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2013-2014 PROJECTS

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MARGO REGIER, Beloit College
Research Advisors: James Rougvie, Beloit College and Joshua M. Feinberg, University of Minnesota

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GEOCHEMICAL VARIABILITY OF OBSIDIAN IN WESTERN NEW MEXICO WITH LABORATORY-BASED PXRF

KAREN ROTH,Washington and Lee University
Research Advisor: Jeffrey Rahl

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INTRA AND INTER-SOURCE MAGNETIC PROVENANCING OF MULE CREEK REGIONAL SOURCE OBSIDIAN

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Research Advisors: James Rougvie**,** Beloit College and Joshua M. Feinberg, University of Minnesota

INTRODUCTION

Artifact provenancing, an archaeological trading route inference method, is powered primarily by geochemical techniques (Shackley, 1988). Recent work (Frahm and Feinberg, 2013) has suggested that magnetism could allow for provenancing at a finer resolution. The Mogollon-Datil Volcanic Field in western New Mexico, where obsidian sources and artifacts are plentiful, is an ideal place to test this hypothesis. One particularly plentiful source of obsidian in the southwest is the Tertiary Mule Creek Regional Source obsidian, which is a regional grouping of geochemically distinct deposits (Shackley, 2005). Antelope Creek, Danny Welch, and North Sawmill Creek are three of these deposits.

Geochemical analysis by X-ray fluorescence is currently the preferred method for obsidian provenancing (Shackley, 2005). Provenancing can only be realized with comprehensive base studies for all regional eruptive events that establish the chemical variances of each obsidian source. These studies attempt to source an artifact to one and only one event or area. This idea, known as the provenance postulate, was first stated by Weigand et al. (1997), and later modified by Neff (2000) as "Sourcing is possible as long as there exists some qualitative or quantitative chemical or mineralogical difference between natural sources that exceeds the qualitative or quantitative variation within each source."

Where chemical distinctions are slight, other methods have proven fruitful. Determination of magnetic parameters, which relies on the physical properties of microscopic crystallites of magnetite, hematite, and ilmenite grains within obsidian, has been moderately successful (McDougall et al., 1983). Provenancing takes advantage of obsidian's magnetic variation, due to magnetic particles' concentrations, compositions, sizes, and orientations, which are influenced by cooling rates, viscosities, temperatures, deformation and oxidation (Frahm and Feinberg, 2013). The concept of magnetic provenancing was suggested as early as 1983 and was initially praised for its economic and non-destructive techniques (McDougall et al., 1983). However, magnetic sourcing has been consistently outperformed by geochemical techniques (Frahm and Feinberg, 2013), due to large variations in magnetic properties within the source, and the subsequent overlapping of sources' magnetic signatures (Church and Caraveo, 1996).

Frahm and Feinberg (2013) shifted the focus of magnetic sourcing by suggesting that the very same scatter that proves problematic for magnetic inter-source provenancing may prove useful for intra-source provenancing. If magnetic properties vary in an expected way across a lava flow, then identification of quarrying sites within a flow may be possible.

There are numerous ways to determine magnetic parameters. Low-field susceptibility, the induced magnetism of a sample under a small applied magnetic field, is a common and portable magnetic method. Another simple and well-established technique is the measurement of hysteresis loops (Day et al., 1977). These curved loops, created by the application of a magnetic field to a vibrating sample, trace out the sample's induced magnetism and several proxy points for grain size and magnetic mineral concentration. These proxies are useful for characterizing the magnetic signal of a sample and could be a key to refining provenancing techniques. Using the Mule Creek Regional Source obsidian, this study evaluates 1) the use of hysteresis for intra-source provenancing 2) the use of hysteresis for inter-source provenancing and 3) the use of low-field magnetic susceptibility for intra-source provenancing.

GEOLOGIC SETTING

The Mule Creek Regional Source obsidian, located about 60 miles northwest of Silver City in southwestern New Mexico, is a geochemically distinct, but spatially related group of obsidian sources within the Mogollon-Datil Volcanic Province. These sources include both in situ obsidian flows and pyroclastic deposits from Tertiary volcanism (Shackley, 2005). Three localities of obsidian, which are geochemically distinct, were utilized for this study – Antelope Creek, North Sawmill Creek and Danny Welch.

