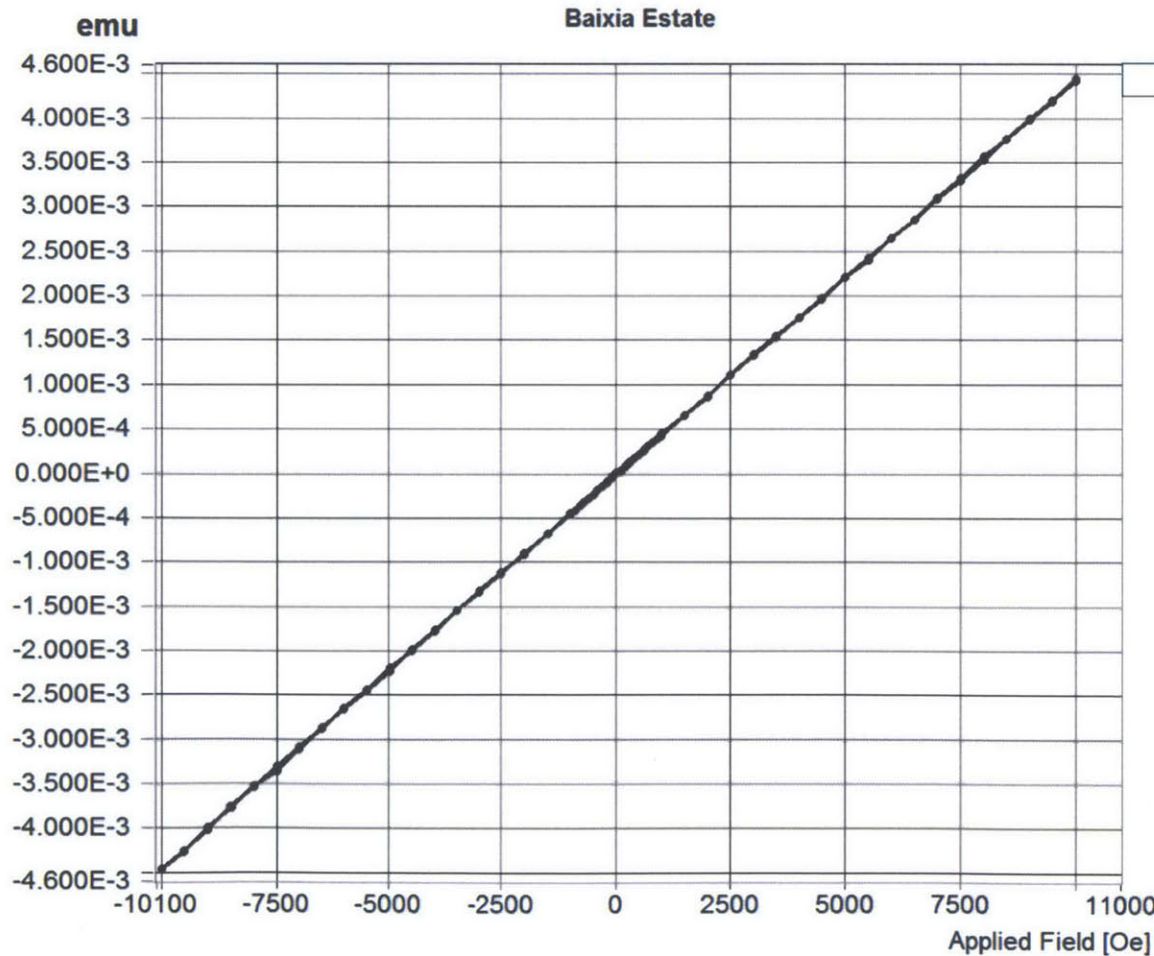
Figure 8. Sample of visual VSM output from a Baixia Estate sample.

oxides that are likely creating the observed magnetic response exhibit paramagnetic behavior. The Sonanchi Crater sample shows a combination of linear and S-curve characteristics, suggesting that there are likely multiple forms of Fe oxides present in the sample. There is discussion later in this section of the likely Fe oxide form compositions of the analyzed samples.
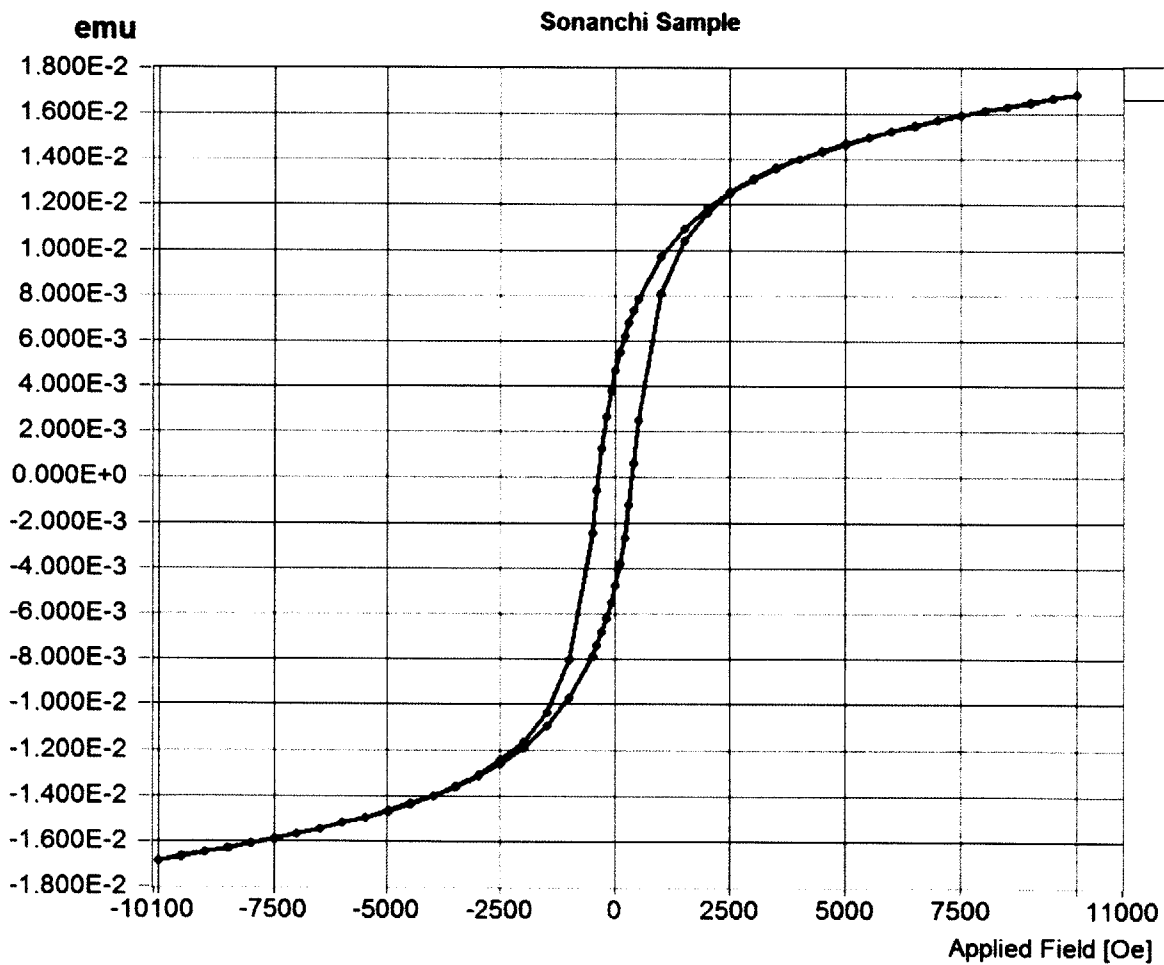
Figure 9. Sample of visual VSM output from a Sonanchi Crater sample.

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Characterization by Squareness and Coercivity

