INL/RPT-23-73575

The geology, geochemistry, and geographic distribution of southern Idaho obsidian

July 2023

A provisional context for archaeological provenance research at the INL CRMO

Jeremias Pink

Archaeologist, INL Cultural Resources Management Office

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/RPT-23-73575

The geology, geochemistry, and geographic distribution of southern Idaho obsidian

A provisional context for archaeological provenance research at the INL CRMO

Jeremias Pink
Archaeologist, INL Cultural Resources Management Office

July 2023

Idaho National Laboratory
Cultural Resources Management Office
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

ABSTRACT

The Snake River Plain Volcanic Province of Southern Idaho is host to an abundance of pyroclastic obsidian deposits that constitute the principal lithic raw material utilized by Native Americans of the region throughout the Precontact Period. Archaeologists have long looked to obsidian as a source of information on past patterns of raw material selection, landscape use, and mobility through geochemical analysis of obsidian artifacts and lithic raw materials. Formation of the Snake River Plain through cataclysmic "super-eruptions" of the Yellowstone hotspot, however, presents one of the most complex and poorly understood obsidian source-scapes of North America. To clarify the geographic distribution of Southern Idaho obsidian source groups, the INL CRMO has compiled a comprehensive reference library of geologic obsidian from 138 source locales distributed across the southern half of the state. In this report, we define 28 geochemically distinct obsidian source groups that occur at these deposits through X-ray Fluorescence spectrometry and contextualize the geographic distribution of each source group relative to the history of silicic magmatism on the Snake River Plain. This research facilitates ongoing investigations at the INL CRMO into patterns of obsidian procurement, conveyance, and exchange in Southern Idaho throughout the Precontact Period.

Page intentionally left blank

CONTENTS

FIGURES

TABLES

Page intentionally left blank

The geology, geochemistry, and geographic distribution of southern Idaho obsidian

A provisional context for archaeological provenance research at the INL CRMO

Introduction

Southern Idaho is home to some of the most heavily utilized and widely-traded obsidian sources of Precontact North America (Griffin, Gordus, and Wright 1969; Hatch et al. 1990; Thompson 2004). This is due, in part, to its position along natural trade and travel corridors at the geographic nexus of the Great Basin, the Great Plains, and the Columbia Plateau. But geology also plays a critical factor. The Snake River Plain is one of North America's largest intracontinental volcanic provinces. It was created through a series of vast, pyroclastic super-eruptions as the North American Plate drifted over the Yellowstone hotspot over the past 16 Ma (Pierce and Morgan 1992; 2009). A by-product of this history of volcanic activity is an abundance of geologic obsidian deposits at a multitude of locales that form a nearly continuous perimeter around the central and eastern Snake River Plain (Figure 1). At most archaeological sites on the Snake River Plain, as much as 80 to 90% of lithic artifacts were produced using obsidian acquired from these sources. Because the geochemical composition of an obsidian artifact is directly related to the volcanic source material that was used to produce it, trace-element analysis is often used by archaeologists in the Intermountain West to assess patterns of toolstone procurement and conveyance evident at the site-level or regional to inter-regional scales (R. E. Hughes 1984; Shackley 2005; 2011). In southern Idaho, however, the immensity of pyroclastic eruptive events produced a complex landscape of closely-related, overlapping, and discontinuous obsidian source areas that defy the ordinary assumptions of archaeological provenance research and that remain poorly understood.

The strength of provenance research in any region (and for any archaeological material) depends on three factors: (1) robust methods of geochemical analysis; (2) rigorous statistical methods of source attribution; and (3) a comprehensive reference database of well-characterized raw materials with well-documented source locations (R. E. Hughes and Smith 1993; R. E. Hughes 1998; Glascock and Neff 2003; Shackley 2005; 2011). Over the past twenty years, there has been substantial attention to the first two issues among the archaeological community (Craig et al. 2007; Frahm 2012; 2013; Glascock 2011; R. E. Hughes 1984; Shackley 2011; 2012; Speakman and Shackley 2013). This report focuses on the third. To effectively guide interpretations of past procurement, transport, and trade in southern Idaho, we argue that obsidian sources must be characterized in terms of three variables: (1) their range of multivariate geochemical variability; (2) the geographic location and extent of deposits; and (3) the spatial continuity of those deposits. An additional challenge is ensuring that source attributions are adequately grounded in a firm understanding of regional geology (R. E. Hughes and Smith 1993; Shackley 2005).

This study benefits from a long history of provenance research in Southern Idaho. To characterize and contextualize obsidian source areas of the Snake River Plain and surrounding areas, we revisited over 150 potential obsidian source locales previously reported by archaeologists or identified through review of the geological literature. Major and trace-element analysis of raw materials from these deposits shows that at least 28 geochemically distinct obsidian source groups were available to Native Americans in Southern Idaho. Ten of these are from large-volume, regionally extensive, pyroclastic deposits associated with hotspot volcanism of the Snake River Plain Volcanic Province. In the following sections, we provide a brief review of past efforts to characterize the distribution of obsidian artifacts and raw materials in southern Idaho, then outline the history of silicic volcanism informing the distribution of Idaho obsidian source areas.

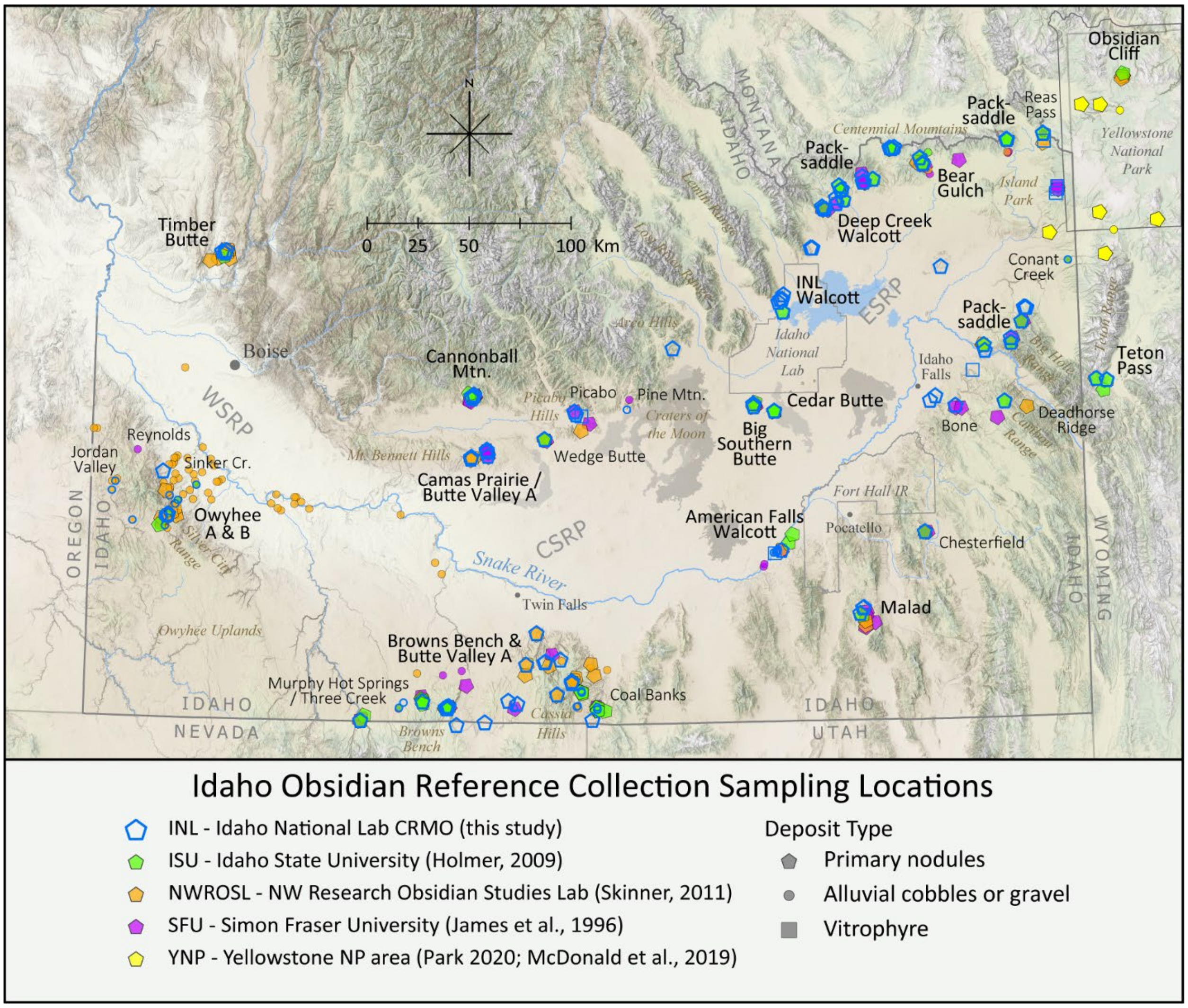

Figure 1: Geographic distribution of Southern Idaho obsidian sampling locations relative to source locales reported by SFU, ISU, and NWROSL. Common names for source groups are shown in bold. Common names for a selection of other source locales are shown in a smaller font.

Sourcing obsidian in Southern Idaho

Archaeologists have conducted studies of obsidian procurement, transport, and trade in Southern Idaho for over fifty years (Frison et al. 1968; Gordus, Wright, and Griffin 1968; Sappington 1981a; 1981b; 1984; Nelson, Jr. 1984; Bailey 1992; James, Bailey, and D'Auria 1996; Holmer 1997; Plager 2001; Willson 2005; 2007; Henrikson 2008; Scheiber and Finley 2011; Fowler 2014; Black 2014; 2015; Arkush and Hughes 2018). Early studies employed Neutron Activation Analysis (Frison et al. 1968; G. A. Wright, Griffin, and Gordus 1969), a robust and reliable method of trace-element characterization (Glascock and Neff 2003; Minc and Sterba 2017), but relied on limited reference collections of geologic obsidian. By the 1980s and 90s, most scholars working in the region had turned to X-ray Fluorescence (XRF) (e.g. Gallagher, 1979; Sappington, 1981a, 1981b, 1984; Green, 1982; Nelson, Jr., 1984; Reed, 1985; Moore, 2009), a rapid, non-destructive, and more affordable method of analysis suitable for geochemical characterization of homogenous materials such as volcanic glass (Shackley 2011). Initial attempts to establish a regional obsidian reference database at the University of Idaho (Sappington 1981a; 1981b), though ambitious, were criticized for insufficient analytical precision, poor documentation, and inappropriate statistical methods of source assignment (R. E. Hughes 1984). Subsequent work was conducted with more analytical rigor (e.g. Nelson, Jr. 1984), but challenges of comparing data between labs required each researcher to develop their own reference database for the region. Adding to these issues, the provenance of some major geochemical groups remained unknown until the 1990s[a]. The result was a profusion of ad hoc, study-specific obsidian collections with inconsistent source names and poorly documented source locations (Holmer 1997).

Over the past thirty years, multiple labs have undertaken independent efforts to compile and characterize obsidian reference collections for southern Idaho and surrounding regions. Building upon pioneering work by Sappington (1981a, 1981b, 1984) and Nelson et al. (1984), researchers at Simon Fraser University (SFU) compiled a "volcanic glass library" for the Pacific Northwest that defined 30 geochemical source groups from 76 localities across southern Idaho (Bailey 1992; James, Bailey, and D'Auria 1996). In 1997, researchers at Idaho State University (ISU) synthesized literature on known Idaho obsidian source locales in an attempt to standardize regional source nomenclature (Holmer 1997). This work ultimately led ISU to compile their own reference collection of 19 groups from 72 localities (Black 2014; 2015) in collaboration with the Geochemical Research Laboratory (GRL), a commercial XRF lab run by Richard Hughes. Parallel to this effort, the Northwest Research Obsidian Studies Laboratory (NWROSL), then run by Craig Skinner, built a reference collection spanning western North America, including 24 groups from 113 sampling locations in southern Idaho (Skinner, 2011a, 2011b, 2011c; Black, 2015). Ten additional source locales have been reported in and around Yellowstone National Park, east of the present study area (Park 2010; MacDonald, Horton, and Surovell 2019).

By the early 2000s, geologic outcrops had been identified for all major Idaho obsidian source groups, facilitating several studies of obsidian procurement and transport at a regional scale (Holmer, 1997; Plager, 2001; Willson, 2005, 2007; Scheiber & Finley, 2011; Black, 2014, 2015; Fowler, 2014). In the first of these efforts, Holmer (1997) and Plager (2001) compiled a comprehensive database of results from earlier Idaho provenance studies to identify broad patterns of obsidian conveyance and assess their implications for Precontact mobility and trade. Results of this work showed that obsidian was transported across southern Idaho over an area spanning the traditional territory of the Northern Shoshone and Bannock peoples, with longer transport distances along the Snake River Plain than across it. Later studies confirmed that these observations held diachronically by building upon this dataset with more recent results and further analyses of temporal diagnostics held in museum collections (Willson 2005; Scheiber and Finley 2011; Fowler 2014; Black 2014). Critiques of such efforts to synthesize results of previous studies into a regional source-use database focused on research design and the theoretical challenge of linking obsidian transport to forager mobility (Willson 2005; 2007). Less scrutiny was paid to the reliability of early source attributions or the comparability of results between labs (but see Hughes, 1984; Holmer, 1997, p. 188; Plager, 2001, pp. 32–33).

The importance of the latter issue was highlighted by Black (2014, 2015), who demonstrated that the rate of statistical source assignment for southern Idaho artifact collections depended strongly on one's choice of XRF reference library. After analyzing 174 artifacts from 11 southern Idaho sites using a Bruker XRF spectrometer at ISU, Black (2015:41) found that just 74.7% of artifacts could be assigned to a southern Idaho obsidian source group through comparison to the ISU obsidian reference library, using a combination of principal components analysis, hierarchical cluster analysis, and visual examination of the data. Subsequent comparison to the NWROSL obsidian reference library for southern Idaho increased the rate of source assignment to 86.8% using the same methods. (Unassigned artifacts were assumed to have

[a] Hughes (1984) has argued that reliance on limited geologic reference collections, combined with use of canonical discriminant analysis for source attributions (e.g. Sappington, 1981a, 1981b, 1984), resulted in misclassification of artifacts in some early studies (R. E. Hughes 1984; 2007b; Arkush and Hughes 2018). This problem may contribute to inconsistencies in findings from later studies that relied to greater and lesser degrees on syntheses of previous work (e.g. Holmer, 1997; Plager, 2001; Scheiber & Finley, 2011; Fowler, 2014).

originated from either outside Idaho or from unknown or uncharacterized sources within Idaho). Given the need to cross-calibrate data between labs, it is unlikely that differences in instrumentation or calibration can account for such an increase in the rate of source assignment. Use of a pooled obsidian reference library that included data from multiple labs simply provided a more comprehensive view of the Idaho obsidian source universe than would have possible through reliance on comparative data from a single lab (Black 2014; 2015).

Figure 1 shows the spatial distribution of sampling locations of geologic obsidian in reference collections compiled by SFU, ISU, and NWROSL. All have sampling locations for heavily utilized sources (as reported by Holmer, 1997; Plager, 2001; and Fowler, 2014), such as “American Falls”, “Big Southern Butte”, “Bear Gulch”, “Browns Bench”, “Malad”, “Obsidian Cliff”, “Owyhee”, and “Timber Butte”. However, SFU and ISU have greater sample coverage on the east side of the Snake River Plain, while NWROSL has far better sample coverage to the west. As a result, the NWROSL database captures several minor source groups in western Idaho that are not represented in the ISU database (e.g., the “Sinker Creek” and “Jordan Valley” groups) while ISU captures eastern sources not that are not represented in the NWROSL database (e.g., “Chesterfield” and “Cedar Butte”). More importantly, the extent and distribution of sampling within extensive or discontinuous source areas, such as those known as “Browns Bench” and “American Falls,” contributes to differences in how each lab statistically defines geochemical source groups and maps them onto the landscape.

Two examples are sufficient to illustrate the latter point. First, while SFU and NWROSL’s sampling locations for the “American Falls” group are restricted to a small area near American Falls, ISU and GRL have located deposits of obsidian from this group over 80 kilometers away on the opposite side of the eastern Snake River Plain (Arkush and Hughes 2018; Keene 2018a). Following Sappington (1981a), ISU and GRL refer to this source group as the “Walcott Tuff” (in reference to the geologic unit it is derived from) to avoid conflation of the geochemical group with its most well-known source locale. Second, source locales have only recently been identified for a group long known as “Butte Valley A” (Page and Bacon 2016; Skinner 2011a) that was first defined through analysis of artifact assemblages from Butte Valley, Nevada (G. T. Jones and Beck 1990; R. E. Hughes and Smith 1993). This group, which is compositionally similar to “Browns Bench” obsidian, has been identified by NWROSL both north and south of the central Snake River Plain (Page and Bacon 2016; Skinner 2011a). The “Camas Prairie” source locale, identified by SFU (Bailey 1992), may correspond to the same source group, but their sample is restricted to the Mt. Bennett Hills north of the plain. ISU has not reported samples of obsidian corresponding to the “Butte Valley A” group either north or south of the plain (Black 2015), and may not recognize this as a group distinct from “Browns Bench”.