Antelope Creek, an in situ obsidian flow, has been K-Ar dated at 17.7±0.6 mya (Ratte and Brooks, 1983; 1989). This flow is characterized by grey perlitic obsidian, obsidian breccia, and nodules of nonhyrated obsidian, called marekenites or Apache tears (Ratte and Brooks, 1989). The 25 m thick obsidian unit exists within a larger 60 m thick rhyolite flow (Ratte and Brooks, 1989).

In contrast, the North Sawmill Creek obsidian is not found in outcrop but is a pyroclastic deposit of obsidian nodules in ash and other fine grained pyroclastic material (Rhodes and Smith, 1972; Weber and Willard, 1959). The third, also not in situ, geochemical group used in this study, Danny Welch, was located and geochemically confirmed during fieldwork in the summer of 2013 (Shackley, personal comm.). This deposit is similar in origins to the pyroclastic flow of obsidian nodules and ash at North Sawmill Creek.

MAGNETICS

An object's induced magnetic moment **M** (SI units of Am^2), can be generated by a exposing the object to a moving electric current or another magnetic field of strength **H** (SI units of T). This magnetism is partially created by the spins of electrons, which can be described as small magnets themselves. If there are unpaired electrons, as there are in iron and nickel, the spins do not cancel out with each other, and entire regions of the material, called domains, will have parallel electron spins. If the sample is brought in contact with a strong magnetic field, the majority of the magnetic domains will line up with one another. The fraction of the magnetization that remains after the induced magnetization is removed is its remanent magnetism (Tauxe et al., 2010).

A specimen's magnetic parameters can be measured by collecting a hysteresis loop under a variable external magnetic field created by a Vibrating Sample Magnetometer (VSM). These parameters include saturation magnetism M_s, which is the maximum magnetic moment (Table 1). This measurement is directly related to the concentration of magnetic material. After saturation, the net remanence is called the saturation remanent magnetization M_r, which can be used as a proxy for magnetic mineral concentration and grain size. Coercivity (H_c), is the needed applied magnetism to coerce the induced magnetism to 0. Coercivity is understood to be inversely related to grain size. Coercivity of remanence (H_{cr}) is the point at which half of the magnetic moments irreversibly flip and is also inversely related to grain size (Frahm and Feinberg, 2013).

Table 1. Magnetic parameters utilized in this study.

Parameter	Definition	Proxy
Magnetic Susceptibility (χ_{lf})	Magnetization under applied field	Concentration of magnetic material
Magnetic Saturation (M_s)	Maximum magnetization	Concentration of magnetic material
Saturation Remanent Magnetization (M_r)	Remanence after saturation	Concentration of Magnetic material and grains size
Magnetic Coercivity (H_c)	Net moment = 0 under applied field	Inversely related to grain size
Coercivity of Remanence (H_{cr})	Net moment = 0 without field	Inversely related to grain size

These changes in magnetism can be plotted as a loop on a graph of magnetic field **H** vs. magnetization **M** (Fig. 1). Assuming that the specimen starts demagnetized, the curve will begin at the origin and follow an initial magnetization curve of low-field (χ_{lf}) and then high field susceptibility (χ_{hf}), or the induced magnetism under an applied field. The curve approaches an asymptote at magnetic saturation. The field is then reduced and the magnetization of the specimen will follow a different curve past saturation remanence on the y-axis and to the opposite magnetic saturation. Coercivity of remanence is measured after the loop is completed and is defined as the field that returns the magnetic remanence to zero (Day et al., 1977).