A combination of the main magnetic properties observed in this study provided accurate characterization for three of the major obsidian sources surveyed, although the other analyzed sources were not easily distinguishable. Figure 10 shows the hysteretic squareness (Sq), which is a ratio of Mr and Ms, plotted against Hc for all analyzed samples. Several of the major obsidian sources tested (Groups 29, 14, and 19) show distinctive differences in both their average values for Sq and Hc, and also the slope that the sample clusters create.
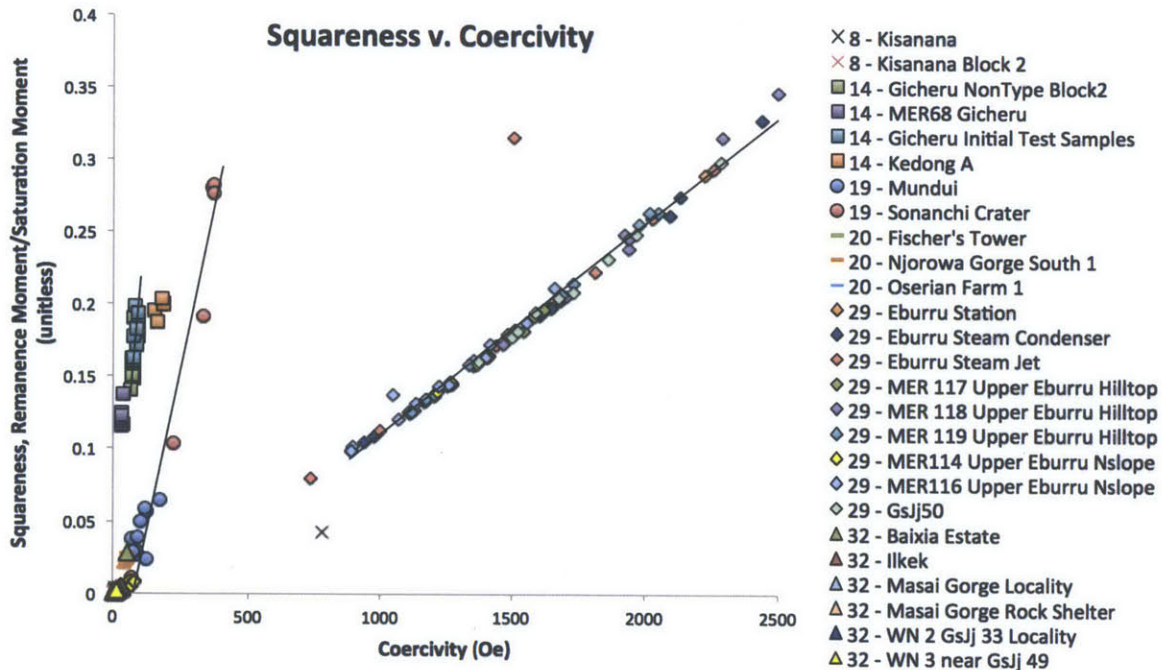
Figure 10. Plot of the coercivity (Hc) versus the hysteretic squareness (Sq).
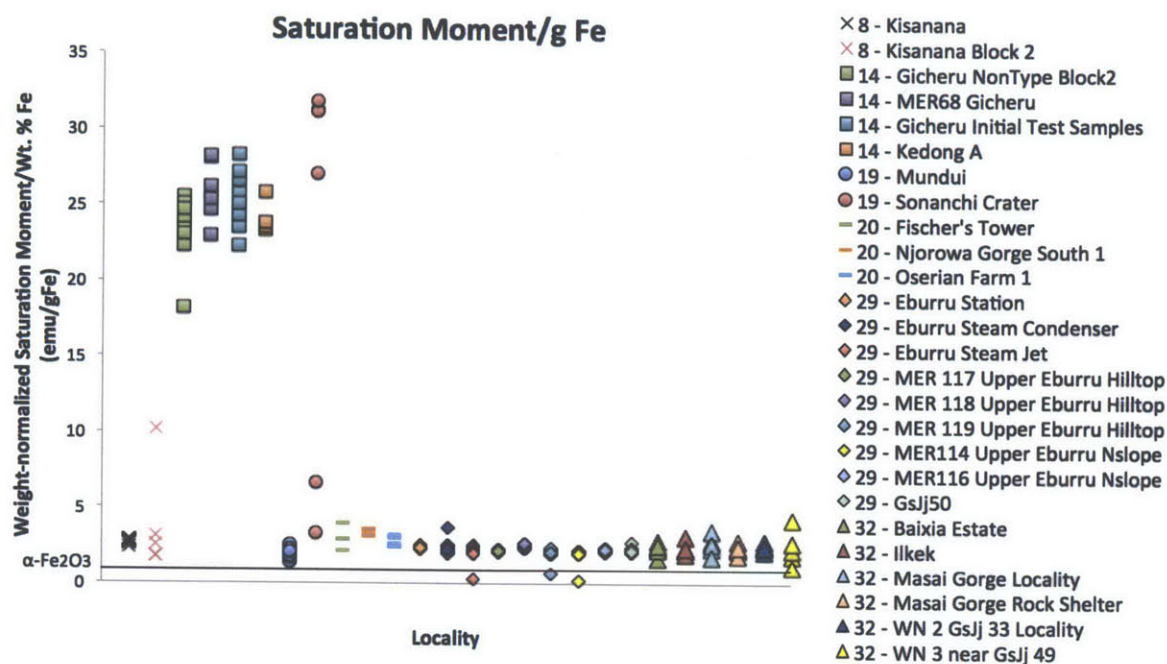
Figure 11. Plot of saturation moment (Ms) per gram of Fe in the sample, ordered by source group and locality. Weight percent Fe$_2$O$_3$ for all samples (except Masai Gorge, WN 2 and WN 3) found in Brown et al. 2013. Previously unpublished Fe$_2$O$_3$ values for these three (Appendix A: Table 1) were provided by Merrick (pers. com. 2014).

Saturation Moment and Fe Percentage Calculations

For the purposes of analysis, the magnetic responses of the samples were assumed to be completely caused by various forms of Fe in the samples, since Fe is the only magnetic mineral found in noticeable concentrations in the analyzed samples (Brown et al. 2013). The saturation moments obtained in this study and the Fe concentrations given for the samples in Brown et al.'s (2013) paper were used to determine the saturation moment per gram of Fe in each sample (see Figure 11).

The calculated Ms/gFe values for the samples were then compared to literature values from pure samples of various Fe oxides to give an approximation of the forms
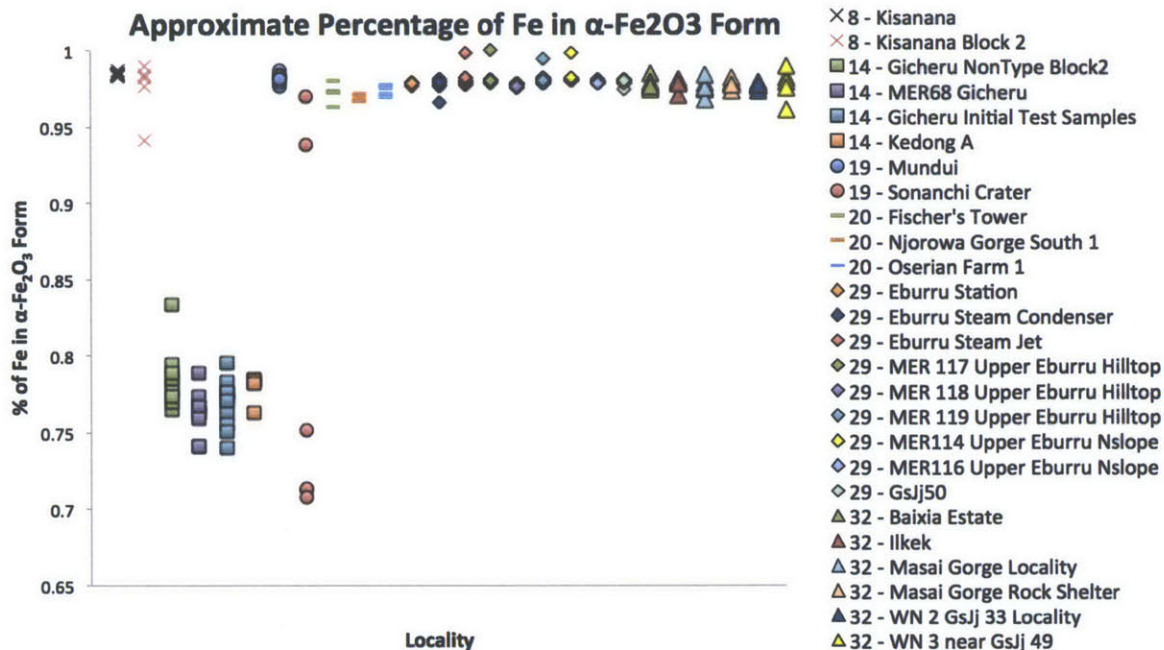
Figure 12. Plot of calculated approximate percentage of Fe in α-Fe₂O₃ form in the sample, ordered by source group and locality. Calculations were performed assuming only α-Fe₂O₃ and Fe₃O₄ forms existed in the obsidian.

of Fe present in the samples. Based on these calculations, the Fe in most of the analyzed sources was almost entirely in α-Fe₂O₃ form (see Figure 12). The only source that had a noticeably distinct percentage of α-Fe₂O₃ was Group 14, which had an average of about 20% less α-Fe₂O₃ than the rest of the sources tested.

Only the three most common iron oxides (α-Fe₂O₃, γ-Fe₂O₃, and Fe₃O₄) were included in the above analysis. For the purpose of analyzing the percentages shown in Figure 12, the percentages were calculated as if there were only α-Fe₂O₃ and γ-Fe₂O₃ in the samples. This calculation was also performed assuming only α-Fe₂O₃ and Fe₃O₄, and there was 1% or less difference between the two calculated values for all the samples except for those in Group 14. These samples showed a maximum

difference of 4%, but the percentages of Fe oxides were still distinct enough to differentiate Group 14 from the other sources.

Precision Calculations

Machine precision for the VSM used in this study was analyzed by re-measuring the same sample several times. In addition, several samples from the same specimen (same block of obsidian, but separately flaked off samples) were analyzed to assess the variance within a specimen. The results of these precision analyses are shown in Table 1.

Table 1. Precision calculations

Single Sample (machine precision analysis)				
N = 4	Ms [emu/g]	Mr [emu/g]	Hc [Oe]	Sq/Hc [1/Oe]
Max	0.6102	0.1081	89.8478	0.0022
Min	0.5765	0.1035	83.6454	0.0020
(Max-Min)/2	0.0169	0.0023	3.1012	0.0001
Avg.	0.5896	0.1061	86.8748	0.0021
St. Dev.	0.0149	0.0020	3.0541	0.0001
% St. Dev	2.5206	1.9078	3.5156	4.0889

Separate samples from same specimen (testing variance within a single specimen)				
N = 8	Ms [emu/g]	Mr [emu/g]	Hc [Oe]	Sq/Hc [1/Oe]
Max	0.6696	0.1085	88.9444	0.0025
Min	0.5277	0.1020	71.5908	0.0020
(Max-Min)/2	0.0709	0.0032	8.6768	0.0002
Avg.	0.5975	0.1060	80.5700	0.0022
St. Dev.	0.0469	0.0026	5.5941	0.0001
% St. Dev	7.8552	2.4114	6.9431	6.1620

Discussion and Conclusions

Conclusions

Based on these magnetic analyses, it is possible to differentiate between three of the main obsidian source groups known to have been used archaeologically, source groups 14 (Kedong), 19 (Sonanchi), and 29 (Upper Eburru) using the classification from Merrick and Brown's work (Merrick and Brown 1984a). Each of the three groups has a distinctive slope when the hysteretic squareness is plotted against the coercivity of the samples. The differentiation between these three sources is stronger than the differentiation seen in previous magnetic provenance studies in other regions (e.g. McDougall et al., 1983; Hillis et al., 2010; Vásquez et al., 2001; etc.), suggesting that such methods could have the potential to still be a useful metric for the characterization of Kenyan obsidians. The remaining three source groups sampled that could not be characterized all had very weak magnetic responses, making it difficult to tell whether any pattern in the ratio of Sq to Hc was due to actual magnetic differences or background noise. This uncertainty could potentially be resolved by analyzing the temperature dependence of the properties measured here. The approximate percentage of Fe in various forms in the samples was also calculated. For almost all sources, the Fe in the samples was almost entirely α-Fe$_2$O$_3$. In the samples from source group 14, approximately 20-25% of the Fe is likely to be in either γ-Fe$_2$O$_3$ or Fe$_3$O$_4$ forms. Both γ-Fe$_2$O$_3$ and Fe$_3$O$_4$ have high Ms values, while α-Fe$_2$O$_3$ has a comparatively very small Ms value, so the percentage of α-Fe$_2$O$_3$ was able to be determined to within 1% (or within 4% for the group 14

samples), but how much of the remainder is $\gamma\text{-}Fe_2O_3$ versus Fe_3O_4 is difficult to determine without further analysis.