In fact, several Idaho obsidian source groups are known to outcrop in a multitude of primary deposits over vast source areas, sometimes separated by over 100 km on opposing sides of the plain (Figure 1). The difficulty of statistically discriminating between material from various sampling locations within these extensive, often discontinuous source areas is an issue that has vexed XRF specialists working in southern Idaho for decades (Arkush and Hughes 2018; Bailey 1992; R. E. Hughes and Smith 1993; Page and Bacon 2016; Willson 2005). Yet these groups are often mapped as singular point locations for illustrative purposes or to facilitate simple estimates of distance and direction to source (e.g. Fowler 2014; Henrikson 2008; Holmer 1997; Keene 2018b; Page and Duke 2015; Plager 2001; Reid 2014; Scheiber and Finley 2011). While some degree of generalization is often needed to produce a legible map, this has occasionally resulted in serious confusion on the part of scholars dependent upon XRF specialists when results appear to suggest abnormally high use of a thought-to-be distant source (e.g. Harris, 2014).

The key issue was identified by Holmer (1997) over twenty-five years ago: “some geochemical types have been referred to by several names often because the material is exposed in several locations (e.g., Big Table Mountain); and some names have been applied to multiple locations with distinct chemical properties". This problem persists due to a lack of publicly available data on the sampling locations or geochemical composition of obsidian reference groups used in source determinations. Following Arkush and Hughes' work on the Walcott Tuff (Arkush and Hughes 2018), this report attempts to address long-standing ambiguities and discrepancies in the mapped distribution of southern Idaho obsidian source groups. To do so, we disentangle geochemical source groups from source locations and attempt to contextualize the spatial distribution of each group in terms of regional silicic geology. Whenever possible, we explicitly relate each group to a known geologic unit representing the specific eruptive event that led to its deposition.

What is an obsidian "source"?

Since the 1960s, obsidian has been widely regarded as an ideal material for provenance research in archaeology (Cann & Renfrew, 1964; Gordus, Wright, & Griffin, 1968; Hughes & Smith, 1993; Hughes, 1984, 1998; Glascock, 2002). Compared to other lithic materials, such as chert, the geochemical composition of most obsidian deposits is both highly homogenous and easily distinguished from other source locales through trace element analysis (R. E. Hughes and Smith 1993; Glascock 2002). Obsidian satisfies the key assumptions of sourcing as defined in the "Provenance Postulate" of Weigand, Harbottle, & Sayre (1977, p. 24): "Implicit in the idea of using chemical analysis to trace artifacts to their source… [is] that there exist differences in chemical composition between different natural sources that exceed, in some recognizable way, the differences observed within a given source" (see also Hughes and Smith 1993; Neff 1998; Glascock and Neff 2003; Frahm 2014).

But what is an obsidian *source*? Some analysts prefer to define sources geochemically through statistical grouping of trace element data (e.g. Hughes & Smith, 1993; Hughes, 1998), while others define sources geographically as source areas or locales (e.g. Harbottle, 1982; Neff, 1998; Rap & Hill, 1998). An implicit assumption of either approach is a close correspondence between geochemical source groups and geographic source areas (Shackley 1988; 2005; R. E. Hughes and Smith 1993; Glascock 2002; Frahm 2014). In general, this works well for obsidian because the geochemical composition of a given deposit is governed by a combination of its unique magmatic source material and the geochemical evolution of the magma melt prior to (and perhaps during) eruption (R. E. Hughes and Smith 1993; Glascock 2002). The details of how this works warrant some attention.

Obsidian is rhyolitic volcanic glass formed through (1) the rapid cooling of high-silica lava; (2) quenching at the margins of intrusive rhyolite sills and dikes; or (3) the degassing and sintering of rhyolitic ash into vitric clasts ejected during a pyroclastic eruptive event (Gardner et al. 2019; Rust and Cashman 2007; Tuffen et al. 2020). The composition of a given obsidian deposit is largely determined by conditions prior to eruption as various elements are partitioned into solid and liquid phases of the silica melt. Compatible elements are those that readily form or substitute into minerals comprising the solid phase of the melt, while incompatible elements are those more likely to be sequestered in the liquid phase (Faure 1997, 625:99–117; White 2015, 98–101). Magmas derived from the upper mantle and oceanic crust are more enriched in compatible elements such as manganese (Mn), iron (Fe), and zinc (Zn). Magmas derived from continental crust tend to be more enriched in incompatible elements, including both large-ion lithophiles (those with a large ionic radius to ionic charge ratio) such as rubidium (Rb), strontium (Sr), and barium (Ba) and high field strength elements (those with a high ionic charge and small ionic radius) such as yttrium (Y), zirconium (Zr), and niobium (Nb) (White 2015, 98–101). The composition of a melt is thus partially a product of the magma source, but factors such as temperature, pressure, mixing, gravimetric sorting, and the convection dynamics of the magma chamber all further influence elemental fractionation (Cashman and Bergantz 1991; Bergantz 1995; Cashman, Sparks, and Blundy 2017). During an eruption, rapid cooling of silicic lava into obsidian flows or the sintering of rhyolitic ash into glassy pyroclasts may prevent mineralization of a portion of the melt, thereby preserving its major and trace element composition at the time of the eruption in volcanic glass (R. E. Hughes and

Smith 1993; Glascock 2002; Rust and Cashman 2007; Gardner et al. 2019). As a result, the composition of obsidian from a given eruption is – in most cases – both highly homogenous and distinct from that of other eruptions, even within the same volcanic system.

Nevertheless, our ability to accurately link obsidian artifacts to a given geographic source area through archaeological chemistry requires knowledge of a few factors: (1) the spatial extent of obsidian-bearing deposits at the time of eruption; (2) the occurrence of any later tectonic and geomorphic processes that may have altered the spatial distribution and exposure of material; and (3) the range of geochemical variability present in the glassy component(s) of the eruptive event. In some geologic settings, obsidian may indeed occur in highly localized, spatially discrete flows or deposits bearing unique geochemical signatures that may be appropriately modeled as point sources when viewed from a regional scale. In the Cascades Range of Oregon, for example, partial melting of the crust above the Cascadia subduction zone has produced a chain of rhyolite domes (e.g. Obsidian Cliff) that bear obsidian deposits that are both compositionally distinct and geographically constrained (Baxter, Connolly, and Skinner 2015; Connolly, Skinner, and Baxter 2015; McMillan, Amini, and Weis 2019). Alluvial transport may increase the extent of such sources through secondary deposits (Baxter, Connolly, and Skinner 2015, 24; Connolly, Skinner, and Baxter 2015, 183), but these examples are something of a best-case scenario for provenance research.

In other geologic settings, the assumption of a neat correspondence between geochemical source groups and geographic source areas does not always hold. Some source areas host deposits of obsidian with multiple geochemical signatures, reflecting complex histories of eruption and the geochemical evolution of magma chambers between eruptive events (e.g. Ericson & Glascock, 2004; Brown, Reid, & Negash, 2009; Morgan et al., 2009; Poupeau et al., 2010; Glascock, 2011; Argote-Espino et al., 2012; Knight et al., 2017). Obsidian from Glass Buttes in central Oregon, for example, can be assigned to as many as nine geochemical source groups, all found within a 200 km^2 area (Ambroz, Glascock, and Skinner 2001; Frahm 2014; Frahm and Feinberg 2015). Of course, given an adequate and representative sample of material from each compositional subgroup, this scenario poses far less of an issue for provenance research than geologic settings where obsidian exhibits little geochemical variability over very large and/or discontinuous source areas (Hughes & Smith, 1993). In the Mogollon-Datil Volcanic Province of Arizona and New Mexico, for example, obsidian deposits are found in several locales over a 40,000 km^2 area that cannot be readily distinguished using elements commonly quantified via XRF alone, requiring supplemental methods of isotope geochemistry and geochronology to confirm distinctions between groups (Shackley, 2005; Shackley, Morgan, & Pyle, 2017). Other examples of geographically extensive source complexes include the Coso Volcanic Field of California (Ericson and Glascock 2004; R. E. Hughes 1988), the Medicine Lake Volcano in northern California (R. E. Hughes 1982), and Laguna del Maule source area in northern Patagonia (Barberena et al. 2019).

As we will show in this study, the obsidian source-scape (Barrientos, Catella, and Oliva 2015; Ozbun 2017; Barberena et al. 2019) of southern Idaho offers examples of all three of the scenarios outlined above. Some well-known sources, such as Big Southern Butte and Malad, are quite localized and geochemically distinct. Others, such as Teton Pass and Cannonball Mountain, are also localized but bear obsidian with multiple geochemical signatures. The key motivation for this research however is that many Idaho obsidian source groups outcrop in a multitude of discontinuous deposits over vast expanses of terrain. The “Browns Bench” and Walcott Tuff source groups are just two of the better-known examples. In fact, the majority of obsidian source locales in southern Idaho are associated with ignimbrite deposits from immense, large-volume “super-eruptions” associated with passage of the North American Plate over the Yellowstone hotspot over the past 12 million years (Bonnichsen et al. 2008; Branney et al. 2008; Ellis et al. 2013; Monnereau et al. 2021; L. A. Morgan and McIntosh 2005). To further complicate matters, the obsidian-bearing ignimbrite tuffs that resulted from these eruptions were largely buried by later rhyolite tuffs, basalt flows, and alluvium, and then rendered even more discontinuous by tectonic subsidence, faulting, erosion, and redeposition (Hackett and Morgan 1988; S. S. Hughes et al. 1999). The resulting source-scape is a patchwork of obsidian deposits belonging to a complex of closely related geochemical groups distributed over immense, discontinuous, and overlapping source areas. In Idaho, as in other regions, our ability to link obsidian artifacts to specific source areas through geochemical data thus depends as highly upon our understanding of the geologic context of available source material as upon our methods of analysis and statistical source assignment.

Regional geologic setting

The Snake River Plain of southern Idaho is one of the most distinctive physiographic features of the Intermountain West. Stretching some 700 km from the Oregon/Idaho border to the Yellowstone Plateau in Wyoming, the plain is a broad (80-100 km wide) arcuate depression of low-relief volcanic terrain and sagebrush steppe separating the mountains of central Idaho from the Northern Great Basin in Utah and Nevada (Lewis et al. 2012). The arc of the Snake River Plain represents the intersection of two major structural features. The western Snake River Plain is a 60-70 km wide rift basin filled with basalt and lacustrine sediments of Miocene-Pliocene Lake Idaho (Wood and Clemens 2002). The central and eastern Snake River Plain are part of the Yellowstone hotspot track, a linear, northeast-trending downwarp created by the slow passage of the North American Plate over a fixed, sub-crustal thermal anomaly that currently underlies the Yellowstone Caldera (Bonnichsen, White, and McCurry 2002; Bonnichsen and Breckenridge 1982; Pierce and Morgan 1992; 2009).

The majority of obsidian source areas in southern Idaho are related, directly or indirectly, to silicic volcanism associated with the Snake River Plain Volcanic Province (SRP-VP). The SRP-VP is a bimodal, time-transgressive sequence of rhyolitic tuffs and basalt flows that record the history and evolution of hotspot volcanism across the central and eastern Snake River Plain over the past 16 million years (Bonnichsen, White, and McCurry 2002; Leeman 1982a). It is one of the only recent examples of an intracontinental hotspot track known throughout the world (Branney et al. 2008).

Several models have been introduced to explain the history of volcanic activity along the Yellowstone hotspot track. But the prevailing hypothesis is that around 20 million years ago, the North American plate began to drift southwest over a fixed, deeply sourced mantle plume (Anders et al. 2014; Camp and Ross 2004; Camp and Wells 2021; Pierce and Morgan 1992; 2009), triggering a chain of cataclysmic eruptive cycles that would carve the path of the Snake River Plain from the edge of the continent (then in eastern Oregon) to the present-day Yellowstone caldera. Pierce and Morgan (2009) outline three stages of volcanism along the Yellowstone hotspot track: (1) eruption of the Columbia River Flood Basalts; (2) formation of the central Snake River Plain Volcanic Province (CSRP-VP); and (3) formation of the eastern Snake River Plain Volcanic Province (ESRP-VP) and the Yellowstone Caldera.

The Columbia River Basalt Group (17 - 14 Ma)

As the North American plate began to override the Yellowstone mantle plume, upwelling mafic magmas were initially impinged by subduction of oceanic crust beneath the western edge of the continent, leading to the accumulation of a 300 km diameter plume-head beneath the subducting slab of the Juan de Fuca plate (Pierce and Morgan 2009: pages). At 17 Ma, the plume-head broke through the slab and pooled beneath the continental boundary, resulting in the eruption of the voluminous Columbia River Basalt Group and Steens Basalts of eastern Oregon and Washington until 14 Ma. From 16.1 – 14 Ma, a series of large-volume rhyolite eruptions occurred at the McDermitt caldera on the Oregon/Nevada border (T. R. Benson, Mahood, and Grove 2017). This was the first of six time-transgressive rhyolitic volcanic fields to develop along the Yellowstone hotspot track between Oregon and Wyoming (Manley and McIntosh 2002; Pierce and Morgan 1992). During the same period, partial melting of granitic crust at western edge of the continental craton initiated a series of lower volume rhyolitic eruptions in northern Nevada and western Idaho, including an obsidian-bearing rhyolite dome complex on the Owyhee Plateau and at Timber Butte north of Boise (Bonnichsen et al. 2008, 320; Wood and Clemens 2002).

The central Snake River Plain Volcanic Province (14 - 10 Ma)

As the North American plate progressed southwest over the hotspot, the initial pulse of upwelling magma from the head of the mantle plume was reduced to a smaller diameter plume tail that continued to pool below the continental crust in a linear track marking the movement of the plate (Pierce and Morgan 2009, fig. 6). Widespread mafic magmatism in Oregon and Washington ceased, and the center of volcanism shifted into southwestern Idaho. Partial melting of the continental crust led to a flare-up of high-temperature (> 1000 °C), large-volume rhyolitic eruptions at volcanic fields of the CSRP-VP, first at the Owyhee-Humbolt EC (13.8 - 12.0 Ma), then the Bruneau-Jarbidge EC (12.5 - 10.8 Ma), and then the Twin Falls EC (10.6 - 8.6 Ma) (Pierce and Morgan 1992; Figure 2). Because the Paleozoic crust is thinner to the west, magmas of the CSRP-VP pooled at greater temperatures and depths, and erupted with greater frequency and volume than those of the ESRP-VP (S. S. Hughes and McCurry 2002). Following periods of silicic volcanism, crustal subsidence and secondary mafic volcanism led to the burial of rhyolite tuffs along the central axis of the hotspot track in the center of the plain (S. S. Hughes et al. 1999; S. S. Hughes and McCurry 2002). Facies associated with the Owyhee-Humboldt EC are almost entirely obscured by later flows of rhyolite and basalt (Manley and McIntosh 2002). Ignimbrite tuffs of the Bruneau-Jarbidge EC are known primarily from distal fallout deposits and exposures in the deep canyon walls of the Bruneau and Jarbidge Rivers (Bonnichsen and Citron 1982; Perkins et al. 1995). Outflow deposits from the Twin Falls EC remain well-exposed in the hills to the north and south of the plain, but are also obscured on the plain itself (Ellis et al. 2013). Obsidian is found in association with several ignimbrites of the CSRP-VP on the margins of the Snake River Plain.

The Yellowstone / eastern Snake River Plain Volcanic Province (10 Ma - present)

Around 10 Ma, the character of SRP-VP silicic volcanism began to change as the hotspot encountered progressively thicker Archaen crust to the east (Pierce and Morgan 2009, 11–13). Upwelling magmas continued to pool at the crust/mantle boundary, but the resulting melts took greater time to rise through the crust and assembled at lower temperatures and depths (S. S. Hughes and McCurry 2002), resulting in the formation of uplifted caldera plateaus, first at the Picabo EC (10.6 – 7.6 Ma), then at the Heise EC (6.6 – 4.6 Ma), and the Yellowstone EC (2.1 – 0.6 Ma). Relative to the CSRP-VP, eruptions of the Yellowstone EC and the ESRP-VP occurred at reduced frequency, temperature, and volume. This is especially true of the Picabo EC, which produced just one regionally extensive ignimbrite and represents something of a hiatus in silicic volcanism along the Yellowstone hotspot track (Anders et al. 2014). At the Heise EC, greater residence times in the upper lithosphere and crustal recycling produced ignimbrites (and obsidian) that are more compositionally evolved and diverse than those of the CSRP-VP. There was also greater variation in eruptive style, with several smaller rhyolite flows erupting at caldera margins between larger eruptive events (L. A. Morgan and McIntosh 2005). In the wake of the hotspot, intra-caldera facies of the Picabo and Heise ECs were interred beneath the plain following caldera collapse, tectonic subsidence, and secondary mafic volcanism. Obsidian outcrops in a multitude of locales on the margin of the plain in association with both regionally-extensive ignimbrite tuffs and smaller rhyolite flows of the ESRP-VP. The Yellowstone EC remains active and rhyolitic ignimbrites and obsidian are exposed at the surface throughout the caldera plateau (Christiansen 2001; MacDonald, Horton, and Surovell 2019).