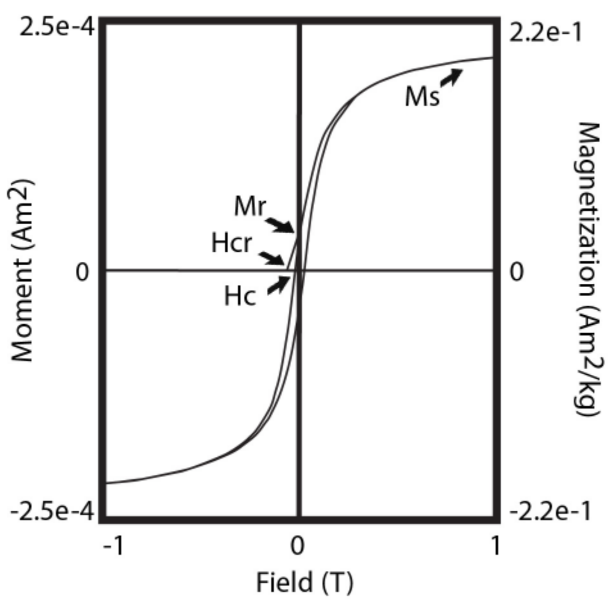

Figure 1. Generic hysteresis loop for obsidian. Magnetic Saturation (M_s), Saturation Remanent Magnetization (M_r), Magnetic Coercivity (H_c), and Coercivity of Remanence (H_{cr}) are shown on the graph of applied field (T) vs. magnetization (Am^2/kg) or normalized moment (Am^2).

METHODOLOGY

Mule Creek obsidian samples were collected in the summer of 2013. At the Antelope Creek locality, six outcrop and five outwash locations were georeferenced and sampled for hysteresis analysis. Additionally, GPS and magnetic susceptibility measurements were made on 100 in situ perlite and nodule locations (Terraplus KT10 Magnetic Susceptibility Meter) and 49 apache tears (Bartington MS2 Susceptibility Meter System). At North Sawmill Creek, individual obsidians were collected and georeferenced. Danny Welch samples were collected without individual georeferencing.

Hysteresis curves were measured at the Institute for Rock Magnetism at the University of Minnesota, Twin Cities. Prepared samples were weighed and placed in the vibrating sample holder of the Princeton Measurements Vibrating Sample Magnetometer 3900. The measurement was taken at room temperature and performed with an applied field maximum of 1 T, and an applied field increment of 2 mT. The anisotropy of hysteresis measurements was analyzed by performing measurements in three perpendicular orientations.

The multivariate discriminate analysis platform on JMP 9 was used to calculate the estimated probability of correct discrimination between sources. Polished sections were imaged and analyzed with scanning electron microscopy and energy dispersive spectroscopy at Beloit College.

RESULTS

Hysteresis parameters displayed geospatial grouping at the inter-source scale. The JMP analysis determined that the top three discriminating parameters for the three sites – Antelope Creek, Danny Welch, and North Sawmill - were M_s, H_c and H_{cr}. A 3D plot of these shows site grouping with some deviations (Fig. 2a). A JMP discriminate analysis using all hysteresis parameters, M_s, M_r, H_c, H_{cr}, and χ_{hf}, reclassifies the samples to the correct location with 94.45% accuracy ($F = 3.0792$, $df = 70{,}82.6$, $p < .0001$), with most of the misidentifications occurring between Antelope Creek and Danny Welch. Incidentally, these sites are located significantly closer to one another than to the North Sawmill Creek site.

North Sawmill displays much more anisotropy than the other sites (Fig. 2b). SEM imaging of polished sections from each site suggests a high degree of preferred orientation defined by grain elongation of crystals in North Sawmill samples, as opposed to the randomly oriented crystals in Danny Welch and Antelope Creek (Fig. 3). This preferred orientation of crystallites in North Sawmill Creek would explain its higher variability of hysteresis parameters.