Limitations

The samples analyzed here were not an ideal sample set for magnetic provenance analysis. They were not originally collected with magnetic studies in mind, but instead were gathered for a chemical analysis study (Merrick and Brown, 1984a; Brown et al., 2013), so most of the sampled localities only have one or maybe two samples each. Chemical analysis usually requires only a few specimens per source to obtain a useful characterization. Due to the chemical homogeneity of most obsidian flows, this approach is generally reasonable. However, since the magnetic properties of obsidian are more varied across a flow -- and even within a single locality -- than chemical properties, it is necessary to collect many samples from each locality to acquire a complete picture of the magnetic properties of the obsidian (Frahm and Feinberg, 2013). If a more thorough magnetic provenance study were to be done in this region, more comprehensive sampling would likely be needed to fully characterize the sources.

Potential Future Work

There are several directions that future researchers could take this work. All of the tests in this study were performed at room temperature, which could be supplemented with data on the temperature dependence of the samples' magnetic properties (as in Schmidbauer et al., 1986) to get a more in-depth understanding of the magnetic properties and material structure of the obsidian. In particular, the

temperature dependence of coercivity can be used to compare the average particle size of the iron oxide grains in the samples, which would provide comparative data about the cooling rates of the various obsidians in the region. These cooling rates could in turn be utilized as part of a more thorough characterization database for the region. In addition, temperature dependence tests would also give better information about the forms of Fe oxides present in the obsidians, which could provide an additional discriminant for characterization purposes.

Not only could this additional research help provide a more complete characterization signature for inter-flow sourcing, this type of analysis also has more potential than any previous work that has been done in Kenya to provide locality-level characterization, as the Fe oxides present and the grain size of the mineral inclusions in obsidian are closely related to its cooling rate. Cooling rates varies across a given flow, possibly enough to make locality-level characterization possible. Such a study using the same samples that were available for this study could look at such intra-flow sourcing within only a handful of sources, as most of the sources with samples available for this study have specimens from only one or two different localities. Only recently was it acknowledged that the magnetic variability within a flow might provide a useful tool for intra-flow obsidian sourcing rather than just being noise, but the first few studies that have looked into this possibility have shown promising initial results (Zanella et al. 2012; Frahm and Feinberg 2013).

Acknowledgements

Appendix A

Magnetic analysis data from all samples.

MER Number or Type Sample? Equivalent	Petrological Group (Merrick and Brown, 1984)	N Latitude (Brown et al., 2013)	E Longitude (Brown et al., 2013)	Sample Number	Analysis Date	Sample Mass (g)	Ms (emu)	Mr (emu)	Squareness (Mr/Ms) [unitless]	Hc/Ms (Oe)	Ms (emu/g) Weight Normalized	Mr (emu/g) Weight Normalized	Wt. % Fe_3O_4 (Brown et al., 2013)	Wt. % Fe_3O_4 (Brown et al., 2013)	Ms/g Fe (emu/gFe)	%α-Fe_2O_3 and χ-Fe_2O_3 | only α.	%α-Fe_2O_3 and Fe_3O_4 | only α.
Kisanana, Block 1																	
36	No	8	0.034	36.064	1	7/12/13	0.0629	0.00753	2.50E-05	0.00332	25.474	0.11974	0.00040	0.101	0.04464	2.682	0.995	0.997
36	No	8	0.034	36.064	1.1	7/12/13	0.0629	0.00794	7.91E-06	0.00100	17.969	0.12623	0.00013	0.101	0.04464	2.828	0.994	0.996
36	No	8	0.034	36.064	2	7/12/13	0.0403	0.00520	2.23E-04	0.04280	778.16	0.12899	0.00552	0.101	0.04464	2.889	0.994	0.996 ^
36	No	8	0.034	36.064	2.1	7/12/13	0.0403	0.00505	2.39E-05	0.00473	38.014	0.12538	0.00059	0.101	0.04464	2.809	0.994	0.996
36	No	8	0.034	36.064	3	7/12/13	0.0577	0.00707	1.24E-05	0.00175	15.690	0.12261	0.00022	0.101	0.04464	2.747	0.994	0.997
36	No	8	0.034	36.064	4	7/12/13	0.1286	0.01487	2.65E-05	0.00178	9.503	0.11565	0.00021	0.101	0.04464	2.591	0.995	0.997
36	No	8	0.034	36.064	5	7/12/13	0.0771	0.00979	1.55E-05	0.00158	10.394	0.12694	0.00020	0.101	0.04464	2.843	0.994	0.996
36	No	8	0.034	36.064	6	7/12/13	0.1444	0.01516	3.09E-05	0.00204	19.020	0.10497	0.00021	0.101	0.04464	2.351	0.996	0.997
36	No	8	0.034	36.064	7	7/12/13	0.0546	0.00663	1.50E-05	0.00226	21.118	0.12142	0.00027	0.101	0.04464	2.720	0.995	0.997
36	No	8	0.034	36.064	8	7/12/13	0.0502	0.00628	2.39E-05	0.00381	11.542	0.12506	0.00048	0.101	0.04464	2.801	0.994	0.996
36	No	8	0.034	36.064	9	7/12/13	0.0728	0.00875	1.29E-05	0.00147	12.243	0.12024	0.00018	0.101	0.04464	2.693	0.995	0.997
36	No	8	0.034	36.064	10	7/12/13	0.0890	0.01092	1.85E-05	0.00169	9.944	0.12266	0.00021	0.101	0.04464	2.748	0.994	0.997
Kisanana, Block 2																	
36	No	8	0.034	36.064	1	12/13/13	0.0330	0.00266	6.65E-06	0.0025	24.131	0.08061	0.00020	0.101	0.04464	1.806	0.997	0.998
36	No	8	0.034	36.064	2	12/13/13	0.0330	0.01505	7.53E-06	0.0005	4.844	0.45606	0.00023	0.101	0.04464	10.216	0.972	0.983
36	No	8	0.034	36.064	3	12/13/13	0.0493	0.00698	6.98E-06	0.0010	6.890	0.14149	0.00014	0.101	0.04464	3.169	0.993	0.996
36	No	8	0.034	36.064	4	12/13/13	0.0548	0.00990	4.95E-06	0.0005	5.173	0.18066	0.00009	0.101	0.04464	4.047	0.991	0.994
36	No	8	0.034	36.064	5	12/13/13	0.0519	0.00645	6.45E-06	0.0010	6.861	0.12428	0.00012	0.101	0.04464	2.784	0.994	0.996
Kedong A																	
1	No	14	-1.230	36.547	1	12/14/13	0.0630	0.03495	6.99E-03	0.2000	183.6	0.55476	0.11095	0.0336	0.01485	37.355	0.891	0.932
1	No	14	-1.230	36.547	2	12/14/13	0.0165	0.00905	1.77E-03	0.1955	153.3	0.54871	0.10727	0.0336	0.01485	36.947	0.892	0.933
1	No	14	-1.230	36.547	3	12/14/13	0.0529	0.02927	5.83E-03	0.1990	186.4	0.55333	0.11011	0.0336	0.01485	37.259	0.891	0.932
1	No	14	-1.230	36.547	4	12/14/13	0.0307	0.01864	3.49E-03	0.1870	163.4	0.60705	0.11352	0.0336	0.01485	40.875	0.880	0.925
1	No	14	-1.230	36.547	5	12/14/13	0.0341	0.01904	3.87E-03	0.2030	179.9	0.55834	0.11334	0.0336	0.01485	37.596	0.890	0.931
Gicheru (MER 68)																	
68	Yes	14	-1.185	36.549	1	6/5/13	0.0566	0.03428	4.00E-03	0.11654	35.19	0.60564	0.07058	0.0341	0.01507	40.183	0.882	0.926
68	Yes	14	-1.185	36.549	2	6/5/13	0.0629	0.04220	4.87E-03	0.11540	32.73	0.67089	0.07742	0.0341	0.01507	44.512	0.869	0.918

^ One or more measured values for this sample were extreme outliers, likely caused by machine malfunction.

Appendix A (continued)