Non-SRP-VP Silicic Volcanism

Even as the North American plate passed over the Yellowstone hotspot, several smaller obsidian-bearing rhyolite flows, domes, and tuffs erupted across southern Idaho that are not directly associated with the SRP-VP. Some, such as Big Southern Butte and Cedar Butte are relatively young (400 - 300 Ka) and are thought to have formed through extreme geochemical fractionation of basaltic magmas associated with crustal extension of the post-hotspot SRP (McCurry, Hackett, and Hayden 1999; McCurry et al. 2008). Others, such as the Tuff of Cannonball Mountain (~10 Ma) and a rhyolite dome complex near Malad, ID

(~6 Ma) are 40 – 50 km from the plain (Lewis 1990; Pope 2002), but erupted concurrent with periods of active volcanism on the plain directly to the north or south. Geochemically, obsidian from these source areas is unrelated to volcanism of the SRP-VP, but these events were likely triggered by tectonic activity associated with hotspot volcanism.

Research Objectives

Past provenance research in southern Idaho has consistently shown that the vast majority of obsidian artifacts were (1) produced with material from a subset of the available geochemical source groups; (2) that material was transported greater distances east-west along the Snake River Plain than perpendicular to it; and (3) that these patterns hold cross-temporally (Bailey 1992; Holmer 1997; Plager 2001; R. E. Hughes 2007b; Henrikson 2008; Fowler 2014; Black 2015; Arkush and Hughes 2018). Obsidian found to have been transported from southern Idaho to sites in other regions of North America comes from an even more limited subset of the available sources (Gordus, Wright, and Griffin 1968; Griffin, Gordus, and Wright 1969; Hatch et al. 1990; Thompson 2004). Understanding the full extent of Idaho obsidian deposits that would have been available to Indigenous peoples of the region is critical to any assessment of how these patterns of tool-stone conveyance and material selection relate to procurement strategies, technological choice, logistic mobility, trade, and interaction.

The principal goal of this study is to better contextualize known patterns of obsidian procurement and conveyance in southern Idaho with respect to the regional distribution of geologic source material. This broad research goal can be broken into a few dependent objectives. First, we revisited obsidian source locales reported by SFU, ISU, and NWROSL, as well as other potential source locales identified through review of the geologic literature, to compile a comprehensive reference collection of southern Idaho obsidians. Second, we define and characterize geochemical source groups available at these locales through major, minor, and trace-element geochemistry. Third, we assess the spatial distribution of these groups on the landscape and evaluate their geologic origin and relation to other groups through a review of geologic maps, literature, and geochemical data. Finally, we offer some preliminary interpretations of factors influencing cross-temporal patterns of Idaho obsidian source selection and conveyance, including clast size, deposit richness, accessibility, and material quality.

Materials and Methods

To map the full spatial extent of southern Idaho obsidian source groups, we systematically revisited potential source locations reported in both the geological and archaeological literature to compile a comprehensive regional obsidian reference collection. This section outlines our field sampling strategy, analytical methods, methods of statistical group definition, and strategies for association of these groups with their parent geologic units.

Permission to sampling geologic materials from federally administered lands was obtained through a Memorandum of Understanding between the US Department of Energy, the US Forest Service, and the US Bureau of Land Management. Critically, the scope of this study is limited to deposits of geologic obsidian found in southern Idaho. It does not cover obsidian sources from the Yellowstone EC of the SRP-VP found east of the study area within lands administered by the US National Park Service (Park 2010; Scheiber and Finley 2011; MacDonald, Horton, and Surovell 2019). Nor does it cover sources that may be associated with the earliest eruptive centers of the SRP-VP in southeastern Oregon and northeastern Nevada. A few sources of tool-quality fine-grained volcanic material were encountered over the course of our research, such as the Pony Creek Dacite in the northern Big Hole range east of Rexburg, ID (Price 2009; Price and Rodgers 2009). Unfortunately, space precludes discussion of these material sources in this report. No archaeological artifacts were collected, sampled, or geochemically characterized for this study.

Geologic Sampling

Given the scale of the study area and the extent of some obsidian deposits, it was infeasible to conduct a comprehensive or randomized field survey to map the full extent of source areas found throughout the region. Instead, our approach was intended to obtain a representative sample of material sufficient to assess the geographic distribution of geochemical obsidian source groups available in southern Idaho relative to mapped geologic units. Potential sampling coordinates were first compiled from those reported for three earlier regional obsidian reference collections: SFU (Bailey 1992; James, Bailey, and D'Auria 1996), ISU (Holmer, 1997; Plager, 2001; Black, 2015), and NWROSL (Skinner, 2011a; Black, 2015). These were plotted in ArcGIS Pro 2.9 (ESRI 2021) relative to geologic maps available through the USGS National Geologic Map Database (NGMDB) (www.ngmdb.usgs.gov) and the Idaho Geological Survey (www.idahogeology.org). This allowed us to identify preliminary geologic associations and potential locations of previously un-sampled obsidian deposits, but also to identify duplicative locations within well-characterized, monogenetic primary source areas, such as Malad and Timber Butte, that did not warrant revisitation or extensive sampling. Finally, potential sampling locations were exported as GPS points and plotted relative to layers for public roads, trails, land status, and topography to facilitate navigation and sampling.

Between 2018 and 2021, CRMO staff visited or attempted to visit 243 of 302 potential sampling points compiled through review of archaeological and geological literature. The presence of obsidian deposits was confirmed within a kilometer of 176 of these locales. At 53 locations, obsidian was either not present or was only available as very sparse alluvial gravels too insufficient in size and abundance to represent viable source locales. Fourteen locations were not sampled because permission to access them could not be readily obtained from private landowners. The majority of the remaining 39 locations were not visited because they were located on terrain comparable to nearby locales where survey had failed to locate material of sufficient size and abundance. The latter were largely located on alluvial fans and floodplains in Southwestern Idaho downslope of the Cassia Hills and the Silver City Range (Skinner 2011c; 2011a). By 2022, CRMO staff had sampled obsidian from 138 discrete locations across southern Idaho, including several previously unknown deposits that were encountered during survey. Sampling was judged unnecessary at 38 locales within well-characterized, unimodal source areas, such as "Timber Butte" and "Malad", where a sufficient sample could be obtained from a few locations.

Table 1: Energy, current, and filter parameters for the Olympus Vanta VMR X-Ray Fluorescence Spectrometer, operating with a three-beam factory "soil" calibration. Elements quantified under each beam setting are listed to the right.

Beam	Energy (kV)	Current (µA)	Filter material	Filter thickness (µm)	Filter diameter (µm)	Elements quantified
1	50	80	Copper (Cu)	350	482	Sr, Y, Zr, Nb, Ba
2	40	100	Aluminum (Al)	2000	482	Fe, Zn, Rb, Pb
3	15	200	Aluminum (Al)	100	482	K, Ca, Ti, V, Cr, Mn

At each location, 10 to 30 samples of obsidian were selected for analysis via X-ray fluorescence spectrometry at the CRMO archaeology lab with the goal of obtaining at least 30 samples per geochemical group. Larger samples ($n \approx 30$) were selected from individual source locales known or suspected to represent a discrete geochemical group (e.g., Wedge Butte) as well as areas where multiple colors or varieties of obsidian appeared to be present (e.g., Howe Point). Smaller samples ($n \approx 10$) were collected from low density deposits within extensive source areas (such as the Kilgore Tuff) where sampling of numerous locales would undoubtedly yield a large total sample (> 100) for that geochemical group. Sampling was avoided in secondary, alluvial or colluvial contexts where it was difficult to find more than five clasts larger than two cm in diameter. The average sample size per location was n = 15. Prior to sampling, each location was assigned a unique ID, UTM coordinates were recorded with a Garmin handheld GPS unit, and photos were taken to document material size, abundance, and depositional setting. Samples were prepared in the field by striking a single large flake from each cobble with a rock hammer. Flakes were then then trimmed with a quartzite hammerstone to remove sharp edges and achieve a flat surface. Whenever possible, sample preparation was conducted at the vehicle location (rather than the deposit) to limit the production of waste flakes in undisturbed contexts. Field notes were taken before proceeding to the next location to record typical clast size, surface density, depositional environment, and impressions of material quality and workability. If archaeological lithic tools or debris were observed at a source locale, or in its immediate vicinity, this was also noted, but sampling was not conducted within archaeological sites and only unworked cobbles were selected for analysis.

Analytical Methods

By the summer of 2022, the CRMO obsidian reference collection contained over 2000 individual samples of obsidian from 138 discrete sampling locations. Prior to analysis, each sample was numbered and cleaned with deionized water and a nylon brush and then air-dried for a minimum of thirty minutes. X-ray fluorescence spectrometry was conducted in the CRMO laboratory using an Olympus Vanta VMR portable XRF unit equipped with a rhodium anode and a large diameter silicon drift detector. To ensure comparability of results with data from obsidian artifacts, the instrument was set to operate with a collimated beam three millimeters in diameter. Use of the collimated beam setting results in a minor loss of analytical precision for mid-Z elements but is useful for avoiding inclusions and generates data comparable to that of small-dimension artifacts that require analysis under a narrow beam setting.

The Olympus Vanta VMR unit used in this study is equipped with a factory "soil" calibration that relies on Compton-normalization and a combination of three beam settings designed to optimize measurement of separate element groups in silica-rich materials. Each sample was analyzed for a total of 180 seconds at

60 seconds per beam setting (Newlander et al. 2015). A suite of 15 elements is regularly quantified by the CRMO for obsidian artifacts and geologic materials. Beam 1 is used to measure strontium (Sr), yttrium (Y), zirconium (Zr), niobium (Nb), and barium (Ba). Beam 2 is used to measure iron (Fe), zinc (Zn), rubidium (Rb), and lead (Pb). Beam 3 is used to measure potassium (K), calcium (Ca), titanium (Ti), vanadium (V), chromium (Cr), and manganese (Mn). Table 1 provides a summary of energy, current, and filter parameters used for each beam setting.

Table 2: Average major and trace-element estimates for the USGS RGM-2 certified standard relative to recommended values for USGS RGM-1. Values for V, Cr, and Pb rely on the Olympus factory "soil" calibration.

		USGS RGM-2 CRMO (n = 224)		USGS RGM-1 Recommended	
		$\bar{x}$	± 1s	$\bar{x}$	± 1s
K_2O	%	4.38	0.10	4.30	0.10
CaO	%	1.14	0.02	1.15	0.07
TiO_2	%	0.27	0.005	0.27	0.020
MnO	%	0.04	0.002	0.036	0.003
FeO	%	1.62	0.02	1.27	0.05
V*	ppm	68	3	13	2
Cr*	ppm	26	6	3.7	
Zn	ppm	35	3	32	7
Rb	ppm	147	3	150	8
Sr	ppm	128	10	110	10
Y	ppm	24	5	25	2
Zr	ppm	245	11	220	20
Nb	ppm	10	3	8.9	0.6
Ba	ppm	778	72	810	46
Pb*	ppm	19	2	24	3

*Factory calibration

Following analysis, the factory calibrated output from each instrument was adjusted using matrix-specific calibration curves derived from analysis of 43 obsidian calibration standards available through the University of Missouri Research Reactor (MURR) (Glascock 2021; Glascock and Ferguson 2012; Speakman 2012). For each of these standards, MURR provides concentration estimates independently derived through neutron activation analysis (NAA) or Laser Ablation Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) for 12 of the 15 elements regularly quantified by the CRMO via XRF. Results for the other three elements (V, Cr, and Pb) are reported here using results of the factory "soil" calibration. Of these latter elements, only V is regularly used by the CRMO in source determinations. Major elements (K, Ca, Ti, Mn, and Fe) are reported as oxides in weight percent (K_2O, CaO, TiO_2, MnO, and FeO) to facilitate comparisons with values reported in the geologic literature. Trace elements (V, Cr, Zn, Rb, Sr, Y, Zr, Nb, Ba, Pb) are reported in parts per million (ppm).

Two check standards were run under equivalent conditions two to three times each over the course of each analytical run to monitor instrument performance: (1) a powdered sample of the USGS RGM-2 rhyolite glass certified reference material; and (2) a solid, slabbed sample of obsidian from Group C at Glass Buttes, OR (Ambroz, Glascock, and Skinner 2001; Frahm and Feinberg 2015). Table 2 reports average elemental estimates for the USGS RGM-2 standard relative to recommended values.

Geochemical group definition

Following XRF analysis and calibration of results, geochemical source groups were established using a standard sequence of multivariate statistical methods common in archaeological provenance studies (Glascock 1992; Neff 2002). First, preliminary geochemical groups were iteratively defined through exploratory data analysis (including bivariate, trivariate, and multivariate parallel plots), hierarchical cluster analysis, and principal components analysis. To avoid the dual errors of assumption that each source locale represents a distinct source group and that only one source group is present at each locale, preliminary groups were defined independently of sampling location. Stepwise discriminant analysis was then used to identify a robust but parsimonious combination of elements that best distinguish each group

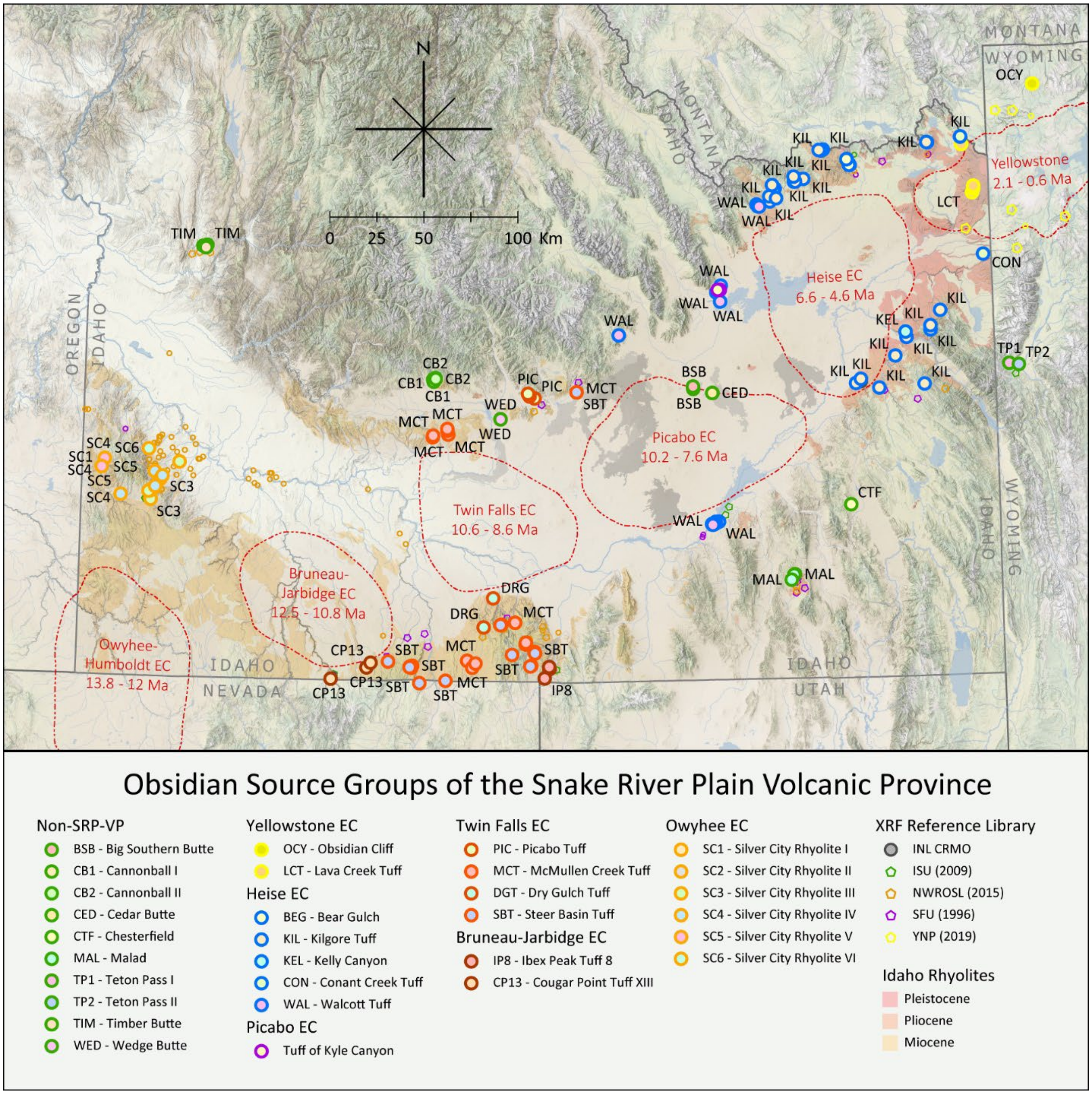

Figure 2: Geographic distribution of obsidian source groups defined in this study relative to Idaho rhyolites and major eruptive centers of the Snake River Plain Volcanic Province. Eruptive centers (ECs) are adapted from Pierce and Morgan (1992) and Perkins et al. (1995). Geologic units are mapped based on statewide geospatial data from Lewis et al. (2012).

from those with similar trace-element compositions. For groups associated with the Heise, Twin Falls, and Bruneau-Jarbidge eruptive centers, this list included Ca, Ti, V, Mn, Fe, Zn, Rb and Ba. For source groups derived from non-SRP-VP rhyolite domes, dikes, and tuffs, Ca, V, Mn, Fe, Rb, Zr, and Nb provided the best discriminant power between groups. Using these variables, reference groups were refined to cull outliers using jack-knifed Mahalanobis distances as a multivariate measure of sample fit within groups. Once the core membership of each was established, Mahalanobis distance probabilities of membership for each group were recalculated for the entire reference dataset to confirm groupings and reevaluate outliers. All methods of group definition and refinement were conducted using the JMP 16 statistical software package ("JMP", 2021).