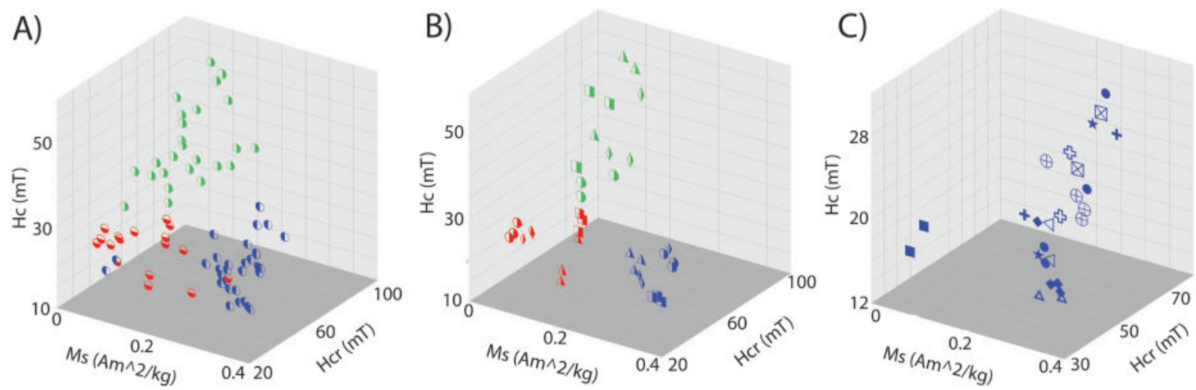

Figure 2. Variation in hysteresis parameters from the sites Antelope Creek (blue), Danny Welch (red), North Sawmill Creek (green). A) Hysteresis loop parameters for the three sites. B) Anisotropy measurements taken in three perpendicular orientations for one sample (three replicates of every symbol) for all three sites. C) Antelope Creek marekanite samples. Filled symbols are in situ outcrops, unfilled symbols are samples that were collected in washes. At least two samples were collected from every site, and anisotropy measurements are included for applicable samples.

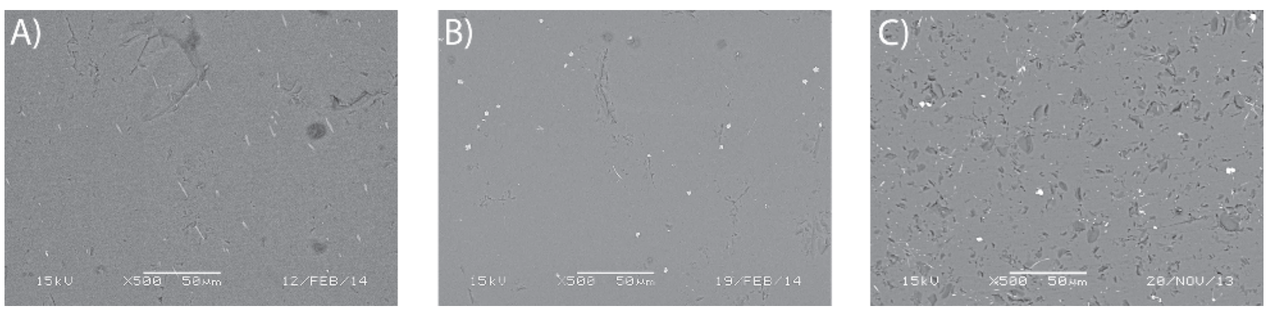

Figure 3. BSE images of obsidian in polished section. A) North Sawmill, B) Danny Welch, C) Antelope Creek.

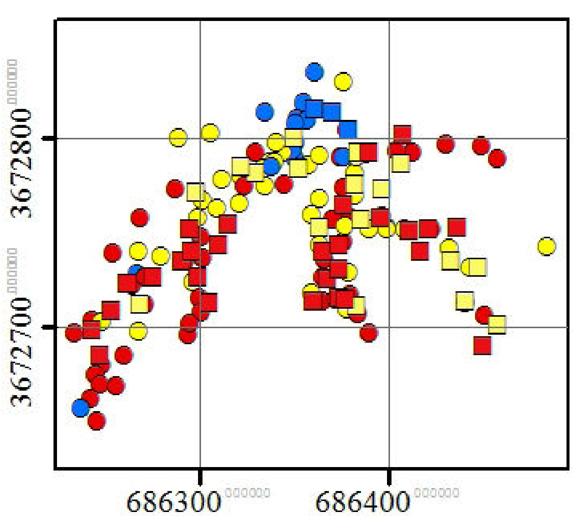

Figure 4. Low-field magnetic susceptibility of in situ perlite (squares) and apache tears (circles) at Antelope Creek (UTM zone 13, NAD 27). Magnetic susceptibility ranges from 0.20-0.50 $m^3 \cdot kg^{-1}$ (blue), 0.50-1.20 $m^3 \cdot kg^{-1}$ (yellow), 1.20-3.50 $m^3 \cdot kg^{-1}$ (red).