MER Number or Equivalent	Type Sample?	Petrological Group (Merrick and Brown, 1984)	Latitude (Brown et al., 2013)	Longitude (Brown et al., 2013)	Sample Number	Analysis Date	Sample Mass [g]	Ms [emu]	Mr [emu]	Squareness [unitless]	HcAVE [Oe]	Ms (emu/g) Weight Normalized	Mr (emu/g) Weight Normalized	Wt. % Fe3O4 (Brown et al., 2013)	Wt. % Fe	Ms/g Fe [emu/gFe]	%α-Fe2O3 only α-	%α-Fe2O3 only α- and γ-Fe2O3
68	Yes	14	-1.185	36.549	3	6/5/13	0.0600	0.03532	4.17E-03	0.11807	33.65	0.58865	0.06950	0.0341	0.01507	39.056	0.886	0.929
68	Yes	14	-1.185	36.549	4	6/5/13	0.0300	0.04047	4.70E-03	0.11602	31.52	1.34889	0.15650	0.0341	0.01507	89.495	0.735	0.834
68	Yes	14	-1.185	36.549	5	6/5/13	0.0501	0.03080	3.83E-03	0.12436	33.29	0.61471	0.07645	0.0341	0.01507	40.784	0.881	0.925
68	Yes	14	-1.185	36.549	6	6/5/13	0.0481	0.02943	3.49E-03	0.11860	32.12	0.61178	0.07256	0.0341	0.01507	40.590	0.881	0.926
68	Yes	14	-1.185	36.549	7	6/5/13	0.0813	0.05463	6.70E-03	0.12263	33.49	0.67201	0.08241	0.0341	0.01507	44.586	0.869	0.918
68	Yes	14	-1.185	36.549	8	6/5/13	0.0422	0.02601	3.15E-03	0.12092	32.39	0.61633	0.07453	0.0341	0.01507	40.892	0.880	0.925
68	Yes	14	-1.185	36.549	9	6/5/13	0.0514	0.03104	3.81E-03	0.12273	32.87	0.60397	0.07412	0.0341	0.01507	40.072	0.883	0.927
68	Yes	14	-1.185	36.549	10	6/5/13	0.0453	0.02831	3.90E-03	0.13756	38.12	0.62504	0.08598	0.0341	0.01507	41.470	0.879	0.924
Gicheru Non-Type, Block 1																		
68-69	No	14	-1.185	36.549	1.1	5/28/13	0.0434	0.02648	4.69E-03	0.17709	89.09	0.61023	0.10806	0.0339	0.01498	40.726	0.881	0.925
68-69	No	14	-1.185	36.549	1.2	5/28/13	0.0434	0.02560	4.66E-03	0.18181	89.85	0.58995	0.10726	0.0339	0.01498	39.373	0.885	0.928
68-69	No	14	-1.185	36.549	1.3	5/28/13	0.0434	0.02502	4.49E-03	0.17945	84.92	0.57653	0.10346	0.0339	0.01498	38.477	0.888	0.930
68-69	No	14	-1.185	36.549	1.4	5/28/13	0.0434	0.02524	4.59E-03	0.18188	83.65	0.58149	0.10576	0.0339	0.01498	38.808	0.887	0.929
68-69	No	14	-1.185	36.549	2	5/28/13	0.0391	0.02465	4.22E-03	0.17117	84.13	0.63054	0.10793	0.0339	0.01498	42.081	0.877	0.923
68-69	No	14	-1.185	36.549	3	5/28/13	0.0213	0.01369	2.20E-03	0.16046	71.59	0.64267	0.10312	0.0339	0.01498	42.891	0.874	0.921
68-69	No	14	-1.185	36.549	4	5/28/13	0.0306	0.02049	3.32E-03	0.16204	76.62	0.66958	0.10850	0.0339	0.01498	44.687	0.869	0.918
68-69	No	14	-1.185	36.549	5	5/28/13	0.0307	0.01620	3.21E-03	0.19824	79.92	0.52770	0.10461	0.0339	0.01498	35.218	0.897	0.936
68-69	No	14	-1.185	36.549	6	5/28/13	0.0371	0.02073	4.02E-03	0.19369	88.94	0.55873	0.10822	0.0339	0.01498	37.289	0.891	0.932
68-69	No	14	-1.185	36.549	7	5/28/13	0.0153	0.00882	1.56E-03	0.17696	76.04	0.57654	0.10203	0.0339	0.01498	38.477	0.888	0.930
68-69	No	14	-1.185	36.549	8	5/28/13	0.0225	0.01334	2.43E-03	0.18254	83.67	0.59275	0.10820	0.0339	0.01498	39.559	0.884	0.928
68-69	No	14	-1.185	36.549	1	7/12/13	0.0434	0.02374	4.49E-03	0.18888	93.49	0.54712	0.10334	0.0341	0.01507	36.300	0.894	0.934
Gicheru Non-Type, Block 2																		
68-69	No	14	-1.185	36.549	1	8/4/13	0.0101	0.00582	8.95E-04	0.15387	75.20	0.57591	0.08861	0.0339	0.01498	38.435	0.888	0.930
68-69	No	14	-1.185	36.549	2	8/4/13	0.0178	0.01012	1.51E-03	0.14875	72.95	0.56860	0.08458	0.0339	0.01498	37.948	0.889	0.931
68-69	No	14	-1.185	36.549	3	8/4/13	0.0203	0.01230	1.82E-03	0.14799	76.13	0.60597	0.08968	0.0339	0.01498	40.442	0.882	0.926
68-69	No	14	-1.185	36.549	4	8/4/13	0.0370	0.01592	3.03E-03	0.19024	75.71	0.43017	0.08184	0.0339	0.01498	28.709	0.917	0.948
68-69	No	14	-1.185	36.549	5	8/4/13	0.0329	0.01953	2.89E-03	0.14801	69.11	0.59350	0.08784	0.0339	0.01498	39.609	0.884	0.928
68-69	No	14	-1.185	36.549	6	8/4/13	0.0354	0.01953	2.89E-03	0.14801	69.11	0.55159	0.08164	0.0339	0.01498	36.812	0.893	0.933
68-69	No	14	-1.185	36.549	7	8/4/13	0.0463	0.02565	3.86E-03	0.15031	70.97	0.55391	0.08326	0.0339	0.01498	36.967	0.892	0.932
68-69	No	14	-1.185	36.549	8	8/4/13	0.0295	0.01562	2.53E-03	0.16229	70.09	0.52938	0.08592	0.0339	0.01498	35.330	0.897	0.936
68-69	No	14	-1.185	36.549	9	8/4/13	0.0430	0.02511	3.53E-03	0.14058	66.68	0.58398	0.08209	0.0339	0.01498	38.974	0.886	0.929

Appendix A (continued)

Mer Number or Equivalent	Petrologic Type Sample?	Petrologic Group (Merrick and Brown, 1984)	Latitude (Brown et al., 2013)	Longitude (Brown et al., 2013)	Sample Number	Analysis Date	Sample Mass [g]	Ms [emu]	Mr [emu]	Squareness (Mr/Ms) [unitless]	Hcave [Oe]	Ms emu/g Weight Normalized	Mr emu/g Weight Normalized	Wt. % Fe₃O₄ (Brown et al., 2013)	Wt. % Fe (et al., 2013)	Ms/g Fe [emu/gFe]	%s-Fe₃O₄ only a.	and χ-Fe₃O₄ only a. Fe₃O₄ and Fe₃O₄
68-69	No	14	-1.185	36.549	10	8/4/13	0.0459	0.02506	3.98E-03	0.15883	71.19	0.54594	0.08671	0.0339	0.01498	36.435	0.894	0.933
Sonanchi Crater																		
7	Yes	19	-0.778	36.266	1	12/13/13	0.0381	0.01690	4.74E-03	0.28050	367.3	0.44353	0.12441	0.0203	0.00897	49.431	0.855	0.909
7	Yes	19	-0.778	36.266	1.1	12/13/13	0.0381	0.01687	4.77E-03	0.28250	368.4	0.44271	0.12507	0.0203	0.00897	49.340	0.855	0.909
7	Yes	19	-0.778	36.266	2	12/13/13	0.0683	0.00324	3.56E-05	0.01100	67.8	0.04738	0.00052	0.0203	0.00897	5.281	0.987	0.992
7	Yes	19	-0.778	36.266	3	12/13/13	0.0546	0.00518	5.37E-04	0.10350	224.5	0.09494	0.00983	0.0203	0.00897	10.581	0.971	0.982
7	Yes	19	-0.778	36.266	4	12/13/13	0.0380	0.01714	4.73E-03	0.27600	368.6	0.45099	0.12447	0.0203	0.00897	50.263	0.852	0.908
7	Yes	19	-0.778	36.266	5	12/13/13	0.0288	0.01104	2.12E-03	0.19150	333.3	0.38349	0.07344	0.0203	0.00897	42.740	0.875	0.922
Mundui																		
8	No	19	-0.802	36.254	1	7/12/13	0.0912	0.00231	6.20E-05	0.02688	94.00	0.02529	0.00068	0.0195	0.00862	2.934	0.994	0.996
8	No	19	-0.802	36.254	2	7/12/13	0.0529	0.00140	7.93E-05	0.05665	125.19	0.02646	0.00150	0.0195	0.00862	3.070	0.994	0.996
8	No	19	-0.802	36.254	2.1	7/12/13	0.0529	0.00140	8.23E-05	0.05864	116.42	0.02651	0.00155	0.0195	0.00862	3.076	0.994	0.996
8	No	19	-0.802	36.254	3	7/12/13	0.0806	0.00259	7.70E-05	0.02979	87.86	0.03207	0.00096	0.0195	0.00862	3.721	0.992	0.995
8	No	19	-0.802	36.254	4	7/12/13	0.0395	0.00140	7.02E-05	0.04995	100.03	0.03556	0.00178	0.0195	0.00862	4.125	0.990	0.994
8	No	19	-0.802	36.254	5	7/12/13	0.0600	0.00119	3.37E-05	0.02820	76.42	0.01991	0.00056	0.0195	0.00862	2.311	0.996	0.997
8	No	19	-0.802	36.254	6	7/12/13	0.0501	0.00119	3.37E-05	0.02820	76.42	0.02385	0.00067	0.0195	0.00862	2.767	0.994	0.997
8	No	19	-0.802	36.254	7	7/12/13	0.0521	0.00130	3.03E-05	0.02325	122.35	0.02502	0.00058	0.0195	0.00862	2.903	0.994	0.996
8	No	19	-0.802	36.254	8	7/12/13	0.0679	0.00189	1.22E-04	0.06448	174.56	0.02787	0.00180	0.0195	0.00862	3.233	0.993	0.996
8	No	19	-0.802	36.254	9	7/12/13	0.0394	0.00121	4.59E-05	0.03793	70.23	0.03072	0.00116	0.0195	0.00862	3.564	0.992	0.995
8	No	19	-0.802	36.254	10	7/12/13	0.0429	0.00122	4.74E-05	0.03892	91.24	0.02839	0.00110	0.0195	0.00862	3.294	0.993	0.996
Oderian Farm 1																		
9	Yes	20	-0.866	36.285	1	12/13/13	0.0632	0.00430	6.45E-06	0.0015	14.89	0.06904	0.00010	0.0394	0.01741	3.907	0.991	0.994
9	Yes	20	-0.866	36.285	2	12/13/13	0.0598	0.00401	1.00E-05	0.0025	19.63	0.06706	0.00017	0.0394	0.01741	3.851	0.991	0.994
9	Yes	20	-0.866	36.285	3	12/13/13	0.0497	0.00422	1.90E-05	0.0045	18.08	0.08495	0.00038	0.0394	0.01741	4.878	0.988	0.993
9	Yes	20	-0.866	36.285	4	12/13/13	0.0542	0.00397	5.95E-06	0.0015	13.20	0.07319	0.00011	0.0394	0.01741	4.203	0.990	0.994
9	Yes	20	-0.866	36.285	5	12/13/13	0.0303	0.00274	5.48E-06	0.0020	13.62	0.09035	0.00018	0.0394	0.01741	5.188	0.987	0.992
Fischer's Tower																		
29	Yes	20	-0.860	36.361	1	12/13/13	0.0293	0.00235	4.70E-06	0.0020	12.492	0.08020	0.00016	0.0392	0.01733	4.629	0.989	0.993
29	Yes	20	-0.860	36.361	2	12/13/13	0.0671	0.00400	4.00E-06	0.0010	7.016	0.05961	0.00006	0.0392	0.01733	3.441	0.992	0.995
29	Yes	20	-0.860	36.361	3	12/13/13	0.0414	0.00339	8.48E-06	0.0025	22.664	0.08188	0.00020	0.0392	0.01733	4.726	0.989	0.993
29	Yes	20	-0.860	36.361	4	12/13/13	0.0414	0.00455	4.55E-06	0.0010	10.630	0.10990	0.00011	0.0392	0.01733	6.343	0.984	0.990