Following definition of geochemical reference groups, sampling points were coded in ArcGIS Pro by group affiliation and depositional context (i.e., vitrophyre, primary volcanic clasts, or secondary alluvial or colluvial clasts). Duplicate points were added to sampling locations where two or more geochemical groups were detected. The spatial distribution of each group was then compared again to geologic maps available through the USGS National Geologic Map Database (NGMDB) (www.ngmdb.usgs.gov) and the Idaho Geological Survey (www.idahogeology.org) to re-evaluate associations with geologic units.

While geologic maps are available for much of southern Idaho, some regions have been mapped more recently or in more detail than others. Furthermore, the physical morphology and field relations of ignimbrites and ashflow tuffs often vary considerably with distance from an eruptive center (Branney and Kokelaar 2002). Given the scale of rhyolitic volcanism in southern Idaho, deposits from some eruptive events have been assigned multiple names by geologists working at different times or in different areas. This study benefits from recent efforts to clarify the stratigraphy, age, and spatial extent of rhyolitic ignimbrite deposits across the SRP-VP through geochemistry, geochronology, and paleo-magnetometry (Perkins et al. 1995; Perkins and Nash 2002; L. A. Morgan and McIntosh 2005; Bindeman et al. 2007; Andrews et al. 2008; Bonnichsen et al. 2008; Branney et al. 2008; Watts, Bindeman, and Schmitt 2011; Ellis et al. 2012; Anders et al. 2014; 2019; Finn et al. 2016; Knott, Branney, et al. 2016; Knott et al. 2020). But this work is ongoing, and some ambiguities and disagreements remain. We have attempted to identify the most current and accepted names for obsidian-bearing geologic units within our study area but acknowledge that some areas and geologic units require further study.

Results: Southern Idaho obsidian source distribution

Results of this study show that Idaho obsidian source locales can be classified into at least 28 geochemical source groups distributed across the southern half of the state, forming a near perimeter around the Snake River Plain (Figure 2). The following sections provide a discussion of the geochemistry, geologic context, and geographic distribution of source groups from the Owyhee EC, the CSRP-VP, the ESRP-VP, and Non-SRP-VP rhyolite domes and tuffs. Six groups are associated with early, pre-SRP-VP rhyolitic volcanism at the Owyhee EC in the Silver City Range of western Idaho. Another six are derived from ignimbrite tuffs of the CSRP-VP, including two newly defined source groups that have not yet been reported elsewhere. Ignimbrites and rhyolite flows of the ESRP-VP (excluding the Yellowstone EC) produced six more obsidian source groups, including a newly defined group from the Picabo EC. Finally, ten obsidian source groups are associated with Non-SRP-VP rhyolitic flows, domes, and tuffs from eight separate source areas. Sampling conducted for this study was far from comprehensive, but it provides the most complete view to date of the southern Idaho obsidian source-scape.

The Owyhee Uplands

One of the most significant discrepancies in the distribution of obsidian sampling locations between SFU, ISU, and NWROSL is around the Silver City Range of Owyhee County in Southwestern Idaho (Black, 2015a, 2015b). While SFU and ISU report just a few sampling locations in the area, NWROSL reports over forty. SFU and ISU identify three geochemical groups in the Silver City Range: “Owyhee I”, “Owyhee II”, and “Reynolds” (Bailey 1992; Holmer 1997). By contrast, NWROSL has identified four groups in the area: “Owyhee”, “Sinker Creek”, “Reynolds”, and “Jordan Creek” (Skinner 2011b; 2011c). Because the geochemical data used to define these groups are unpublished, it is unclear how groups reported by SFU and ISU correspond to those reported by NWROSL.

We define five geochemical groups of obsidian from the Owyhee volcanic field through analysis of nearly 250 samples from 14 locations. However, we were unable to relocate deposits corresponding to the “Sinker Creek” group defined by NWROSL and we suspect that at least six geochemical source groups are available in the Owyhee uplands. All are associated with a complex of rhyolite flows, domes, and ashfall tuffs known as the Silver City Rhyolites that predate the hotspot volcanism of the Snake River Plain volcanic province (Asher 1968; Pansze Jr. 1975; Bonnichsen 1983; Manley and McIntosh 2002; Wood and Clemens 2002; Hasten 2012).

Rhyolites of the Silver City Range

The geology of the Silver City Range of Owyhee County is relatively simple. The range occupies a triangular area of desert highlands at the western edge of the continental craton that underlies much of Idaho (Figure 3). It is bounded to the west by Miocene flood basalts (Pierce, Morgan, and Saltus 2002; Camp and Wells 2021), to the southeast by early rhyolitic terrain of the Snake River Plain volcanic province (Manley and McIntosh 2002), and to the northeast by the extensional graben of the western Snake River Plain (Wood and Clemens 2002). The range itself consists of granodiorites of the Idaho Batholith (66 – 62 Ma) overlain by middle Miocene flood basalts (16.6 – 16.0 Ma) and the Silver City Rhyolites, which date between 16.4 and 15.7 Ma (Asher, 1968; Pansze Jr., 1975; Bonnichsen, 1983; Ekren, McIntyre, & Bennett, 1984; Bonnichsen et al., 2008; Hasten, 2012; Gillerman et al., 2021). A series of younger (15 – 14 Ma), intrusive rhyolite domes are exposed along the centerline of the range (Hasten 2012; Gillerman et al. 2021), but fieldwork conducted for this study suggests that obsidian deposits of the Owyhee uplands are derived exclusively from the Silver City Rhyolites. Tool quality obsidian was not found in association with later, intrusive rhyolite domes, despite tantalizing place-names such as “Glass Hill” (Hasten 2012).

Gold and silver mineralization resulting from hydrothermal alteration of rhyolites in the Silver City Range has attracted the attention of geologists since the late 19th century (Asher, 1968; Pansze Jr., 1975; Bonnichsen, 1983), but stratigraphic divisions and interpretations vary. Even within cooling units, the Silver City Rhyolites range widely in texture, minerology, and composition. In general, units are phenocryst-poor, but grade upward from ash-fall tuffs and porphyritic lavas to banded or aphanitic flows, domes, and welded tuffs. Mineral compositions are dominated by sanidine, plagioclase, and quartz with considerable variability between rhyolites outcropping on the eastern and western flanks of the range

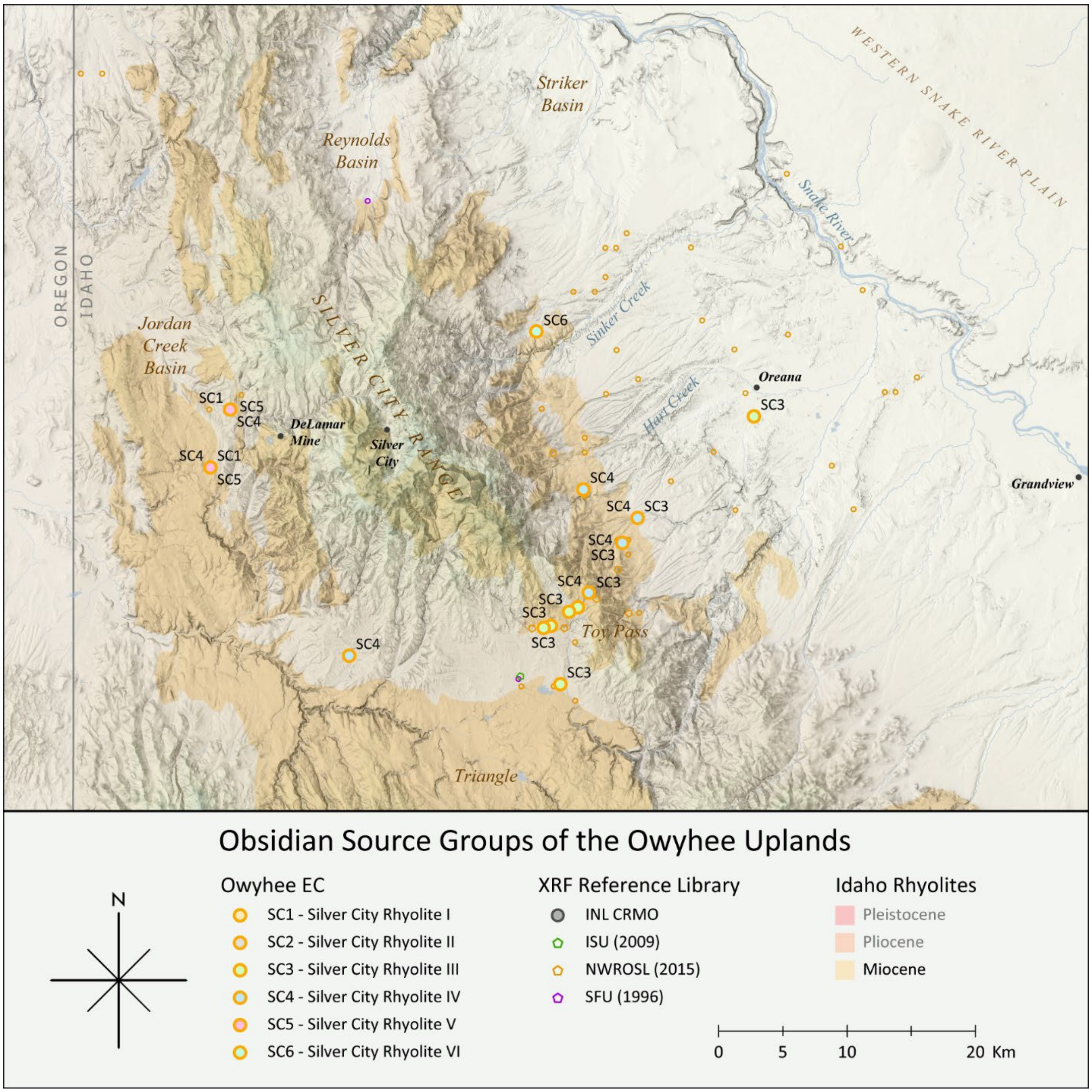

Figure 3: Distribution of sampling locations for obsidian source groups defined in this study for the Owyhee uplands of southwestern Idaho.

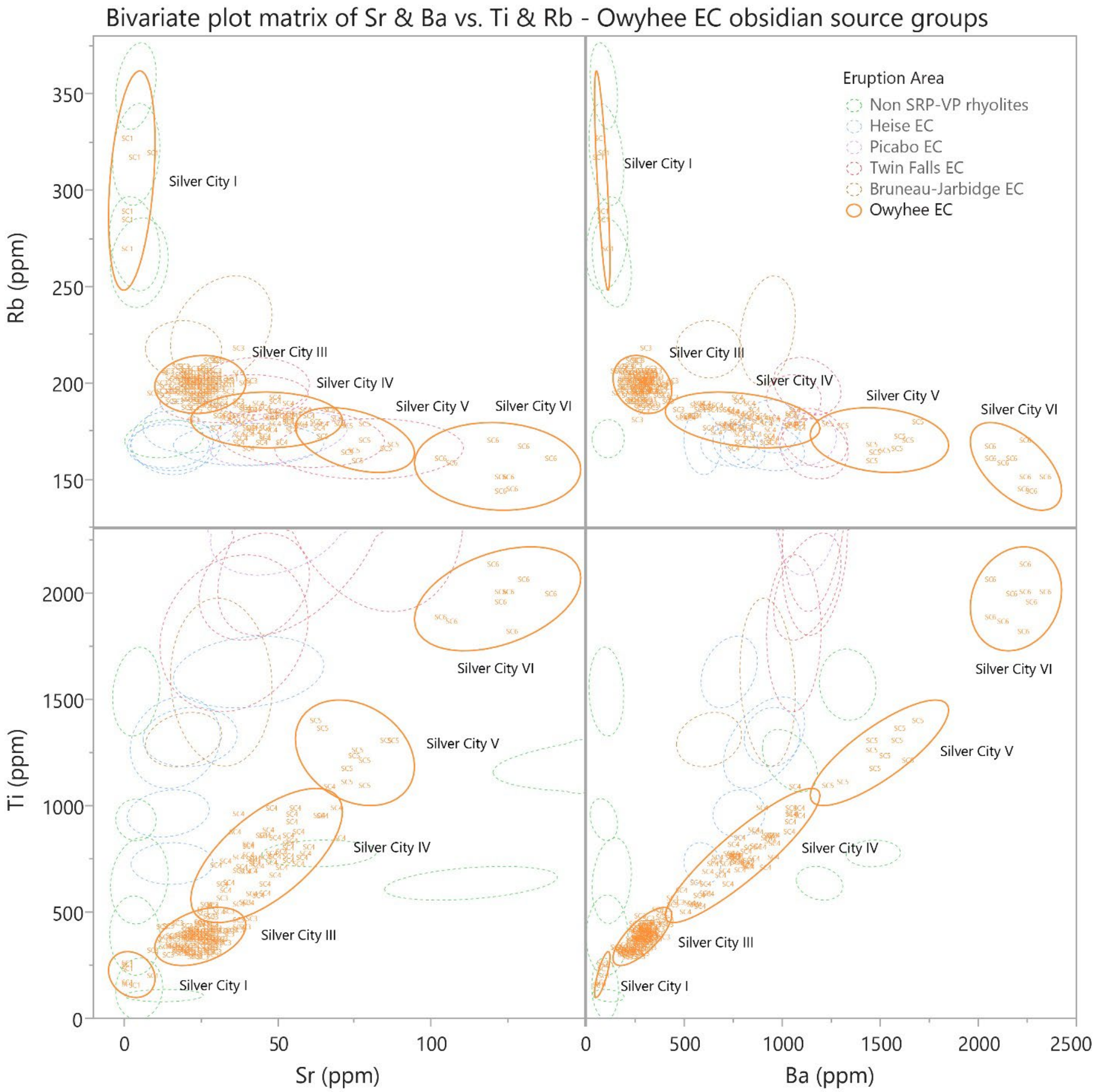

Figure 4: Bivariate plot matrix of Sr and Ba vs. Ti and Rb for obsidian source groups from the Owyhee EC.

(Asher, 1968; Pansze Jr., 1975; Bonnichsen, 1983; Ekren, McIntyre, & Bennett, 1984; Gillerman et al., 2021). Hasten (2012, p. 10) provides a summary table correlating stratigraphic divisions employed in major studies of the area. For the purposes of this study, it is perhaps sufficient to say that on the western side of the range, earlier units of the Silver City Rhyolites have been mapped as the Flint Creek Tuff and later units are mapped as the Millsite Rhyolite (Ekren et al., 1981; Bonnichsen & Godchaux, 2006). Obsidian has only been noted in geologic studies of the area in two locations: (1) at the base of an undifferentiated member of the Silver City Rhyolite near Toy Pass in the southern Silver City Range (Ekren et al., 1981); and (2) at the base of the Flint Creek Tuff on the southwestern flank of the range (Hasten 2012, 46).

Table 3: Major and Trace-element composition of obsidian source groups of the Owyhee EC.