The Antelope Creek intra-source hysteresis measurements showed significant variation within individual outcrops and washes (Fig. 2c). While some individual outcrop and wash samples are grouped, others overlap.

Intra-source GIS projection of low-field magnetic susceptibility for Antelope Creek in situ perlite and apache tears shows a pattern of low susceptibility to the north and high susceptibility to the south (Fig. 4). The susceptibilities of Apache tears range over 1.29 m^3 kg^{-1}, while perlite spans 3.17 m^3 kg^{-1}. The hysteresis properties and ratios show little observable pattern for both outcrop and outwash samples.

DISCUSSION

Interflow Provenancing

This study supports previous suppositions that magnetic properties can sometime differentiate between different volcanic deposits (McDougall et al., 1983). In our study, hysteresis measurements effectively discriminate the three sites to 94.45% accuracy. However, due to the availability of cheap and effective geochemical provenancing techniques, magnetic methods may only be useful when geochemical methods fail to unambiguously provenance an artifact.

Intraflow Provenancing

The supposition that magnetism is a possible way to provenance to a specific location or quarry is also supported by this study. The observable geospatial pattern in low-field magnetic susceptibility across the sampled area shows strong promise for further studies linking artifacts to a specific area or quarry within an obsidian flow. However, the utility of hysteresis parameters in this endeavor is unclear. While hysteresis parameters from the same outcrop or outwash display some grouping, the variability at Antelope Creek is too great to be magnetically distinguishable. Furthermore, the hysteresis properties do not map in any observable pattern at the scale sampled. Further studies should test whether patterns appear at either larger or smaller scales.

Suggestions for Further Study

A further property that complicates magnetic sourcing is anisotropy. The anisotropy of susceptibility is well-established and can be used to orient flow of the lava (Cañón-Tapia and Castro, 2004). When obtaining susceptibility measurements from in situ obsidian, anisotropy may skew the data and lead to inaccurate provenancing. The anisotropy of hysteresis parameters is also highly variable between obsidian flows. Provenancing on flows with as much anisotropy as North Sawmill samples requires multiple measurements in a variety of orientations in order to rigorously determine an average value. Otherwise, the use of hysteresis parameters yields equivocal results. However, provenancing may be straightforward for obsidian with smaller amounts of anisotropy, as displayed by Antelope Creek and Danny Welch samples. Therefore, it is important to determine the degree of anisotropy of the obsidian before attempting any of these methods. This information could be obtained by magnetic testing in multiple orientations, or by using SEM imaging to visually assess magnetic grain orientation.

Another process that must be considered when interpreting magnetic properties of obsidian is perlitization. At Antelope Creek, this process appears to increase magnetic susceptibility. However, these values should be viewed critically, for they were obtained with two different susceptibility meters – one for the Apache Tears and one for the perlite. At this time it is unclear if perlite can be used to provenance obsidian artifacts to a particular location or quarry within a flow. Therefore, it is important to quantify the effects of perlitization on magnetic parameters before utilizing perlitized obsidian for provenancing.

CONCLUSION

Magnetic properties of obsidian may provide a way to provenance archaeological artifacts to an obsidian flow or specific quarry within the flow. However, magnetic variation is complex and necessitates detailed study of the flow at various scales and with numerous magnetic techniques. A magnetic provenancing method that succeeds at one site may not translate to another. Therefore, more baseline studies on the variation of magnetism across and within obsidian flows, as well as the effects of perlitization and anisotropy are needed.

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