Appendix A (continued)

MER Number or Equivalent	Type Sample? (Merrick and Brown, 1984)	Petrological Group (Merrick and Brown, 1984)	Latitude (Brown et al., 2013)	Longitude (Brown et al., 2013)	Sample Number (Brown et al., 2013)	Analysis Date	Sample Mass [g]	Ms [emu]	Mr [emu]	Squareness (Mr/Ms) [unitless]	HcAvg [Oe]	Weight Normalized Ms [emu/g]	Weight Normalized Mr [emu/g]	Wt. % Fe_3O_4 (Brown et al., 2013)	Wt. % Fe [Brown et al., 2013]	Ms/g Fe [emu/gFe]	%t-Fe_2O_3	only α-Fe_2O_3	only α- and γ-Fe_2O_3	only α-Fe_2O_3	only Fe_3O_4 and Fe_2O_3
29	Yes	20	-0.860	36.361	5	12/13/13	0.0330	0.00266	6.65E-06	0.0025	24.131	0.08061	0.00020	0.0392	0.01733	4.652	0.989	0.993
Njorowa Gorge South 1																		
82-83	No	20	-0.955	36.311	1	12/13/13	0.0632	0.00593	1.66E-04	0.0280	54.93	0.09381	0.00263	0.0381	0.01684	5.570	0.986	0.991
82-83	No	20	-0.955	36.311	2	12/13/13	0.0553	0.00478	8.60E-05	0.0180	42.75	0.08640	0.00156	0.0381	0.01684	5.130	0.987	0.992
82-83	No	20	-0.955	36.311	3	12/13/13	0.0464	0.00444	9.10E-05	0.0205	51.20	0.09567	0.00196	0.0381	0.01684	5.681	0.986	0.991
82-83	No	20	-0.955	36.311	4	12/13/13	0.0764	0.00640	1.54E-04	0.0240	49.58	0.08372	0.00201	0.0381	0.01684	4.971	0.988	0.992
82-83	No	20	-0.955	36.311	5	12/13/13	0.0426	0.00408	7.95E-05	0.0195	45.22	0.09570	0.00187	0.0381	0.01684	5.683	0.986	0.991
GsJJ50																		
13	Yes	29	-0.631	36.254	1	8/4/13	0.0367	0.00518	1.06E-03	0.20463	1679	0.14108	0.02887	0.0856	0.03784	3.729	0.992	0.995
13	Yes	29	-0.631	36.254	2	8/4/13	0.0450	0.00584	1.03E-03	0.17707	1500	0.12977	0.02298	0.0856	0.03784	3.430	0.992	0.995
13	Yes	29	-0.631	36.254	3	8/4/13	0.0423	0.00525	1.02E-03	0.19411	1591	0.12404	0.02408	0.0856	0.03784	3.278	0.993	0.996
13	Yes	29	-0.631	36.254	4	8/4/13	0.0515	0.00668	1.07E-03	0.16022	1375	0.12967	0.02078	0.0856	0.03784	3.427	0.992	0.995
13	Yes	29	-0.631	36.254	5	8/4/13	0.0146	0.00239	9.72E-04	0.40696	2755	0.16359	0.06658	0.0856	0.03784	4.324	0.990	0.994
13	Yes	29	-0.631	36.254	6	8/4/13	0.0296	0.00395	9.83E-04	0.24855	1967	0.13355	0.03319	0.0856	0.03784	3.530	0.992	0.995
13	Yes	29	-0.631	36.254	7	8/4/13	0.0432	0.00566	1.03E-03	0.18132	1522	0.13111	0.02377	0.0856	0.03784	3.465	0.992	0.995
13	Yes	29	-0.631	36.254	8	8/4/13	0.0309	0.00412	9.54E-04	0.23135	1864	0.13338	0.03086	0.0856	0.03784	3.525	0.992	0.995
13	Yes	29	-0.631	36.254	9	8/4/13	0.0235	0.00329	9.82E-04	0.29840	2283	0.13997	0.04177	0.0856	0.03784	3.699	0.992	0.995
13	Yes	29	-0.631	36.254	10	8/4/13	0.0366	0.00477	9.94E-04	0.20824	1730	0.13035	0.02714	0.0856	0.03784	3.445	0.992	0.995
Eburru Steam Condenser																		
25	No	29	-0.636	36.254	1	7/22/13	0.0404	0.00546	1.11E-03	0.20259	1681.5	0.13513	0.02738	0.0868	0.03837	3.522	0.992	0.995
25	No	29	-0.636	36.254	2	7/22/13	0.0225	0.00354	1.16E-03	0.32703	2439.6	0.15737	0.05147	0.0868	0.03837	4.102	0.990	0.994
25	No	29	-0.636	36.254	3	7/22/13	0.0261	0.00586	1.16E-03	0.19757	1636.3	0.22466	0.04439	0.0868	0.03837	5.856	0.985	0.991
25	No	29	-0.636	36.254	4	7/22/13	0.0410	0.00562	1.11E-03	0.19781	1652.0	0.13711	0.02712	0.0868	0.03837	3.574	0.992	0.995
25	No	29	-0.636	36.254	5	7/22/13	0.0230	0.00351	9.62E-04	0.27421	2132.2	0.15245	0.04180	0.0868	0.03837	3.974	0.991	0.994
25	No	29	-0.636	36.254	6	7/22/13	0.0259	0.00384	1.01E-03	0.26160	2090.6	0.14840	0.03882	0.0868	0.03837	3.868	0.991	0.994
25	No	29	-0.636	36.254	7	8/5/13	0.0778	0.00993	1.03E-03	0.10404	936.5	0.12769	0.01328	0.0868	0.03837	3.328	0.993	0.995
25	No	29	-0.636	36.254	8	8/5/13	0.0341	0.00473	9.70E-04	0.20498	1694.5	0.13870	0.02843	0.0868	0.03837	3.615	0.992	0.995
25	No	29	-0.636	36.254	9	8/5/13	0.0782	0.00965	1.05E-03	0.10874	976.8	0.12342	0.01342	0.0868	0.03837	3.217	0.993	0.996
25	No	29	-0.636	36.254	10	8/5/13	0.0382	0.00522	1.00E-03	0.19255	1607.1	0.13657	0.02630	0.0868	0.03837	3.560	0.992	0.995

Appendix A (continued)

Eburru Steam Jet

MER Number or Type Equivalent	Type Sample?	Petrological Group (Merrick and Brown, 1984)	Latitude (Brown et al., 2013)	Longitude (Brown et al., 2013)	Sample Number	Analysis Date	Sample Mass [g]	Ms [emu]	Mr [emu]	Squareness (Mr/Ms) [unitless]	HcAve [Oe]	Weight Normalized Ms [emu/g]	Weight Normalized Mr [emu/g]	Wt. % Fe_3O_4 (Brown et al., 2013)	Wt. % Fe	Ms/g Fe [emu/gFe]	%α-Fe_2O_3 only / α- and Fe_3O_4	%α-Fe_2O_3 only / α- and Fe_3O_4 and Fe_3O_4
26	No	29	-0.641	36.250	1	7/22/13	0.0563	0.00760	1.11E-03	0.14574	1271.8	0.13491	0.01966	0.0858	0.03792	3.558	0.992	0.995
26	No	29	-0.641	36.250	2	7/22/13	0.0492	0.00656	1.08E-03	0.16447	1415.5	0.13334	0.02193	0.0858	0.03792	3.516	0.992	0.995
26	No	29	-0.641	36.250	3	7/22/13	0.2610	0.00374	9.72E-04	0.25978	2029.3	0.01433	0.00372	0.0858	0.03792	0.378	1.002	1.001
26	No	29	-0.641	36.250	4	7/22/13	0.0226	0.00342	1.08E-03	0.31559	1508.1	0.15121	0.04772	0.0858	0.03792	3.987	0.991	0.994
26	No	29	-0.641	36.250	4.1	7/22/13	0.0226	0.00340	9.98E-04	0.29373	2259.2	0.15034	0.04416	0.0858	0.03792	3.964	0.991	0.994
26	No	29	-0.641	36.250	5	7/22/13	0.0319	0.00449	9.99E-04	0.22229	1811.2	0.14081	0.03130	0.0858	0.03792	3.713	0.992	0.995
26	No	29	-0.641	36.250	6	8/5/13	0.0453	0.00598	1.02E-03	0.17134	1440.5	0.13193	0.02260	0.0858	0.03792	3.479	0.992	0.995
26	No	29	-0.641	36.250	7	8/5/13	0.0567	16666.5	16666.5	1.00000	--	293941.8	293941.8	0.0858	0.03792	7750894	-23199.1	-14512.3 ^
26	No	29	-0.641	36.250	8	8/5/13	0.0792	0.00945	1.06E-03	0.11233	999.2	0.11937	0.01341	0.0858	0.03792	3.148	0.993	0.996
26	No	29	-0.641	36.250	9	8/5/13	0.0620	0.00786	1.04E-03	0.13246	1166.2	0.12676	0.01679	0.0858	0.03792	3.343	0.993	0.995
26	No	29	-0.641	36.250	10	8/5/13	0.1112	0.01310	1.04E-03	0.07940	737.0	0.11779	0.00935	0.0858	0.03792	3.106	0.993	0.996