		Silver City I (n = 7)		**Silver City III** (n = 140)		**Silver City IV** (n = 69)		**Silver City V** (n = 11)		**Silver City VI** (n = 10)	
		x̄	± 1s	x̄	± 1s	x̄	± 1s	x̄	± 1s	x̄	± 1s
K_2O	%	4.40	0.11	4.93	0.24	5.02	0.28	5.21	0.51	5.53	0.49
CaO	%	0.47	0.04	0.60	0.03	0.65	0.04	0.75	0.07	1.34	0.53
TiO_2	%	0.03	0.01	0.06	0.01	0.13	0.02	0.21	0.02	0.34	0.05
MnO	%	0.02	0.00	0.02	0.00	0.02	0.00	0.03	0.00	0.05	0.01
FeO	%	1.12	0.06	0.92	0.05	1.03	0.09	1.32	0.13	2.42	0.10
V*	ppm	14	2	28	5	64	13	118	12	180	12
Cr*	ppm	23	5	22	5	30	8	38	6	61	9
Zn	ppm	135	5	33	4	35	5	41	5	122	7
Rb	ppm	305	23	199	6	181	6	173	11	157	9
Sr	ppm	3	3	25	6	47	10	77	9	120	12
Y	ppm	105	9	23	7	22	7	22	7	52	8
Zr	ppm	180	9	99	11	129	18	175	17	454	29
Nb	ppm	44	10	11	4	11	4	13	5	24	7
Ba	ppm	82	16	288	65	788	162	1514	149	2174	107
Pb*	ppm	53	3	24	3	24	3	25	3	32	2
Alt. source names		Jordan Creek		**Owyhee** Owyhee 1 Toy Pass		Owyhee 2					
Correlate rhyolites		Silver City Rhyolites		Silver City Rhyolites		Silver City Rhyolites		Silver City Rhyolites		Silver City Rhyolites	

*Factory calibration

Our efforts to revisit sampling locations reported by SFU, ISU, and NWROSL quickly revealed that while obsidian occurs occasionally among mixed gravels in the expansive alluvial fans between the Silver City Range and the Snake River, these locales do not represent viable sources of toolstone. For this reason, we focused our sampling efforts on higher-elevation locales with greater potential to yield primary source material. Even so, the obsidian source groups defined in this study cannot be easily assigned to individual geologic units within the Silver City Rhyolite complex. Neither geologic mapping of the area nor available geochemical data are sufficiently detailed to correlate obsidian source groups with member units of the Silver City Rhyolites, such as the Flint Creek Tuff or the Millsite Rhyolite. This problem is compounded by a paucity of sampling locations from primary volcanic deposits in our present sample.

Five geochemical groups may be discerned through trace-element analyses of obsidian from the Silver City Range (Table 3). These groups exhibit a clear compositional gradient across several elements, suggesting they are the product of multiple eruptive events and/or cooling units derived from geochemical evolution of a common magmatic source material. Most notably, there is a negative log-linear relationship between Rb and Sr ($R2 = .75$, $F(1, 217) = 659$, $p < 0.0001$) and Rb and Ba ($R2 = .70$, $F(1, 217) = 500$, $p < 0.0001$) that is complemented by strong positive correlations between Sr, Ba, and Ti (Figure 4; Table 3). Given a common magma source (granitic melt of the Idaho Batholith), these patterns likely reflect geochemical evolution of the magma chamber over time and/or differential partitioning of elements into alkali (K-rich) feldspars and Sr, Ba, and Ti into plagioclase (Ca-rich) feldspars between eruptive events.

Geochemical groups in our sample of obsidian from the Silver City Range are numbered sequentially along this compositional gradient, with Silver City II reserved for the Sinker Creek group defined by NWROSL. Silver City I is most enriched in Rb and most depleted in Sr, Ba, Ti, and V. Silver City VI is most depleted in Rb and most enriched in Sr, Ba, Ti, and V. Unpublished data from a 2015 analysis of the NWROSL Idaho obsidian reference collection suggest that it is has Rb and Sr concentrations intermediate between the Silver City Rhyolite groups I and III on this compositional gradient (Pink, unpublished data, 2015). We tentatively suggest that the "Sinker Creek" group corresponds to a sixth group of obsidian associated with the Silver City Rhyolites that is not represented in our present sample.

On the east side of the range, sampling locations for three groups are mapped within "undifferentiated" units of Silver City Rhyolite (Tsc) (Ekren et al., 1981; Bonnichsen & Godchaux, 2006; Gillerman et al., 2021). The Silver City III and IV groups outcrop in the vicinity of Toy Pass in locations corresponding to the "Owyhee 1" and "Owyhee 2" groups of SFU and ISU (Bailey 1992; Holmer 1997). These groups are common in alluvium and stream deposits east and south of the Silver City Range. The Silver City VI group is limited to a highly localized deposit of gravel-sized marekanites near Sinker Creek Road. This outcrop was sampled while attempting to locate NWROSL's "Sinker Creek" group (our hypothesized Silver City II group), which we suspect outcrops uphill to the west.

On the west side of the Silver City Range, all four of our sampling locations map within an extensive deposit of quaternary and tertiary gravels composed of material of mixed lithology eroded from hills to the east (Ekren et al., 1981; Bonnichsen & Godchaux, 2006). Gravels east of Toy Pass contain obsidian corresponding to the Silver City III and IV groups. Gravels on the west slope of the range to the north contain mixed deposits of obsidian from Silver City I, Silver City IV, and Silver City V. These locales are downslope of areas mapped as the Flint Creek Tuff and the Millsite Rhyolite (Ekren et al., 1981; Bonnichsen & Godchaux, 2006). Further sampling at primary outcrops would be required to refine associations between obsidian geochemical groups and geologic units.

The central Snake River Plain volcanic province

The central Snake River Plain volcanic province (CSRP-VP) hosts some of the most geographically extensive and geochemically variable obsidian source groups in North America (Figure 5). Thirty years ago, Hughes and Smith (1993) correctly observed that two major source groups from this area, "Browns Bench" and "Butte Valley A", were derived from large-volume ashflow tuffs rather than the smaller rhyolitic lava flows that are more common in other areas. They hypothesized that the greater range of geochemical variability evident in these groups was a product of both horizontal and vertical gradients in glass composition within cooling units of one or more ashflow tuffs (R. E. Hughes and Smith 1993, 85–89). In the decades since, intensive study of SRP volcanism (Branney et al., 2008) has yielded a wealth of new information on the chemical composition, spatial extent, and eruptive history of ignimbrite tuffs of the region (Perkins et al. 1995; Perkins and Nash 2002; Bonnichsen et al. 2008; Ellis et al. 2012; 2013; Finn et al. 2016; Knott, Branney, et al. 2016). Drawing on this research, we identify and contextualize six compositionally distinct obsidian source groups associated with the Bruneau-Jarbidge and Twin Falls eruptive centers of the CSRP-VP.

The "Browns Bench" group takes its name from a ridgeline source locale atop the Browns Bench fault escarpment between Twin Falls, ID and Jackpot, NV (Bowers and Savage 1962; Sappington 1981a; 1981b; Nelson, Jr. 1984; Ellis et al. 2012). Obsidian deposits attributed to this group have been found over an area of nearly 5,500 km^2 along the Idaho border with Nevada and Utah, from the Cassia Hills in the east to Three Creek in the Bruneau Desert to the west (Sappington 1981a; 1981b; Nelson, Jr. 1984; Bailey 1992; R. E. Hughes and Smith 1993; James, Bailey, and D'Auria 1996; Holmer 1997; Skinner 2011a). Obsidian deposits attributed to the "Butte Valley A" group have been identified by NWROSL within the same area, but also north of the plain in the Mount Bennett Hills (Skinner 2011b; 2011a;

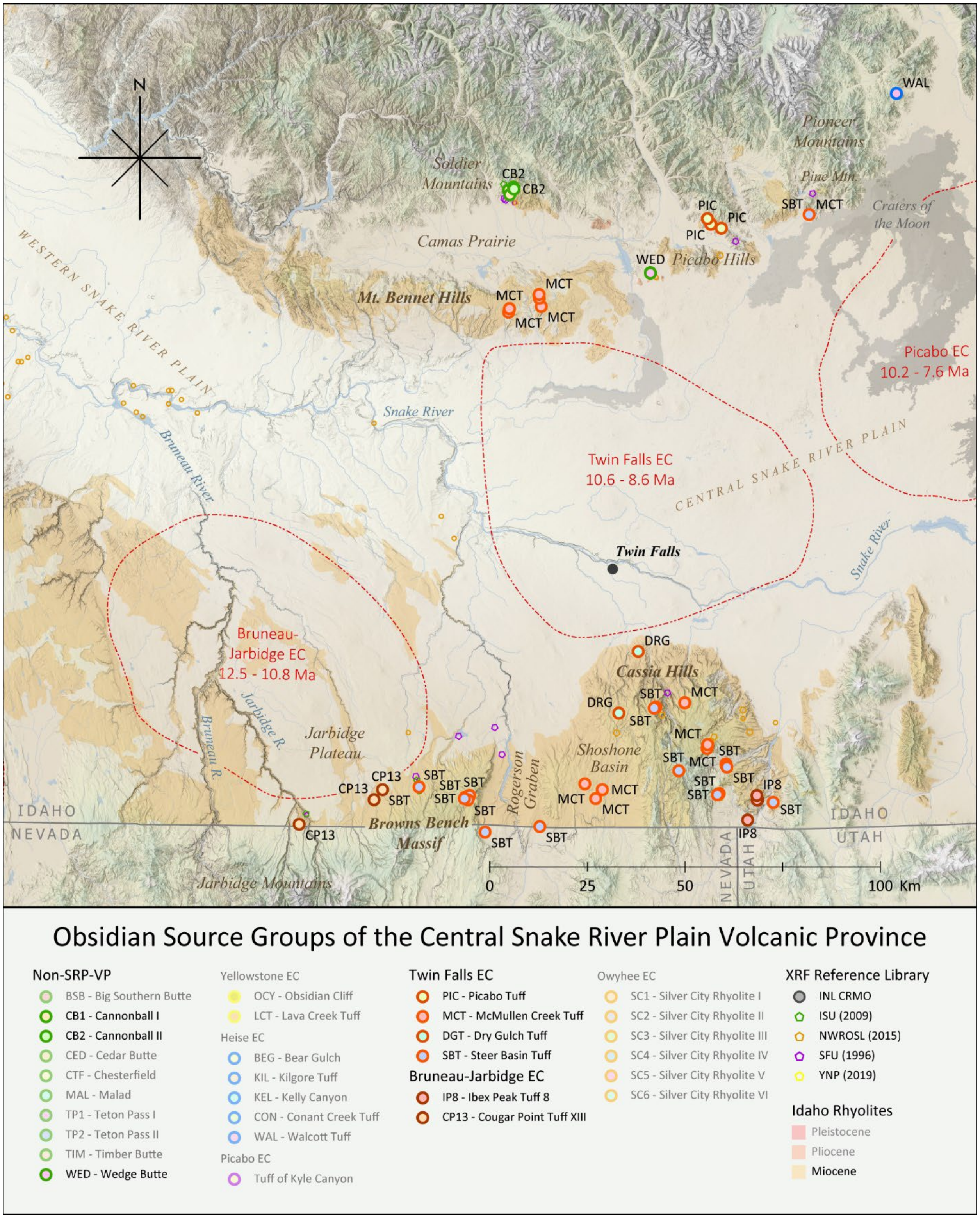

Figure 5: Distribution of sampling locations for obsidian source groups of the central Snake River Plain Volcanic Province. Additional deposits of obsidian of the Twin Falls EC and the Bruneau-Jarbidge EC outcrop south of the Idaho/Nevada border to the Jarbidge Mountains.

group to the east they called “Picabo Hills” (Bailey 1992; James, Bailey, and D’Auria 1996; Holmer 1997). South of the plain, other previously identified groups include “Coal Banks”, a blue-gray to red obsidian found along Coal Banks Creek southeast of the Cassia Hills, and “Murphy Hot Springs” near the Jarbidge River canyon on the Idaho/Nevada border (Bailey 1992; Holmer 1997).

Results of this study show that at least six geochemical groups of obsidian from the CSRP-VP are available over an immense area both north and south of the central Snake River Plain (Figure 5), including (from west to east) the Bruneau-Jarbidge plateau, the Browns Bench Escarpment, the Rogerson Graben, the Cassia Hills, and, north of the Plain, the Mount Bennett and Picabo Hills. These six groups exhibit broad similarities in composition across the mid-Z elements (Rb, Sr, Y, Zr, and Nb), but they can be distinguished through bivariate and multivariate comparisons of CaO, MnO, TiO_2, FeO (Figure 6; Tables 4 and 5). We attribute these geochemical groups to six obsidian-bearing ignimbrite tuffs of the CSRP-VP, including two from the Bruneau-Jarbidge eruptive center (12.7-10.75 Ma) and four from the Twin Falls eruptive center (10.6 – 8.6 Ma) (Bonnichsen et al., 2008). Below we summarize the geologic context, geochemistry, and geographic distribution of each group, as well their relation to named source groups more familiar to the archaeological community.

The Bruneau-Jarbidge eruptive center

We define two geochemical groups from the Bruneau-Jarbidge EC. Obsidian from the Cougar Point Tuff XIII corresponds to the group known as “Murphy Hot Springs”, “Three Creek”, and “Browns Bench Area” among archaeologists (Bailey 1992; Holmer 1997; Page and Bacon 2016). Obsidian from Ibex Peak 8 Tuff corresponds to the “Coal Banks” or “Coal Banks Springs” group (Bailey 1992; Holmer 1997). Obsidian corresponding to our Cougar Point Tuff XIII group has been reported in several locales spanning the Idaho/Nevada border between Browns Bench and the Jarbidge River (Figure 5; Page and Bacon 2016). Primary surficial deposits of Ibex Peak Tuff 8 obsidian appear to be limited to the Coal Banks and Beaverdam Creek drainages north of the Idaho border with Nevada and Utah. Both, however, are associated with ignimbrite tuffs that have been correlated by geologists across multiple exposures spanning a > 150 km wide area south of the central Snake River Plain. We thus cannot exclude the possibility that additional surface deposits of the obsidian source groups described here outcrop elsewhere north or south of the Plain.

The Bruneau-Jarbidge eruptive center (12.7-10.7 Ma) is third in the time-transgressive sequence of rhyolitic volcanic fields created by passage of the North American plate over the Yellowstone mantle plume (Pierce and Morgan 1992; 2009; Camp and Wells 2021). Like the Owyhee-Humboldt eruptive center (14.5-12.0 Ma) to the west, much of the Bruneau-Jarbidge eruptive sequence has been buried and obscured by later flows of rhyolitic and basaltic lavas (Bonnichsen, 1982; Manley & McIntosh, 2002). Our understanding of the eruptive history of this area is thus drawn largely from deep vertical exposures of ignimbrite tuffs in canyon walls along the Bruneau and Jarbidge Rivers in Owyhee County of southwestern Idaho (Bonnichsen & Citron, 1982; Cathey & Nash, 2004). Recent efforts to correlate these units with vertical exposures to the east at the Browns Bench fault scarp, in the Rogerson Graben, at Trapper Creek in the Cassia Hills, and in the Mount Bennett and Picabo Hills north of the plain (Andrews et al. 2008; Bonnichsen et al. 2008; Ellis et al. 2012; Finn et al. 2016; Knott, Branney, et al. 2016; Knott, Reichow, et al. 2016) have demonstrated that the scale and frequency of CSRP-VP super-eruptions may have exceeded those of the more recent Heise and Yellowstone eruptive centers (Ellis, Schmitz, and Hill 2019; Knott et al. 2020).