Upper Eburru North Slope (MER 114)

MER Number or Type Equivalent	Type Sample?	Petrological Group	Latitude	Longitude	Sample Number	Analysis Date	Sample Mass [g]	Ms [emu]	Mr [emu]	Squareness (Mr/Ms)	HcAve [Oe]	Weight Normalized Ms	Weight Normalized Mr	Wt. % Fe_3O_4	Wt. % Fe	Ms/g Fe	%α only/α- and Fe_3O_4	%α/all
114	Yes	29	-0.619	36.254	1	7/22/13	0.4990	0.00645	1.06E-03	0.16422	1413	0.01294	0.00212	0.0844	0.03730	0.347	1.002	1.001
114	Yes	29	-0.619	36.254	2	7/22/13	0.0507	0.00645	1.05E-03	0.16325	1407	0.12723	0.02077	0.0844	0.03730	3.410	0.993	0.995
114	Yes	29	-0.619	36.254	3	7/22/13	0.0578	0.00721	1.00E-03	0.13905	1220	0.12473	0.01734	0.0844	0.03730	3.344	0.993	0.995
114	Yes	29	-0.619	36.254	4	7/22/13	0.0562	0.00716	1.05E-03	0.14606	1266	0.12743	0.01861	0.0844	0.03730	3.416	0.992	0.995
114	Yes	29	-0.619	36.254	5	7/22/13	0.0518	0.00669	1.06E-03	0.15879	1371	0.12917	0.02051	0.0844	0.03730	3.463	0.992	0.995
114	Yes	29	-0.619	36.254	6	8/4/13	0.0390	0.00476	3.95E-05	0.00828	56.82	0.12215	0.00101	0.0844	0.03730	3.274	0.993	0.996 ^
114	Yes	29	-0.619	36.254	7	8/4/13	0.0257	0.00307	1.40E-05	0.00455	67.42	0.11938	0.00054	0.0844	0.03730	3.200	0.993	0.996 ^
114	Yes	29	-0.619	36.254	9	8/4/13	0.0423	0.00511	4.35E-05	0.00851	78.46	0.12070	0.00103	0.0844	0.03730	3.236	0.993	0.996 ^
114	Yes	29	-0.619	36.254	10	8/4/13	0.0392	0.00460	3.30E-05	0.00717	79.28	0.11726	0.00084	0.0844	0.03730	3.143	0.993	0.996 ^

Upper Eburru North Slope (MER 116)

MER Number or Type Equivalent	Type Sample?	Petrological Group	Latitude	Longitude	Sample Number	Analysis Date	Sample Mass [g]	Ms [emu]	Mr [emu]	Squareness (Mr/Ms)	HcAve [Oe]	Weight Normalized Ms	Weight Normalized Mr	Wt. % Fe_3O_4	Wt. % Fe	Ms/g Fe	%α only/α- and Fe_3O_4	%α/all
116	Yes	29	-0.619	36.254	1	8/5/13	0.0564	0.00750	1.09E-03	0.14475	1263.2	0.13297	0.01925	0.0837	0.03700	3.594	0.992	0.995
116	Yes	29	-0.619	36.254	2	8/5/13	0.0674	0.00859	1.48E-03	0.17279	1421.3	0.12747	0.02203	0.0837	0.03700	3.446	0.992	0.995
116	Yes	29	-0.619	36.254	3	8/5/13	0.0552	0.00760	1.09E-03	0.14348	1225.3	0.13763	0.01975	0.0837	0.03700	3.720	0.992	0.995
116	Yes	29	-0.619	36.254	4	8/5/13	0.0442	0.00591	1.11E-03	0.18732	1557.6	0.13376	0.02506	0.0837	0.03700	3.616	0.992	0.995
116	Yes	29	-0.619	36.254	5	8/5/13	0.0584	0.00814	1.11E-03	0.13697	1048.9	0.13933	0.01908	0.0837	0.03700	3.766	0.991	0.995
116	Yes	29	-0.619	36.254	6	8/5/13	0.0896	0.01101	1.08E-03	0.09834	891.6	0.12285	0.01208	0.0837	0.03700	3.321	0.993	0.995
116	Yes	29	-0.619	36.254	7	8/5/13	0.0652	0.00876	1.15E-03	0.13156	1134.5	0.13436	0.01768	0.0837	0.03700	3.632	0.992	0.995

^ One or more measured values for this sample were extreme outliers, likely caused by machine malfunction.

Appendix A (continued)

MER Number or Equivalent	Type Sample?	Petrological Group (Merrick and Brown, 1984)	Latitude (Brown et al., 2013)	Longitude (Brown et al., 2013)	Analysis Number Sample	Analysis Date	Sample Mass [g]	Ms [emu]	Mr [emu]	Squareness (Mr/Ms) [unitless]	HcAVE [Oe]	Weight Normalized Ms [emu/g]	Weight Normalized Mr [emu/g]	Wt. % Fe_3O_4 (Brown et al., 2013)	Wt. % Fe (et al., 2013)	Ms/g Fe [emu/gFe]	%α-Fe_2O_3 | only α- and γ-Fe_2O_3	%α-Fe_2O_3 | only α- and γ-Fe_2O_3 and Fe_3O_4
116	Yes	29	-0.619	36.254	8	8/5/13	0.0468	0.00631	1.34E-03	0.21183	1660.5	0.13477	0.02855	0.0837	0.03700	3.643	0.992	0.995
116	Yes	29	-0.619	36.254	9	8/5/13	0.0689	0.00898	1.08E-03	0.12044	1070.7	0.13038	0.01570	0.0837	0.03700	3.524	0.992	0.995
116	Yes	29	-0.619	36.254	10	8/5/13	0.0496	0.00675	1.10E-03	0.16326	1401.9	0.13609	0.02222	0.0837	0.03700	3.679	0.992	0.995
Upper Eburru Hilltop (MER 117)																		
117	Yes	29	-0.633	36.255	1	8/5/13	0.0483	0.00661	1.08E-03	0.16297	1411	0.13682	0.02230	0.0842	0.03722	3.676	0.992	0.995
117	Yes	29	-0.633	36.255	2	8/5/13	0.0392	0.00527	1.04E-03	0.19646	1621	0.13446	0.02642	0.0842	0.03722	3.613	0.992	0.995
117	Yes	29	-0.633	36.255	3	8/5/13	0.0582	0.00744	1.02E-03	0.13708	1206	0.12779	0.01752	0.0842	0.03722	3.434	0.992	0.995
117	Yes	29	-0.633	36.255	4	8/5/13	0.0611	0.00758	1.01E-03	0.13310	1174	0.12401	0.01651	0.0842	0.03722	3.332	0.993	0.995
117	Yes	29	-0.633	36.255	5	8/5/13	0.0646	0.00816	1.03E-03	0.12565	1111	0.12634	0.01587	0.0842	0.03722	3.395	0.993	0.995
117	Yes	29	-0.633	36.255	6	8/5/13	0.0423	0.00549	1.05E-03	0.19146	1586	0.12971	0.02483	0.0842	0.03722	3.485	0.992	0.995
117	Yes	29	-0.633	36.255	7	8/5/13	0.0432	0.00577	1.05E-03	0.18164	1545	0.13356	0.02426	0.0842	0.03722	3.589	0.992	0.995
117	Yes	29	-0.633	36.255	8	8/5/13	0.0646	0.00815	1.03E-03	0.12657	1132	0.12610	0.01596	0.0842	0.03722	3.388	0.993	0.995
117	Yes	29	-0.633	36.255	9	8/5/13	0.0519	0.00663	1.05E-03	0.15804	1364	0.12783	0.02020	0.0842	0.03722	3.435	0.992	0.995
117	Yes	29	-0.633	36.255	10	8/5/13	0.0582	16666.5	16666.5	1.00000	9200	286366	286366	0.0842	0.03722	7694618	-23030.6	-14406.9 ^
Upper Eburru Hilltop (MER 118)																		
118	Yes	29	-0.633	36.255	1	7/23/13	0.0459	0.00668	1.15E-03	0.17242	1469	0.14556	0.02510	0.0828	0.03660	3.977	0.991	0.994
118	Yes	29	-0.633	36.255	2	7/23/13	0.0541	0.00757	1.10E-03	0.14475	1270	0.13995	0.02026	0.0828	0.03660	3.824	0.991	0.995
118	Yes	29	-0.633	36.255	3	7/23/13	0.0512	0.00695	1.14E-03	0.16379	1407	0.13582	0.02225	0.0828	0.03660	3.711	0.992	0.995
118	Yes	29	-0.633	36.255	4	7/23/13	0.0553	0.00751	1.08E-03	0.14356	1255	0.13586	0.01950	0.0828	0.03660	3.712	0.992	0.995
118	Yes	29	-0.633	36.255	5	7/23/13	0.0261	0.00399	9.51E-04	0.23863	1939	0.15269	0.03644	0.0828	0.03660	4.172	0.990	0.994
118	Yes	29	-0.633	36.255	6	8/5/13	0.0373	0.00520	1.07E-03	0.20570	1704	0.13946	0.02869	0.0828	0.03660	3.811	0.991	0.995
118	Yes	29	-0.633	36.255	7	8/5/13	0.0313	0.00439	1.09E-03	0.24860	1923	0.14021	0.03486	0.0828	0.03660	3.831	0.991	0.995
118	Yes	29	-0.633	36.255	8	8/5/13	0.0299	0.00435	1.07E-03	0.24513	1938	0.14551	0.03567	0.0828	0.03660	3.976	0.991	0.994
118	Yes	29	-0.633	36.255	9	8/5/13	0.0191	0.00297	1.03E-03	0.34603	2495	0.15531	0.05374	0.0828	0.03660	4.244	0.990	0.994
118	Yes	29	-0.633	36.255	10	8/5/13	0.0219	0.00333	1.05E-03	0.31573	2292	0.15200	0.04799	0.0828	0.03660	4.153	0.990	0.994
Upper Eburru Hilltop (MER 119)																		
119	Yes	29	-0.633	36.255	1	8/5/13	0.0611	0.00770	9.63E-04	0.12494	1113.0	0.12608	0.01575	0.0826	0.03651	3.454	0.992	0.995
119	Yes	29	-0.633	36.255	1.1	8/5/13	0.0611	0.00741	1.00E-03	0.13492	1174.6	0.12131	0.01637	0.0826	0.03651	3.323	0.993	0.995
119	Yes	29	-0.633	36.255	2	8/5/13	0.1257	0.00474	9.79E-04	0.20630	1686.6	0.03774	0.00779	0.0826	0.03651	1.034	1.000	1.000
119	Yes	29	-0.633	36.255	2.1	8/5/13	0.0365	0.00467	1.00E-03	0.21415	1732.4	0.12806	0.02742	0.0826	0.03651	3.508	0.992	0.995

^ One or more measured values for this sample were extreme outliers, likely caused by machine malfunction.

Appendix A (continued)

MER Number or Equivalent	Type Sample?	Petrological Group (Merrick and Brown, 1984)	N Latitude (Brown et al, 2013)*	E Longitude (Brown et al, 2013)*	Sample Number	Analysis Date	Sample Mass (g)	Ms (emu)	Mr (emu)	Squareness (Mr/Ms) [unitless]	HCave (Oe)	Ms Weight Normalized (emu/g)	Mr Weight Normalized (emu/g)	Wt. % Fe₃O₄ (Brown et al, 2013)**	Wt. % Fe	Ms/g Fe (emu/gFe)	%α-Fe₂O₃ only α- and γ-Fe₂O₃	%α-Fe₂O₃ only α- Fe₃O₄ and Fe₃O₄
119	Yes	29	-0.633	36.255	3	8/5/13	0.0288	0.00387	9.88E-04	0.25559	1979.8	0.13422	0.03431	0.0826	0.03651	3.676	0.992	0.995
119	Yes	29	-0.633	36.255	3.1	8/5/13	0.0288	0.00386	1.02E-03	0.26338	2047.4	0.13407	0.03531	0.0826	0.03651	3.672	0.992	0.995
119	Yes	29	-0.633	36.255	4	8/5/13	0.0584	0.00729	9.97E-04	0.13675	1208.1	0.12477	0.01706	0.0826	0.03651	3.418	0.992	0.995
119	Yes	29	-0.633	36.255	4.1	8/5/13	0.0584	0.00719	9.91E-04	0.13782	1206.3	0.12313	0.01697	0.0826	0.03651	3.372	0.993	0.995
119	Yes	29	-0.633	36.255	5	8/5/13	0.0490	0.00613	9.91E-04	0.16164	1356.5	0.12506	0.02021	0.0826	0.03651	3.425	0.992	0.995
119	Yes	29	-0.633	36.255	6	8/5/13	0.0274	0.00373	9.83E-04	0.26312	2015.2	0.13628	0.03586	0.0826	0.03651	3.733	0.992	0.995
119	Yes	29	-0.633	36.255	7	8/5/13	0.0889	0.01035	1.02E-03	0.09835	888.3	0.11637	0.01145	0.0826	0.03651	3.187	0.993	0.996
119	Yes	29	-0.633	36.255	8	8/5/13	0.0857	0.00982	9.93E-04	0.10104	895.4	0.11462	0.01158	0.0826	0.03651	3.140	0.993	0.996
119	Yes	29	-0.633	36.255	9	8/5/13	0.0700	0.00800	1.00E-03	0.12547	1118.0	0.11431	0.01434	0.0826	0.03651	3.131	0.993	0.996
119	Yes	29	-0.633	36.255	10	8/5/13	0.0498	0.00609	9.66E-04	0.15851	1339.1	0.12231	0.01939	0.0826	0.03651	3.350	0.993	0.995
Eburru Station																		
72-73	No	29	-0.578	36.258	1	7/23/13	0.0435	0.00604	1.08E-03	0.17904	1488	0.13886	0.02486	0.08365	0.03697	3.756	0.991	0.995
72-73	No	29	-0.578	36.258	2	7/23/13	0.0440	0.00617	1.12E-03	0.18198	1512	0.14025	0.02552	0.08365	0.03697	3.793	0.991	0.995
72-73	No	29	-0.578	36.258	3	7/23/13	0.0509	0.00689	1.09E-03	0.15781	1354	0.13539	0.02137	0.08365	0.03697	3.662	0.992	0.995
72-73	No	29	-0.578	36.258	4	7/23/13	0.0238	0.00364	1.05E-03	0.28972	2223	0.15286	0.04429	0.08365	0.03697	4.134	0.990	0.994
72-73	No	29	-0.578	36.258	5	7/23/13	0.0365	0.00508	1.02E-03	0.20121	1655	0.13916	0.02800	0.08365	0.03697	3.764	0.991	0.995
WN #2 GsJ 33 **																		
3	No	32	-0.622	36.352	1	12/14/13	0.0441	0.00593	8.89E-06	0.0015	16.529	0.13439	0.00020	0.0754	0.03333	4.033	0.991	0.994
3	No	32	-0.622	36.352	2	12/15/13	0.0461	0.00539	5.39E-06	0.0010	9.431	0.11692	0.00012	0.0754	0.03333	3.508	0.992	0.995
3	No	32	-0.622	36.352	3	12/15/13	0.0688	0.00900	9.00E-06	0.0010	9.301	0.13074	0.00013	0.0754	0.03333	3.923	0.991	0.994
3	No	32	-0.622	36.352	4	12/15/13	0.0338	0.00516	1.29E-05	0.0025	27.276	0.15260	0.00038	0.0754	0.03333	4.579	0.989	0.993
3	No	32	-0.622	36.352	5	12/15/13	0.0601	0.00793	1.19E-05	0.0015	17.156	0.13195	0.00020	0.0754	0.03333	3.959	0.991	0.994
WN #3 near GsJ 49 **																		
4	No	32	-0.664	36.325	1	12/15/13	0.0389	0.00400	2.00E-06	0.0005	3.218	0.10290	0.00005	0.0769	0.03399	3.028	0.994	0.996
4	No	32	-0.664	36.325	2	12/15/13	0.0473	0.01078	5.39E-06	0.0005	8.779	0.22791	0.00011	0.0769	0.03399	6.705	0.983	0.989
4	No	32	-0.664	36.325	3	12/15/13	0.0682	0.00845	1.69E-05	0.0020	14.876	0.12386	0.00025	0.0769	0.03399	3.644	0.992	0.995
4	No	32	-0.664	36.325	4	12/15/13	0.0851	0.00539	5.39E-06	0.0010	5.155	0.06334	0.00006	0.0769	0.03399	1.863	0.997	0.998
4	No	32	-0.664	36.325	5	12/15/13	0.0377	0.00550	1.10E-05	0.0020	15.713	0.14594	0.00029	0.0769	0.03399	4.293	0.990	0.994

** Previously unpublished values for WN #2 and WN #3 are from Merrick 2014 (pers. com.)

Appendix A (continued)

MER Number or Equivalent	Type Sample?	Petrologic Group (Merrick and Brown, 1984)	N Latitude (Brown et al., 2013)*	E Longitude (Brown et al., 2013)*	Sample Number (Brown et al., 2013)*	Analysis Date	Sample Mass [g]	Ms [emu]	Mr [emu]	Squareness [Mr/Ms] (unitless)	HcAvE [Oe]	Weight Normalized Ms [emu/g]	Weight Normalized Mr [emu/g]	Wt. % Fe₃O₄ (Brown et al., 2013) **	Wt. % Fe **	Ms/g Fe [emu/g Fe]	%α-Fe₃O₄ only α- and γ-Fe₃O₄	%α-Fe₃O₄ only α- and Fe₃O₄	%α-Fe₃O₄ only α-, FeₓOₓ and Fe₃O₄
**Masai Gorge Locality **																			
28	No		-0.647	36.333	1	12/14/13	0.0599	0.00760	1.14E-05	0.0015	13.537	0.12682	0.00019	0.0777	0.03434	3.693	0.992	0.995	0.995
28	No		-0.647	36.333	2	12/14/13	0.0268	0.00411	1.44E-05	0.0035	34.662	0.15346	0.00054	0.0777	0.03434	4.469	0.989	0.993	0.993
28	No		-0.647	36.333	3	12/14/13	0.0528	0.01000	5.00E-06	0.0005	6.447	0.18939	0.00009	0.0777	0.03434	5.515	0.986	0.991	0.991
28	No		-0.647	36.333	4	12/14/13	0.0255	0.00368	1.29E-05	0.0035	24.848	0.14448	0.00051	0.0777	0.03434	4.207	0.990	0.994	0.994
28	No		-0.647	36.333	5	12/14/13	0.0613	0.00593	8.90E-06	0.0015	12.792	0.09674	0.00015	0.0777	0.03434	2.817	0.994	0.996	0.996
Bahria Estate																			
32	Yes		-0.666	36.325	1	12/15/13	0.0632	0.00593	1.66E-04	0.0280	54.935	0.09381	0.00263	0.0792	0.03501	2.680	0.995	0.997	0.997
32	Yes		-0.666	36.325	2	12/15/13	0.0366	0.00500	7.50E-06	0.0015	11.748	0.13668	0.00021	0.0792	0.03501	3.904	0.991	0.994	0.994
32	Yes		-0.666	36.325	3	12/15/13	0.0570	0.00890	8.90E-06	0.0010	9.435	0.15608	0.00016	0.0792	0.03501	4.459	0.989	0.993	0.993
32	Yes		-0.666	36.325	4	12/15/13	0.0619	0.00790	7.90E-06	0.0010	8.675	0.12757	0.00013	0.0792	0.03501	3.644	0.992	0.995	0.995
32	Yes		-0.666	36.325	5	12/15/13	0.0335	0.00480	1.44E-05	0.0030	29.460	0.14323	0.00043	0.0792	0.03501	4.092	0.990	0.994	0.994
Ilkek																			
70-71	No		-0.593	36.367	1	12/15/13	0.0638	0.00800	4.00E-06	0.0005	4.535	0.12539	0.00006	0.07855	0.03472	3.612	0.992	0.995	0.995
70-71	No		-0.593	36.367	2	12/15/13	0.0330	0.00416	1.04E-05	0.0025	24.348	0.12600	0.00032	0.07855	0.03472	3.629	0.992	0.995	0.995
70-71	No		-0.593	36.367	3	12/15/13	0.0594	0.01040	1.04E-05	0.0010	11.657	0.17500	0.00018	0.07855	0.03472	5.040	0.988	0.992	0.992
70-71	No		-0.593	36.367	4	12/15/13	0.0354	0.00396	9.90E-06	0.0025	20.372	0.11181	0.00028	0.07855	0.03472	3.220	0.993	0.996	0.996
70-71	No		-0.593	36.367	5	12/15/13	0.0511	0.00660	9.90E-06	0.0015	14.344	0.12909	0.00019	0.07855	0.03472	3.718	0.992	0.995	0.995
Masai Gorge Rock Shelter																			
90-91	No		-0.639	36.334	1	12/14/13	0.0284	0.00378	1.70E-05	0.0045	30.836	0.13306	0.00060	0.0813	0.03593	3.703	0.992	0.995	0.995
90-91	No		-0.639	36.334	2	12/14/13	0.0575	0.00745	1.49E-05	0.0020	18.579	0.12952	0.00026	0.0813	0.03593	3.604	0.992	0.995	0.995
90-91	No		-0.639	36.334	3	12/14/13	0.0478	0.00525	1.05E-05	0.0020	14.877	0.10988	0.00022	0.0813	0.03593	3.058	0.994	0.996	0.996
90-91	No		-0.639	36.334	4	12/14/13	0.0673	0.01090	1.09E-05	0.0010	11.172	0.16189	0.00016	0.0813	0.03593	4.505	0.989	0.993	0.993
90-91	No		-0.639	36.334	5	12/14/13	0.0306	0.00425	8.51E-06	0.0020	18.050	0.13897	0.00028	0.0813	0.03593	3.867	0.991	0.994	0.994