The type locality used to define the Bruneau-Jarbidge eruptive sequence is at Cougar Point along the Jarbidge River canyon near the Idaho/Nevada border (Coats 1964). Here, geologists have identified ten strata of ignimbrite tuffs that are broadly similar in morphology, minerology, and geochemical composition (Bonnichsen & Citron, 1982; Cathey & Nash, 2004). After some refinement, these have been

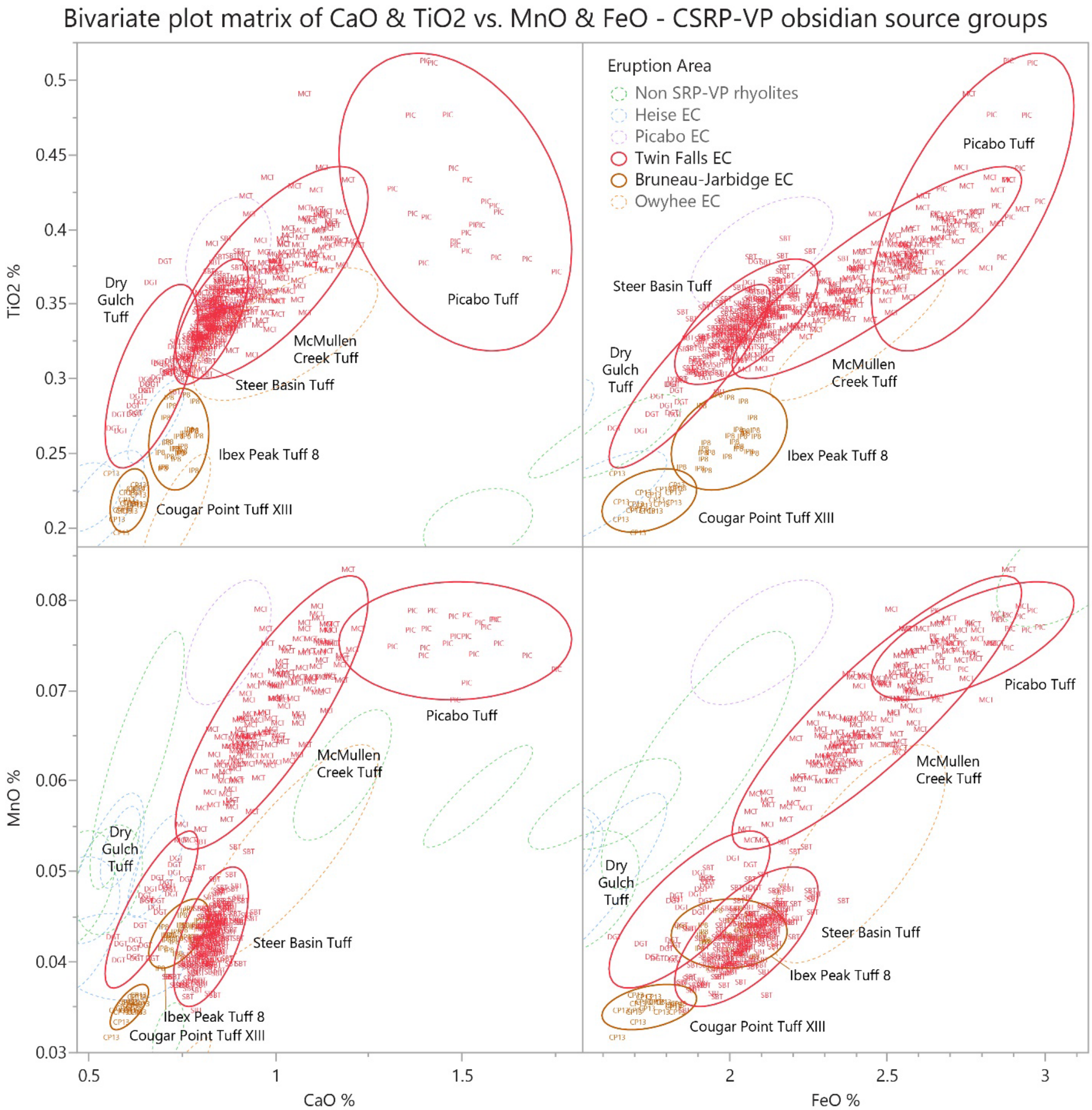

Figure 6: Bivariate plot matrix of CaO and FeO vs. MnO and TiO_2 for obsidian source groups of the Central Snake River Plain Volcanic Province.

designated Cougar Point Tuffs III, V, VII, IX, X, XI, XII, XXIII, XVj, and XVb, in order of depositionb. Cougar Point XVb (10.75 ± 0.07 Ma) has been correlated with the Steer Basin Tuff (10.63 ± 0.08 Ma) of the Twin Falls EC through a robust combination of 40Ar/39Ar geochronology, paleo-magnetometry, and geochemistry (see discussion of the Twin Falls EC below; (Ellis et al. 2012; Finn et al. 2016)). Cougar Point XIII (10.96 ± 0.06 Ma) has been correlated through equivalent methods to the Jackpot member (BBU-7) of the Browns Bench formation (11.05 ± 0.06 Ma), the Big Bluff Tuff (10.96 ± 0.06 Ma) of the Cassia formation at Trapper Creek, and the Tuff of Fir Grove (11.03 ± 0.02 Ma) in the Mt. Bennett Hills

[b] Cougar Point XVb is the upper-most unit exposed in the Bruneau River Canyon. The superficially similar but chemically distinct Cougar Point XVj is the upper-most unit exposed in the Jarbidge River Canyon to the east (Cathey and Nash 2004).

(Bonnichsen et al. 2008; Ellis et al. 2012; Finn et al. 2016; Ellis, Schmitz, and Hill 2019). Earlier tuffs in the Cougar Point sequence (CP III to CP XII) have been correlated with a series of deposits grouped under the Ibex Peak Tuff (12.82 ± 0.02 – 10.83 ± 0.03 Ma) at Trapper Creek in the Cassia Hills through geochronology and geochemistry (Perkins et al. 1995; 1998; Perkins and Nash 2002; Nash and Perkins 2012).

Two of the obsidian source groups identified in our sample from the CSRP-VP are associated with ignimbrite tuffs of the Bruneau-Jarbidge EC. These correspond to the "Murphy Hot Springs" and "Coal Banks" groups defined by SFU and ISU (Bailey 1992; Holmer 1997). They are best distinguished from those affiliated with the later Twin Falls eruptive center by their higher concentrations of Rb and lower concentrations of TiO_2, MnO, and Ba (Table 4). We attribute the "Murphy Hot Springs" group to the Cougar Point XIII/Big Bluff Tuff (10.96 ± 0.06 Ma; Bonnichsen et al., 2008) and the "Coal Banks" group to the Cougar Point VII/Ibex Peak 8 Tuff (11.81 ± 0.03 Ma; Nash and Perkins 2012). Evidence for the association of these two groups with specific eruptive events is outlined below.

Cougar Point Tuff XIII

Obsidian samples in our database that correspond to the "Murphy Hot Springs" or "Browns Bench Area" group were collected near sampling locations of SFU and ISU on the Jarbidge Plateau near Three Creek and Murphy Hot Springs (Bailey 1992; Holmer 1997). Mapping and stratigraphic descriptions of the Jarbidge Canyon show that the Cougar Point Tuff dips northward beneath the overlying Banbury Basalt at Murphy Hot Springs (Coats, 1964; Bonnichsen, 1982b). In this area, obsidian occurs as 5 – 10 cm subrounded clasts in a 6 m thick, bedded deposit of well-sorted alluvial cobbles, gravels, and ash between the Cougar Point Tuff and the Banbury Basalt (Coats 1964, M16–17). This stratum is exposed at the surface in the northern Jarbidge Quadrangle (Coats 1964) and in a roadcut that follows the upper surface of the Cougar Point Tuff on the western wall of Jarbidge Canyon above Murphy Hot Springs (Bonnichsen 1982a, 244–45). Obsidian is found in a similar stratum of sediments in the Three Creek area. Bonnichsen (1982b:239-245) argues that these deposits belong to a much wider "moat-zone" of sediments that accumulated at the edge of a paleo-escarpment marking the southern boundary of the Bruneau-Jarbidge EC. Page and Bacon (2016) report several other sampling locations for the "Browns Bench Area" source group 9.5 km east of Three Creek and 40 km to the southeast in the O'Neil Basin of northern Nevada. All of these locales are also described as secondary, alluvial contexts, though obsidian-bearing sediments in Nevada are found in an alluvial system unrelated to the hypothesized moat-zone.

Two lines of evidence suggest that "Murphy Hot Springs" obsidian is derived from Cougar Point Tuff XIII, despite the lack of primary deposits in the present sample: (1) stratigraphic proximity to overlying gravel deposits; and (2) geochemical similarity to vitric horizons and obsidian pyroclasts of Cougar Point Tuff XIII. Our interpretation differs from that of Page and Bacon (2016) for this group, warranting a detailed discussion of each point.

(1) Obsidian-bearing gravels overlying the Cougar Point Tuff on the Jarbidge Plateau contain lithics derived from rocks of the Jarbidge Mountains to the south, including rhyolites of the Cougar Point Tuff sequence (Bonnichsen and Jenks 1995b; 1995a). Deposition of these gravels on the upper-most surface of the Cougar Point Tuff indicates that sediment accumulation was triggered by subsidence of the Bruneau-Jarbidge EC following deposition of Cougar Point Tuff XIII, the most recent ignimbrite exposed in the Jarbidge Canyon (Bonnichsen 1982a; Bonnichsen and Citron 1982). Geologists have noted dense vitric clasts in an upper horizon of tuffs correlated with Cougar Point Tuff XIII in the Rogerson Graben (Branney et al., 2008; Andrews et al., 2008; Knott, Reichow, et al., 2016) and the Mt. Bennett Hills (Monnereau et al. 2021). Vitric clasts have also been noted in an upper horizon of Cougar Point XI (Ellis et al. 2012, 264), but obsidian from Cougar Point XIII would have been more exposed to erosion and incorporation into overlying gravels than material from lower strata.

Table 4: Major and trace-element composition of obsidian source groups of the Bruneau-Jarbidge EC.

		Cougar Point Tuff XIII						**Ibex Peak Tuff 8**				**CPT VII**	
		obsidian (n = 29)		pyroclasts[1]		vitrophyre[2]		obsidian (n = 32)		welded tuff[3]		vitrophyre[2]	
		x̄	± 1s	x̄	± 1s	x̄	± 1s	x̄	± 1s	x̄	± 1s	x̄	± 1s
K_2O	%	5.76	0.22	7.61	0.63	5.88	0.24	6.52	0.34	6.17	0.31	5.85	0.12
CaO	%	0.61	0.03	0.62	0.09	0.79	0.18	0.74	0.04	0.67	0.06	1.14	0.23
TiO_2	%	0.23	0.03	0.23	0.01	0.29	0.02	0.26	0.03	0.27	0.04	0.44	0.03
MnO	%	0.04	0.00	0.03	0.01	0.03	0.01	0.04	0.00	0.04	0.01	0.05	0.01
FeO	%	1.75	0.08	1.74	0.22	2.19	0.17	1.99	0.11	2.06	0.05	2.63	0.32
V*	ppm	71	5	2	0	3	1	98	7			10	5
Cr*	ppm	54	7			7	8	63	7			9	8
Zn	ppm	53	5	92	13	81	3	92	15	50	10	55	5
Rb	ppm	218	7	222	21	206	5	227	11	189	2	214	7
Sr	ppm	20	6	23	2	39	13	32	7	35	8	64	14
Y	ppm	58	9	67	7	73	4	71	9	52	6	54	2
Zr	ppm	342	30	343	19	460	30	420	30	395	23	455	12
Nb	ppm	43	9	46	4	51	2	48	8	42	2	45	2
Ba	ppm	621	65	628	45	677	18	923	57	797	81	932	29
Pb*	ppm	28	2	31	2	30	1	26	9			32	8
Alt. source names		Murphy Hot Springs, Three Creek, Browns Bench Area						Coal Banks, Coal Bank Spring					
Correlate tuffs		BBU-6 (BB), Jackpot Member (BB/RG), Big Bluff Tuff (CH), Tuff of Fir Grove (MBH), Tuff of Frenchman Springs (MBH)						Cougar Point Tuff VII (CPT), BBU-3 (BB), Browns Bench Member (BB/RG)					
*Factory calibration		CPT = Cougar Point Tuff; BB = Browns Bench Escarpment; RG = Rogerson Graben; CH = Cassia Hills; MBH = Mt. Bennet Hills											
Reference data cited		[1]Monnereau et al. 2021: Supplementary Data; [2]Bonnichsen et al. 2008: Appendix 3A; [3]Perkins et al. 1995: Table 3											

(2) In contrast to our interpretation, Page and Bacon (2016:9–10; Hughes 2015:299) suggest that "Browns Bench Area" obsidian may be derived from Cougar Point Tuff XII. Support for this view includes: (a) similarities in mean Rb, Sr, and Zr content with data reported from a single sample from a devitrified horizon of BBU-6 in the Browns Bench Escarpment (Bonnichsen et al. 2008, apps. 3B and 4B); and (b) reference to a stratigraphic correlation between BBU-6 and Cougar Point Tuff XII (Ellis et al. 2012, fig. 2). Cougar Point Tuff XII is unique among ignimbrites of the Bruneau-Jarbidge EC for its high concentrations of CaO, TiO_2, MnO, and FeO, low Rb, and high Sr, Zr, and Ba (Bonnichsen et al. 2008, apps. 3A and 4A). It is a poor fit for the "Browns Bench Area" group using Rb, Sr, and Zr values reported by Page and Bacon (2016: Table 1). Elsewhere, BBU-6 has been correlated with Cougar Point Tuff XI through geochronology, paleomagnetism, and whole rock and glass compositions (Bonnichsen et al. 2008; Finn et al. 2016).

Results of this study show that obsidian corresponding to the "Browns Bench Area"/"Murphy Hot Springs" source group is qualitatively similar in major and trace-element composition to vitrophyres of

Cougar Point Tuffs V, IX, XI, and XIII (Bonnichsen et al. 2008, apps. 3A and 4A). Although there are gross temporal trends in composition among ignimbrites in the Cougar Point Tuff sequence, Tuffs V, IX, XI, and XIII have overlapping ranges in composition for major (CaO, TiO_2, MnO, and FeO) and trace-elements (Zn, Rb, Sr, Zr, Nb, Ba) (Bonnichsen et al. 2008; Finn et al. 2016) that may be quantified via XRF. Discerning which tuff is the most likely source of “Murphy Hot Springs” obsidian is difficult to achieve through reference to whole rock data. Glass compositions tend to be more evolved and homogenous than whole rock samples from both lithoidal and vitrophyric horizons (Bonnichsen et al. 2008, 327–28) Differences in analytical methods and reporting standards can further frustrate efforts to compare data across disciplines.

Trace-element data from a recent study of obsidian pyroclasts from Cougar Point Tuff XIII (Monnereau et al. 2021) provides a cleaner basis of comparison than whole rock data, and confirms that this is the principal source of obsidian deposited in “moat-zone” gravels overlying the Cougar Point Tuff on the Jarbidge Plateau. A key finding of the study is that obsidian pyroclasts of Cougar Point Tuff XIII are compositionally identical to the welded ash groundmass of the tuff, and distinct from the groundmass of Cougar Point Tuff XI, demonstrating that they are juvenile in composition (not composed of material entrained from prior eruptions). Obsidian of Cougar Point Tuff XIII appears indistinguishable from the groundmass of Tuff XI in terms of major element composition, but it is higher in Rb, Y, and Pb. Our data for this group align well with obsidian pyroclasts of Cougar Point Tuff XIII on CaO, TiO_2, FeO, Rb, Sr, Y, Zr, Nb, Ba, and Pb (Table 4; Monnereau et al. 2021: supplementary data).

Beyond the Jarbidge-Plateau, the Cougar Point XIII Tuff has been correlated with the Jackpot member of the Browns Bench and Rogerson Formations, the Big Bluff Tuff in the Cassia Hills, and the Tuffs of Fir Grove and Frenchman Springs in the Mount Bennet Hills (Ellis et al. 2012; Ellis, Schmitz, and Hill 2019; Finn et al. 2016; Monnereau et al. 2021). Vitric clasts occur in the upper horizon of the Jackpot member of the Rogerson Formation (Andrews et al. 2008, 272; Branney et al. 2008, fig. 8), as well as the Big Bluff Tuff (Ellis 2009, 32; Ellis et al. 2012; Knott, Branney, et al. 2016), and the Tuff of Fir Grove (Monnereau et al. 2021). Yet none of our sampling locations, nor those of Page and Bacon (2016), yielded obsidian corresponding to the Cougar Point Tuff XIII group in the Cassia Hills or the Rogerson Graben. Vitric clasts documented by geologists in these areas are typically just 1-3 cm in diameter and embedded in a weakly welded ashfall matrix (Andrews et al. 2008, 271; Branney et al. 2008, fig. 8; Knott, Reichow, et al. 2016, fig. 6). We hypothesize that the size of obsidian clasts from this group may decline with distance from the Cougar Point XIII EC and that larger clasts are unavailable beyond the source locales documented by Page and Bacon (2016).

Ibex Peak Tuff 8

The second obsidian source group we attribute to the Bruneau-Jarbidge EC is found among strata of the Ibex Peak Tuff in the Coal Banks and Beaverdam Creek drainages southeast of the Cassia Hills (Mytton, Williams, and Morgan 1990; Perkins et al. 1995). The Ibex Peak Tuff is a 440 m thick series of unconsolidated, white, vitric ash-fall tuffs interbedded with occasional strongly welded ashflow tuffs and lenses of tuffaceous shale, lignite, and conglomerate (Mytton, Williams, and Morgan 1990; Perkins et al. 1995). It underlies later ignimbrites of the Cassia Formation that originated at the Twin Falls EC (Perkins et al. 1995; Knott, Branney, et al. 2016) and represents a distal expression of the more intensely welded rheomorphic ignimbrite units of the Cougar Point Tuff exposed in the Bruneau and Jarbidge Canyons (Perkins et al. 1995; Perkins and Nash 2002)**.**

Obsidian in the Coal Banks and Beaverdam Creek drainages is found in the form of blue-gray pyroclasts partially embedded in the upper surface of a distinctive red-brown vitrophyre 180 to 200 m below the uppermost stratum of the Ibex Peak Tuff. Pyroclasts often exhibit textural zonation from flow-banding, microbubbles, and incomplete welding of vitric shards. Both the pyroclasts and the vitrophyre are sufficiently glassy to yield a conchoidal fracture. The parent stratum likely corresponds to a reddish-brown welded tuff unit described at the base of the upper Salt Lake Formation in tributary drainages of Goose Creek in southeast Cassia County, Idaho, northeast Nevada, and northwest Utah (Mapel and Hail 1959, 234). The Salt Lake Formation is equivalent to and has been superseded by the Ibex Peak Tuff in Idaho (Mytton, Williams, and Morgan 1990; Perkins et al. 1995).