* All locality map coordinates are from Brown et al 2013, (on-line supplemental materials: Appendix 1, Supplemental Table 1).

** Previously unpublished values for Masai Gorge are from Merrick 2014 (pers. com.)

Bibliography

Bigazzi, G., Yeğingil, Z., Ercan, T., Oddone, M., Özdogan, M., 1997. Age determination of obsidian bearing volcanics in Eastern Anatolia using the fission track dating method. *Geological Bulletin of Turkey* 40 (2), pp. 57-73.

Binder, D., Gratuze, B., Mouralis, D., and Balkan-Atlı, N., 2011. New Investigations of the Göllüdağ Obsidian Lava Flows System: A Multi-Disciplinary Approach. *Journal of Archaeological Science* 38(12), pp. 3174–3184.

Borradaile, G.J., Stewart, J.D., and Ross, W.A., 1998. Characterizing Stone Tools by Rock-Magnetic Methods. *Geoarchaeology* 13(1), pp. 73–91.

Brown, F.H., Nash, B.P., Fernandez, D.P., Merrick, H.V., and Thomas, R.J., 2013. Geochemical Composition of Source Obsidians from Kenya. *Journal of Archaeological Science* 40(8), pp. 3233–3251.

Cann, J.R., and Renfrew, C., 1964. The Characterization of Obsidian and Its Application to the Mediterranean Region. *Proceedings of the Prehistoric Society* 30, pp. 111-133.

Cañón-Tapia, E., and Castro, J., 2004. AMS Measurements on Obsidian from the Inyo Domes, CA: A Comparison of Magnetic and Mineral Preferred Orientation Fabrics. *Journal of Volcanology and Geothermal Research* 134(3), pp. 169–182.

Carmichael, R.S. "rock." *Encyclopaedia Britannica Online Academic Edition.* Encyclopædia Britannica Inc., 2014. Web. 15 Apr. 2014. <http://www.britannica.com/EBchecked/topic/505970/rock>.

Coleman, M.E., Ferguson, J.R., Glascock, M.D., Robertson, J.D., Ambrose, S.H., 2008. A new look at the geochemistry of obsidian from East Africa. *International Association of Obsidian Studies Bulletin* 39, pp. 11-14.

Durkee, H., and Brown, F. H., in press. Correlation of volcanic ash layers between the Acheulean sites of Isinya, Kariandusi, and Olorgesailie, Kenya. Submitted to *Journal of Archaeological Science*, January, 2014.

Duttine, M., Scorzelli, R.B., Cernicchiaro, G., Poupeau, G., Guillaume-Gentil, N., 2008. Magnetic properties and electron spin resonance of Ecuadorian obsidians. Application to provenance research of archaeological samples. *Journal of Magnetism and Magnetic Materials* 320, pp. 136-138.

Frahm, E., 2010. The Bronze-age Obsidian Industry at Tell Mozan (Ancient Urkesh), Syria. Ph.D. dissertation. Department of Anthropology, University of Minnesota.

Frahm, E., Feinberg, J.M., 2013. From flow to quarry: magnetic properties of obsidian and changing the scale of archaeological sourcing. *Journal of Archaeological Science* 40, pp. 3706-3721.

Game, P.M. 1945. Appendix: Note on the interrelationships of various obsidians collected by Mrs. Leakey in Kenya Colony, p. 406-409. In Leakey, M.D. 1945. Report on the excavations at Hyrax Hill, Nakuru, Kenya Colony, 1937-1938. *Transactions of the Royal Society of South Africa* 30(4), pp. 271-409.

Glascock, M.D., Braswell, G., Cobean, R.H., 1998. A systematic approach to obsidian source characterization. In: Shackley, M.S. (Ed.), *Archaeological Obsidian Studies: Method and Theory*, pp. 15-65.

Hall, M. and Kimura, H., 2002. Quantitative EDXRF Studies of Obsidian Sources in Northern Hokkaido. *Journal of Archaeological Science* 29, pp. 259–266

Hallam, B. R., Warren, S. E. & Renfrew, C. 1976. Obsidian in the West Mediterranean: Characterisation by neutron activation analysis and optical emission spectroscopy. *Proceedings of the Prehistoric Society* 42, pp. 85-110.

Hillis, A., Feinberg, J.M., Frahm, E., Johnson, C., 2010. Magnetic Sourcing of Obsidian Artifacts: Successes and Limitations. American Geophysical Union, Fall Meeting, San Francisco, California, 13-17 December.

Leakey, M. D. (with contributions by L. S. B. Leakey and P. M. Game), 1945. Report on the excavations at Hyrax Hill, Nakuru, Kenya Colony, 1937-1938. *Transactions of the Royal Society of South Africa* 30(4), pp. 271-409.

McDougall, J.M., 1978. An Analytical Study of Obsidian from Europe and the Near East by Examination of Magnetic Parameters. M.A. dissertation. Bradford University.

McDougall, J.M., Tarling, D.H., and Warren, S.E., 1983. The Magnetic Sourcing of Obsidian Samples from Mediterranean and Near Eastern Sources. *Journal of Archaeological Science* 10, pp. 441-452.

Merrick, H.V. and Brown, F.H., 1984a Obsidian Sources and Patterns of Source Utilization in Kenya and Northern Tanzania: Some Initial Findings. *The African Archaeological Review*, 2, pp. 129-152.

Merrick, H.V. and Brown, F.H., 1984b. Rapid chemical characterization of obsidian artifacts by electron microprobe analysis. *Archaeometry* 26, pp. 230-236.

Merrick, H.V., Brown, F.H. and Nash, W.P., 1994. Use and movement of obsidian in the Early and Middle Stone ages of Kenya and northern Tanzania. In: Childs, S. (Ed.), *Society, Culture, and Technology in Africa*. MASCA Research Papers in Science and Archaeology, Philadelphia. supplement to vol. 11, pp. 29-43.

Michels, J.W., Tsong, I.S.T., and Nelson, C.M., 1983. Obsidian dating and east African archaeology. *Science* 219, pp. 361-66.

Miller, J. "Obsidian Is Hot Stuff.", 2014. *Volcano World.* Web. 28 Apr. 2014. <http://volcano.oregonstate.edu/obsidian>.

Nash, B.P., Merrick, H.V. and Brown, F.H., 2011. Obsidian types from Holocene sites around Lake Turkana, and other localities in northern Kenya. *Journal of Archaeological Science* 38, pp. 1371-1376.

Nave, R. "Hysteresis Loop", 2014. *HyperPhysics.* Web. 01 May. 2014

Ndiema, K.E., Dillian, C.D., Braun, D.R., Harris, J.W.K. and Kiura, P.W., 2011. Transport and subsistence patterns at the transition to pastoralism, Koobi Fora, Kenya. *Archaeometry* 53, pp. 1085-1098.

O'Handley R.C., 2000. Modern Magnetic Materials: Principles and Applications. Wiley, New York.

Rapp, G.R. and Hill, C.L., 2006. Geoarchaeology: the Earth-science Approach to Archaeological Interpretation, second ed. Yale University Press, New Haven.

Schmidbauer, E., Mosheim, E., Semioschkina, N., 1986. Magnetization and 57Fe Mössbauer study of obsidians. *Physics and Chemistry of Minerals* 13, pp. 256-261.

Sheppard, P., Irwin, G., Lin, S., McCaffrey, C., 2011. Characterization of New Zealand obsidian using PXRF. *Journal of Archaeological Science* 38, pp. 45-56.

Stewart, S.J., Cernicchiaro, G., Scorzelli, R.B., Poupeau, G., Acquafredda, P., De Francesco, A., 2003. Magnetic properties and 57Fe Mössbauer spectroscopy of Mediterranean prehistoric obsidians for provenance studies. *Journal of Non-Crystalline Solids 323*, pp. 188-192.

Urrutia-Fucugauchi, J., 1999. Preliminary Results of a Rock-Magnetic Study of Obsidians from Central Mexico. *Geofísica Internacional*, vol. 38, numero 002, pp. 83-94.

Vásquez, C.A., Nami, H.G., Rapalini, A.E., 2001. Magnetic sourcing of obsidians in southern South America: some successes and doubts. *Journal of Archaeological Science* 28, pp. 613-618.

Walsh, J. and Powys, P.G. 1970. Obsidian flakes from Laikipia District, Kenya. *Azania* 5, pp. 178-79.

Zanella, E., Ferrara, E., Bagnasco, L., Ollà, A., Lanza, R., Beatrice, C., 2012. Magnetite grain-size analysis and sourcing of Mediterranean obsidians. *Journal of Archaeological Science* 39, pp. 1493-1498.