Relative to Cougar Point XIII obsidian, samples from the Coal Banks and Beaverdam Creek areas are more enriched in MnO, CaO, TiO_2, FeO, Zn, and Ba (Figure 6; Table 4), suggesting that they are from a less evolved phase of the Bruneau-Jarbidge eruptive sequence (Bonnichsen et al. 2008; Knott, Reichow, et al. 2016). The closest compositional match for this group among tuffs of the Trapper Creek area is Ibex Peak Tuff 8 (11.81 ± 0.03 Ma) (Perkins et al. 1995). Ibex Peak Tuff 8 has been characterized through XRF and electron microprobe analyses of glass shards from strata 30 (ashflow tuff) and 31 (airfall tuff) at Trapper Creek (Perkins et al. 1995, fig. 3). Individual shards have a distinctly tri-modal FeO and CaO composition that permit its identification in tephra deposits as far as Washington, California, Nevada, and Nebraska (Nash and Perkins 2012; Perkins et al. 1998; Perkins and Nash 2002). XRF analysis averages the variability between individual shards, yielding results that are comparable to obsidian found in the Coal Banks Creek and Beaverdam Creek drainages (Table 4). Page and Bacon (2016:37) group obsidian from the Coal Banks Creek locale with the "Browns Bench" source group. GRL recognizes it as a distinct geochemical group based on lower concentrations of Ba and Sr (Arkush and Hughes 2018; R. E. Hughes 2015).

Ibex Peak Tuff 8 has been correlated with Cougar Point Tuff VII (11.81 ± 0.03 Ma) of the Bruneau-Jarbidge area through geochemistry and geochronology (Perkins et al. 1995; 1998; Perkins and Nash 2002; Nash and Perkins 2012). Cougar Point VII, in turn, has been correlated with the Browns Bench member (11.86 ± 0.006 Ma) of the Rogerson Formation and Browns Bench Escarpment (Finn et al. 2016; Knott, Reichow, et al. 2016). At their type locations, these units are described as very thick (> 90 m), intensely welded rheomorphic ashflow tuffs that form a series of stepped cliffs that indicate a sequence of short-interval ashflow emplacements that combined to form a simple cooling unit (Bonnichsen et al. 2008; Bonnichsen and Citron 1982; Knott, Reichow, et al. 2016). At present there is no indication that tool-quality clasts of obsidian are available in association with correlate tuffs outcropping west of the Cassia Hills. For this reason, we associate obsidian corresponding to the "Coal Banks" group with Ibex Peak Tuff 8 at Trapper Creek rather than equivalent units closer to the presumed locus of eruption in the Bruneau-Jarbidge area.

The Twin Falls eruptive center

Obsidian source groups of the Twin Falls EC of the CSRP-VP are found in extensive, discontinuous surface deposits both north and south of the central Snake River Plain (Figure 5). Like obsidians from the Bruneau-Jarbidge EC, and in contrast to groups from the later Heise EC, they exhibit a high degree of intragroup compositional variability and intergroup similarity, posing significant challenges for provenance research. We define four geochemical groups from the Twin Falls EC. Obsidian from the Steer Basin Tuff corresponds to the "Browns Bench" group familiar to archaeologists (Bailey 1992; R. E. Hughes and Smith 1993; James, Bailey, and D'Auria 1996; Holmer 1997; Skinner 2011a; 2011c). The McMullen Creek Tuff is the source of the elusive "Butte Valley A" group first defined through characterization of lithic tools in eastern Nevada (R. E. Hughes and Smith 1993; G. Jones et al. 2003; G. T. Jones and Beck 1990; Page and Duke 2015; Skinner 2011b). Obsidian of the other two groups, the Dry Gulch Tuff and the Picabo Tuff, is difficult to separate from the McMullen Creek Tuff using the mid-Z elements (Rb, Sr, Y, Nb, and Zr), but they can be distinguished through differences in major element composition (especially TiO_2, MnO, and CaO) (Figure 6). Archaeologically, the Steer Basin Tuff and the McMullen Creek Tuff are the most well-utilized obsidian-bearing ignimbrites from the Twin Falls EC. They are also the most geographically extensive.

Table 5: Major and trace-element composition of obsidian source groups from the Central Snake River Plain Volcanic Province.

Element		Ibex Peak Tuff 8 (n = 32) x̄	± 1s	Cougar Point Tuff XIII (n = 29) x̄	± 1s	Steer Basin Tuff (n = 256) x̄	± 1s	Dry Gulch Tuff (n = 30) x̄	± 1s	McMullen Creek Tuff (n = 175) x̄	± 1s	Picabo Tuff n = (27) x̄	± 1s
K_2O	%	6.52	0.34	5.76	0.22	5.78	0.23	5.45	0.33	5.49	0.28	5.52	0.30
CaO	%	0.74	0.04	0.61	0.03	0.83	0.04	0.67	0.05	1.00	0.12	1.48	0.18
TiO_2	%	0.26	0.03	0.23	0.03	0.34	0.02	0.30	0.03	0.37	0.03	0.42	0.04
MnO	%	0.04	0.01	0.04	0.01	0.04	0.01	0.05	0.01	0.07	0.01	0.08	0.01
FeO	%	1.99	0.11	1.75	0.08	2.05	0.10	1.88	0.12	2.48	0.20	2.79	0.16
V*	ppm	98	7	71	5	107	6	100	6	115	6	115	5
Cr*	ppm	63	7	54	7	55	7	59	7	63	7	60	7
Zn	ppm	92	15	53	5	54	6	53	4	67	7	71	7
Rb	ppm	227	11	218	7	198	7	191	5	172	8	166	7
Sr	ppm	32	7	20	6	42	8	36	9	58	12	81	20
Y	ppm	71	9	58	9	52	9	59	11	60	11	59	10
Zr	ppm	420	30	342	30	427	43	380	45	520	55	573	34
Nb	ppm	48	8	43	9	43	7	47	6	52	8	50	8
Ba	ppm	923	57	621	65	1126	74	1061	61	1164	73	1163	69
Pb*	ppm	26	9	28	2	28	4	28	4	27	3	26	3
Alternate source names		**Coal Banks** Coal Bank Spring		Browns Bench Area **Murphy Hot Springs** Three Creek		**Browns Bench** Hudson Ridge Jackpot Mahogany Butte Rock Creek				**Butte Valley A** Camas Prairie Hudson Ridge		**Picabo Hills**	
Potential correlate tuffs		Cougar Pt. VII (CPT) BBU-3 (BB) Browns Bench Tuff (BB/RG)		BBU-6 (BB) Jackpot (BB/RG) Big Bluff (CH) Frenchman Springs & Fir Grove (MBH)		Tuff of Knob (MBH) Rabbit Spr. (BB/RG)		Picabo A (PH)		McMullen 4 (CH) Idavada old (LH)		Picabo B (PH)	
*Factory calibrated		CPT = Cougar Point Tuff; BB = Browns Bench Escarpment; RG = Rogerson Graben; CH = Cassia Hills; MBH = Mt. Bennet Hills; LH = Lake Hills											

The Twin Falls EC (10.6 – 8.6 Ma) is the fourth major rhyolitic volcanic field of the Snake River Plain volcanic province (Pierce and Morgan 1992; 2009; K. E. Wright, McCurry, and Hughes 2002; Knott, Branney, et al. 2016). In contrast to Owyhee-Humboldt (14.5-12.0 Ma) and Bruneau-Jarbidge ECs (12.7-10.7 Ma), ignimbrites of the Twin Falls EC remain exposed at the surface in extensive deposits both north and south of the plain[c]. Like ignimbrite tuffs of the Bruneau-Jarbidge EC, those of the Twin Falls EC

[c] Individual units of the Twin Falls EC sequence have been mapped in considerable detail in several areas, including the Cassia Hills (Mytton, Williams, and Morgan 1990; Williams, Mytton, and Covington 1990; Williams, Covington, and Mytton 1991;

exhibit a range of depositional characteristics and stratigraphic field relations that differ with distance and direction from their inferred loci of eruption. This study benefits from recent efforts to characterize the scale of individual eruptive events through correlation of named units in various exposures north and south of the plain (Andrews et al. 2008; Bonnichsen et al. 2008; Ellis et al. 2012; Anders et al. 2014; Finn et al. 2016; Knott, Branney, et al. 2016; Knott, Reichow, et al. 2016; Anders et al. 2019; Knott et al. 2020).

Ignimbrites of the Twin Falls EC are best characterized in the Cassia Hills area south of Twin Falls, ID (Mytton, Williams, and Morgan 1990; Williams, Mytton, and Covington 1990; Williams, Covington, and Mytton 1991; Parker 1996; K. E. Wright 1998; Watkins 1998; Williams, Mytton, and Morgan 1999; K. E. Wright, McCurry, and Hughes 2002; Knott, Branney, et al. 2016). Here, geologists have identified a stratified sequence of over a dozen ignimbrites exposed in the walls of several deep drainages. Lower ignimbrites of the Cassia Hills (the Ibex Peak Tuff, Magpie Basin Tuff, and Big Bluff Tuff) are associated with the Bruneau-Jarbidge EC (12.7-10.7 Ma) (Perkins et al. 1995; Knott, Branney, et al. 2016). The earliest ignimbrite of the Twin Falls EC is the Steer Basin Tuff (10.62 ± 0.09 Ma), followed by the Wooden Shoe Tuff (10.14 ± 0.01), the Little Creek Tuff (poorly dated), the Dry Gulch Tuff (poorly dated), the Indian Springs Tuff (poorly dated), the McMullen Creek Tuff (8.99 ± 0.03 Ma), and the Gray's Landing Tuff (8.72 ± 0.07 Ma) (Perkins et al. 1995; Branney et al. 2008; Ellis et al. 2012; Knott, Branney, et al. 2016). Two later caldera-fill ignimbrites, the Castleford Crossing Tuff and the Kimberly Tuff, are known primarily through borehole strata; they have limited surface exposures and are largely obscured by later rhyolite lava, basalt, and alluvium of the Snake River Plain (Knott, Branney, et al. 2016).

Whole-rock analyses of vitrophyric and lithoidal horizons of ignimbrites of the Cassia formation have revealed cyclical trends in major and trace-element geochemistry (Ellis et al. 2012; Knott, Branney, et al. 2016; Knott, Reichow, et al. 2016). Within each cycle, the composition of ignimbrites shifted systematically through four to five major eruptive events. Over time, (1) SiO2, Rb, La, and Th decreased while (2) TiO_2, CaO, FeO, MgO, Sr, Ba, and Zr increased until (3) compositions 'reset' to begin a new cycle (Perkins et al. 1995; Perkins and Nash 2002; Knott, Branney, et al. 2016; Knott, Reichow, et al. 2016). Two complete cycles are evident among strata of the Cassia formation. The first began with the Magpie Basin Tuff and ended with the Little Creek Tuff. The second began with the Dry Gulch Tuff and ended with the Castleford Crossing Tuff (Knott, Branney, et al. 2016). The Steer Basin Tuff and the McMullen Creek Tuff are intermediate in composition within the first and second cycles, respectively.

Trends toward less evolved compositions (increases in compatible elements) among units of the Cassia formation are contrary to what one would expect given simple maturation of a melt through cooling and crystal fractionation (Knott, Reichow, et al. 2016, 18). To account for these observations, Knott, Branney, et al. (2016) propose a model involving (1) gradual hybridization of mid-crustal melts with mantle-derived basalts; (2) ascent and incorporation of low-silica rhyolites into shallow reservoirs in the upper crust; and (3) decreases in fractional crystallization in upper crustal reservoirs due to lower temperature contrasts between magma and the surrounding crust. Under this model, new cycles are initiated as the source of magmatism shifts to more pristine regions of the middle crust with migration of the North American Plate over the Yellowstone hotspot. These trends help us contextualize patterns evident in the composition of obsidian source groups of the CSRP-VP.

Comparisons of major and trace-element data for obsidian source groups of the Twin Falls EC (Figure 6; Table 5) reveal that some combine to form compositional gradients that recall the cyclical trends observed

---

Williams, Mytton, and Morgan 1999), the Rogerson Graben (Andrews et al. 2008; Knott, Reichow, et al. 2016), the Mt. Bennett Hills (Oakley 2006; Kurt L. Othberg et al. 2007; Kurt L. Othberg and Kauffman 2009; Kauffman, Othberg, and Garwood 2010; Garwood et al. 2014), and the Picabo Hills (Garwood, Kauffman, and Othberg 2011; Garwood et al. 2014).

among Cassia Formation ignimbrites, but others do not. Three obsidian groups – the Dry Gulch Tuff, the McMullen Creek Tuff, and the Picabo Tuff – exhibit strong positive correlations between compatible elements (e.g., TiO_2, MnO, FeO, Sr, and Zr) and negative correlations between these elements and Rb. Along this gradient, obsidian of the Dry Gulch Tuff exhibits the most evolved composition. Obsidian of the McMullen Creek Tuff exhibits an enormous range of compositional variability across a suite of major elements, including CaO, MnO, TiO_2, and FeO, that do not relate to differences in sampling location, reflecting the complex eruptive history of this unit (Knott et al. 2020). Obsidian of the Picabo Tuff overlaps with the McMullen Creek Tuff at the higher end of the latter's broad compositional range for the major and compatible elements. Only higher values for CaO allow us to regard it as a distinct compositional group. At a minimum, this supports the current view that the Picabo Tuff originated at the Twin Falls EC rather than the Picabo EC (Anders et al. 2014; 2019). But given the similarity in the age and overlapping composition of the Picabo and McMullen Creek Tuffs, we suspect that the Picabo Tuff is a late, localized product of a complex series of short-interval eruptions that produced what is elsewhere mapped as the McMullen Creek Tuff. Finally, obsidian of the Steer Basin Tuff does not fall on the compositional gradient formed by the other three groups from the Twin Falls EC (it has higher ratios of FeO and TiO_2 to MnO), but it also does not group with obsidian of the Bruneau-Jarbidge EC along a second compositional gradient of compatible elements. If the model proposed by Knott, Branney, et al. (2016) is correct, this may suggest that a shorter compositional cycle of just two to three eruptions may have occurred between events that produced the Cougar Point XIII/Big Bluff Tuff and the Dry Gulch Tuff.

Steer Basin Tuff

The Steer Basin Tuff has been previously recognized as the parent ignimbrite of "Browns Bench" obsidian (Page and Bacon 2016), the most well-known and archaeologically significant obsidian source group from the Twin Falls EC. The "Browns Bench" source group is known to outcrop in a multitude of locales over a 5,500 km^2 area encompassing the Cassia Hills, the Shoshone Basin, The Rogerson Graben, and the Browns Bench Massif near the Idaho/Nevada border (R. E. Hughes and Smith 1993; Page and Bacon 2016; Skinner 2011a). Results of this study confirm the association between Browns Bench obsidian and the Steer Basin Tuff and the ubiquity of this source group in the Cassia Hills and Browns Bench area.

In the Cassia Hills, the Steer Basin Tuff is more exposed to the south at higher elevations where it is not overlain by later ignimbrites (Ellis 2009; Ellis et al. 2012; Knott, Branney, et al. 2016). Through a combination of geochemistry, geochronology, and paleomagnetism, the Steer Basin Tuff (10.62 ± 0.09 Ma) has been correlated with the Cougar Point XVb tuff of the Bruneau-Jarbidge plateau and the Rabbit Springs Tuff of the Browns Bench Escarpment and Rogerson Graben (Perkins et al. 1995; 1998; Ellis et al. 2012; Finn et al. 2016). It has not yet been identified north of the plain, but Ellis (2009, p. 146) suggests that it may correlate to the Tuff of Knob (10.6 ± 0.2 Ma) in the Mt. Bennett Hills (Oakley and Link 2006) based on age, bulk chemistry, and crystal assemblage.

Descriptions of the Steer Basin Tuff offered in maps of the Cassia Hills state that the "basal vitrophyre contains obsidian used by prehistoric Indians to make projectile points" (Mytton, Williams, and Morgan 1990; Williams, Mytton, and Covington 1990; Williams, Covington, and Mytton 1991; Williams, Mytton, and Morgan 1999). This is misleading. Like many SRP ignimbrites, a characteristic feature of the Steer Basin Tuff is a distinctive basal horizon of densely welded, blocky, black vitrophyre (densely welded, glassy ashflow tuff) that grades upward into a much thicker lithoidal horizon of devitrified tuff (Watkins 1998; Ellis et al. 2010; Knott, Branney, et al. 2016). Material from this horizon is crystal poor and geochemically similar to "Browns Bench" obsidian (see data reported by Perkins et al., 1995 and Ellis 2009), but it is not sufficiently glassy to serve as tool-stone. Underlying the basal vitrophyre of the Steer Basin Tuff, Watkins (1998, pp. 36-43) describes a co-ignimbrite zone of precursor fallout tephra containing abundant obsidian pyroclasts. A similar zone of fallout tephra is now recognized as a basal component of the Rabbit Springs Tuff at Browns Bench (Knott, Reichow, et al. 2016). These descriptions are more consistent with our field observations of tool-quality obsidian deposits associated with the Steer Basin Tuff. In geologic maps of the Cassia Hills, this horizon corresponds to upper portions of a unit mapped as "Unnamed Tuff 1" that occurs immediately below the Steer Basin Tuff (Mytton, Williams, and Morgan 1990; Williams, Mytton, and Covington 1990; Williams, Covington, and Mytton 1991; Williams, Mytton, and Morgan 1999). This unit is not well described in more recent work (Ellis 2009; Ellis and Branney 2010; Ellis et al. 2010; Knott, Branney, et al. 2016). Following Watkins (1998), we interpret the upper portion of this unit as a precursor component of the Steer Basin Tuff based on geochemical similarity and universal co-occurrence in mapped areas of the Cassia Hills.

We collected obsidian from two primary deposits in the Cassia Hills mapped as Steer Basin Tuff: near the summit of Monument Peak and below Wooden Shoe Butte (Mytton, Williams, and Morgan 1990; Williams, Covington, and Mytton 1991). Other deposits were found among colluvium in superficial association with lower strata in locales such as Ibex Hollow in the Trapper Creek drainage (Mytton, Williams, and Morgan 1990). In the Rogerson Graben, Steer Basin Tuff obsidian was collected from two locations near the Idaho/Nevada border in areas mapped or described as the Jackpot 7 or Rabbit Springs Tuffs (Andrews et al. 2008; Ellis et al. 2012; Finn et al. 2016; Knott, Reichow, et al. 2016). At the Browns Bench Massif, Steer Basin Tuff obsidian was sampled from two groups of locations along the top of the escarpment in areas corresponding to the Rabbit Springs Tuff (Ellis et al. 2012; Finn et al. 2016; Knott, Reichow, et al. 2016). To the west, we collected obsidian that grouped with other samples from the Steer Basin Tuff at two locations: along House Creek Road and near Three Creek, where it occurred in a mixed secondary deposit with Cougar Point XIII obsidian. North of the plain, we encountered Steer Basin Tuff obsidian as alluvial cobbles in a drainage below Pine Mountain, north of Craters of the Moon. Further fieldwork is needed in this area to determine if more substantial deposits are present north of the plain (See discussion of McMullen Creek Tuff obsidian below).

Dry Gulch Tuff

The Dry Gulch Tuff is a recently defined ignimbrite of the Cassia Hills (Knott, Branney, et al. 2016) that is host to abundant 2 – 15 cm diameter pyroclasts of obsidian. It corresponds to Member 1 of the former Tuff of McMullen (Williams, Mytton, and Covington 1990; Williams, Covington, and Mytton 1991; K. E. Wright 1998; K. E. Wright, McCurry, and Hughes 2002), which has been formally separated into four units: the Dry Gulch Tuff (poorly dated), the Indian Springs Tuff (9.00 ± 0.03 Ma), the McMullen Creek Tuff (8.99 ± 0.03 Ma), and the Gray's Landing Tuff (8.71 ± 0.07 Ma) (Knott, Branney, et al. 2016, tbl. 1; Knott et al. 2020). The unit consists of a thin (1.5 m) precursor layer of pumice lapilli and ash overlain by a thick, densely welded rheomorphic ignimbrite. Its upper vitrophyre is heavily brecciated and overlain by three meters of unwelded, stratified pumice and ash (Knott, Branney, et al. 2016). The Dry Gulch Tuff is only recognized in the northern Cassia Mountains, but Anders et al. (2019) have suggested that it may correlate to Picabo Tuff A (9.12 ± 0.08 Ma) north of the plain based on geochemistry and magnetic polarity (see discussion of the Picabo Tuff below).

An obsidian source group corresponding to the Dry Gulch Tuff has not been previously defined in archaeology. Dry Gulch Tuff obsidian is more evolved in composition than obsidian of the McMullen Creek Tuff, with lower concentrations of CaO, TiO_2, MnO, and FeO. It can also be distinguished from Steer Basin Tuff obsidian on bivariate plots of MnO vs. CaO and FeO (Figure 6). Our present sample of material from this group was collected from two locations: Dry Gulch and the McMullen Basin. Both sampling locations are near the base of the composite unit mapped as the Tuff of McMullen in geologic maps of the Cassia Hills (Williams, Mytton, and Covington 1990; Williams, Covington, and Mytton 1991).

At our Dry Gulch sampling locale, obsidian occurs in small (< 3 cm in diameter) clasts exposed in a two-track below a prominent balanced rock at the crest of an anticline on the western side of the Dry Gulch drainage. Recognizable exposures of the Indian Springs Tuff and the McMullen Creek Tuff overly the exposure, suggesting that it is eroding from either a basal horizon of the Indian Springs Tuff or an upper horizon of the Dry Gulch Tuff. Obsidian clasts are not evident in stratigraphic exposures of the Indian Springs Tuff or the Dry Gulch Tuff at its type location in the Dry Gulch Quarry (Knott, Branney, et al. 2016, 1130–31). But qualitative comparisons to major and trace element data reported for member units of the former Tuff of McMullen (K. E. Wright 1998; K. E. Wright, McCurry, and Hughes 2002) suggest that Member 1 (the Dry Gulch Tuff) is the closest match for this obsidian source group.

In the McMullen Basin, a far richer deposit of obsidian clasts up to 15 cm in diameter is exposed at the surface over an area of at least ten acres. High densities of debitage, core fragments, and discarded preforms suggest that this area was among the more heavily utilized source locales in the Cassia Hills. Our present sample was collected from an exposure of smaller (2 – 7 cm) clasts exposed in a two-track road south of this site. Page and Bacon (2016: Table 8) assign the majority of obsidian that they collected from sampling areas in the McMullen Basin to the "Browns Bench" group. Indeed, the Dry Gulch Tuff and the Steer Basin Tuff are similar in composition among the mid-Z elements (Knott, Branney, et al. 2016, tbl. S1). Major element compositions and stratigraphic associations allow us to define a distinct source group associated with the Dry Gulch Tuff.

The number of obsidian source locales corresponding to the Dry Gulch Tuff in our present sample is small, but it may outcrop discontinuously over an area of over 500 km^2 in the northern Cassia Hills. Within this area, the Dry Gulch Tuff is overlain by a series of later ignimbrites, and it is thought to pinch out within 20 kilometers of the plain (Knott, Branney, et al. 2016, fig. 19). Exposures in the McMullen Basin would be among the more distal expressions of this tuff, suggesting that obsidian pyroclasts may be more common with distance from the eruptive center. Updated mapping of the surficial geology of the Cassia Hills would clarify the distribution of the Dry Gulch Tuff and other recently defined ignimbrites from the Twin Falls EC.

McMullen Creek Tuff

The second-most widespread obsidian source group of the Twin Falls EC is found in association with the McMullen Creek Tuff (Knott, Branney, et al. 2016; Knott et al. 2020), which corresponds to Member 4 of the former Tuff of McMullen (Williams, Mytton, and Covington 1990; Williams, Covington, and Mytton 1991; K. E. Wright 1998; K. E. Wright, McCurry, and Hughes 2002). The McMullen Creek Tuff (8.99 ± 0.03 Ma) is one of the more recent ignimbrites of the Cassia Hills. It is also known to outcrop to the west in the Shoshone Basin and the Rogerson Graben, but it is not present as far as the Brown's Bench Escarpment (Knott et al. 2020). North of the plain, it has been correlated by Knott et al., (2020) with a unit mapped as the "Idavada Volcanic Group, oldest" in the Lake Hills area north of Craters of the Moon (Kuntz et al. 2007; Michalek 2009). Contiguous deposits in the Picabo Hills to the west are mapped as the Picabo Tuff (Garwood, Kauffman, and Othberg 2011; Garwood et al. 2014). As noted above, the McMullen Creek and Picabo Tuffs are equivalent in age (~ 9 Ma) and obsidian from the two areas overlaps geochemically for all elements except CaO (see discussion of Picabo Tuff obsidian below).

The McMullen Creek Tuff is described as a compound ignimbrite cooling unit overlying a precursor ashfall and overlain by a paleosol separating it from later units (Knott, Branney, et al. 2016; Knott et al. 2020). It has a complex vertical profile bounded by dark, glassy upper and lower vitrophyres that grade inward to a dark brown devitrified lithoidal zone divided by a distinct, 10 m thick middle zone of less welded lapilli tuff. The latter zone grades inward from densely welded to less welded. It is separated from the lithoidal zones by upper and lower lithophysal vitrophyres and it contains abundant small (< 1 cm) vitric lapilli that increase in size toward the less-welded center of the tuff (K. E. Wright 1998; K. E.

Wright, McCurry, and Hughes 2002; Knott et al. 2020). Such zonation reflects a complex process of emplacement that may help explain the broad compositional variability of McMullen Creek Tuff obsidian. The tuff is thicker and more widespread in the north Cassia Hills, thinning with distance from the plain to a single compact vitrophyre to the south (Williams, Mytton, and Covington 1990; Williams, Covington, and Mytton 1991; Knott et al. 2020).

Descriptions of the McMullen Creek Tuff do not mention vitric or glassy clasts among unwelded portions of the tuff, but available major and trace-element data (K. E. Wright 1998; K. E. Wright, McCurry, and Hughes 2002) are consistent with the range of values we observe for this source group. Obsidian of the McMullen Creek Tuff was sampled in several locations throughout the Cassia Hills and the Shoshone Basin. Interestingly, the size and abundance of obsidian associated with this group appears to increase to the south with distance from the presumed eruptive center on the plain. At Hudson Ridge (30 km south of the plain) obsidian pyroclasts over 20 cm in diameter were encountered in an area mapped as the Tuff of McMullen (Mytton, Williams, and Morgan 1990). But the most abundant material from this source group is found in the Shoshone Basin between the Cassia Hills and the Rogerson Graben. In this area, red and black obsidian may be found in patchy but extensive deposits over much of the landscape. Two of our sampling locations in this area are mapped as the Steer Basin Tuff (Williams, Mytton, and Morgan 1999), but all samples from these sites group with obsidian of the McMullen Creek Tuff. We hypothesize that at this distance from the McMullen Creek Tuff eruptive center, the lower volume and cooler temperature of pyroclastic density currents resulted in a thinner deposit of unwelded, obsidian-bearing fallout tephra that is not adequately captured in geologic maps.

Major and trace-element analyses of obsidian collected from “Butte Valley A” and “Camas Prairie” source locales in the Mt. Bennett Hills (Bailey 1992; Skinner 2011a; 2011c), confirmed that obsidian from these locations can be attributed to the McMullen Creek Tuff group. However, none of our sampling locations in the Mt. Bennett Hills appear to be primary deposits. Obsidian clasts found in the Mt. Bennett Hills were small (<7 cm), distinctly water-rounded gravels and cobbles occurring in areas mapped as the Gravel of Hash Springs (Thsg), a locally extensive Miocene deposit of unconsolidated silt, sand, and gravel (Kauffman, Othberg, and Garwood 2010; Garwood et al. 2014). The underlying Tuff of Gwin Springs (~9.6 Ma) is substantially older than the McMullen Creek Tuff (8.99 ± 0.03 Ma) and it differs in major and trace element composition (Kauffman, Othberg, and Garwood 2010; Knott, Branney, et al. 2016). Evidently, McMullen Creek Tuff obsidian is present in the Mt. Bennett Hills as gravel mobilized by an ancient alluvial system from somewhere to the south or east within the hypothesized extent of the McMullen Creek Tuff super-eruption (Knott et al. 2020). To the east, we also encountered McMullen Creek Tuff obsidian among alluvial cobbles in a drainage at the base of Pine Mountain north of Craters of the Moon. SFU reports sampling locations at higher elevations on Pine Mountain to the north (Bailey 1992), but access to these locales is impeded by private land. We were unable to locate primary deposits of obsidian in the drainage uphill of our sampling location.

Picabo Tuff

The Picabo Tuff was identified as a source of Idaho obsidian as early as 1992 (Bailey 1992), but to our knowledge it has not been sampled by archaeologists in the years since. As a geologic unit, it is a densely welded gray to purplish-brown ignimbrite extruded onto an irregular topographic surface in the Picabo Hills north of the CSRP (Schmidt 1962; Garwood, Kauffman, and Othberg 2011). Schmidt (1962) divided the Picabo Tuff into lower and upper subunits (Tuffs A and B) separated by a poorly exposed layer of white tuffaceous sediment. Each subunit represents a series of rapidly emplaced ashflows or cooling units (Schmidt 1962; Leeman 1982a; Honjo et al. 1986; Anders et al. 2019). Picabo Tuff A (9.12 ± 0.08 Ma) is a thick, densely welded rheomorphic ashflow tuff with elongate lithophysal cavities and a dense black basal vitrophyre. Picabo Tuff B (9.02 ± 0.11 Ma) has a dense basal vitrophyre that grades into a less welded, granular ashflow tuff with 25-50% lithophysal cavities (Schmidt 1962; Anders et al.

2019). Subunits of the Picabo Tuff are not mapped separately on current geologic maps of the Picabo Hills or Mount Bennett Hills (K. L. Othberg and Kauffman 2010; Garwood, Kauffman, and Othberg 2011), but our principal obsidian sampling location for this group is on a ridgeline east of Gannett, ID where Picabo Tuff B was first identified and defined (Schmidt 1962, 27–29).

While the Picabo EC takes its name from the Picabo Tuff (Pierce and Morgan 1992), current evidence suggests that the latter originated at the Twin Falls EC farther west (Schmidt 1962; Leeman 1982a; Anders et al. 2014; 2019). Similarities in geochronology, geochemistry, mineral assemblages, and magnetic polarity have led some to correlate Picabo Tuff A with the Dry Gulch Tuff and Picabo Tuff B with the McMullen Creek and Indian Springs Tuffs (Bonnichsen et al., 2008; Anders et al., 2019). Anders et al. (2019) observe that Picabo Tuff B (9.02 ± 0.11 Ma) is closer in age to the McMullen Creek Tuff (8.99 ± 0.03 Ma) than the Idavada "oldest" ignimbrite (9.22 ± 0.02 Ma) in the Lake Hills to the east (Michalek 2009; Anders et al. 2019). Whole-rock major and trace-element geochemistry reported for the Picabo Tuff (Garwood, Kauffman, and Othberg 2011) are broadly consistent with data reported for both the McMullen Creek Tuff and the Idavada "oldest" ignimbrite in the Lake Hills (Knott et al. 2020), suggesting that the three units are derived from a common magma source.

To determine whether Picabo Tuff obsidian represents a geochemically distinct source group, we attempted to revisit sampling locations reported by SFU in the Picabo Hills area (Bailey 1992; James, Bailey, and D'Auria 1996). Access to some locations in this area was inhibited by private land, but we were able to obtain 30 samples from an exposure of Picabo Tuff B on a ridgeline east of Gannett, ID (Schmidt 1962, 28). Here, abundant black pyroclasts of obsidian were found along the ridge within an area covering just a few acres. Clasts were five to ten cm in diameter with abundant white phenocrysts. Fractured surfaces are comparable in appearance to McMullen Creek Tuff obsidian from the Cassia Hills south of the plain. Other exposures of Picabo Tuff obsidian may be present in the hills south of Gannett. Geochemically, Picabo Tuff obsidian cannot be distinguished from McMullen Creek Tuff obsidian using the mid-Z elements, but higher concentrations of CaO allow us to define it as a separate compositional group.

The eastern Snake River Plain volcanic province

Like the CSRP-VP, the eastern Snake River Plain volcanic province (ESRP-VP) is host to ubiquitous, extensive, and discontinuous obsidian deposits associated with the large-volume pyroclastic eruptions that created the Snake River Plain (Figure 7). Obsidian-bearing rhyolitic ignimbrites and lava flows of the eastern plain were extruded from two major eruptive centers: the Picabo EC (10.2 – 7.6 Ma) and the Heise EC (6.6 – 4.6 Ma). The Heise EC produced some of the most well utilized and geographically widespread obsidian source groups in southern Idaho. One geochemical group, formerly known as "American Falls", has been linked to the Walcott Tuff (Holmer 1997; R. E. Hughes and Pavesic 2005; R. E. Hughes 2007b), enabling identification of additional deposits on the opposite side of the plain (R. E. Hughes 2015; Arkush and Hughes 2018). There has been less archaeological investigation into the geologic origin, spatial extent, and distribution of other well-known, genetically related ESRP source groups, such as "Bear Gulch" and "Packsaddle." Fortunately, the eruptive history of the ESRP-VP is well understood and there is broad agreement on the stratigraphy and surficial extent of major ignimbrite units (L. A. Morgan and McIntosh 2005; Bindeman et al. 2007; Pierce and Morgan 2009; Watts, Bindeman, and Schmitt 2011; Anders et al. 2014; 2019; Ellis et al. 2017; Jean et al. 2018).

An examination of the combined distribution of previously reported Idaho obsidian sampling locations (James, Bailey, and D'Auria 1996; Holmer 1997; Skinner 2011b; Black 2015; Arkush and Hughes 2018) reveals a parabolic belt of source locales (Figure 7) that corresponds closely to the surficial distribution of Pliocene Rhyolites around the eastern plain (Scott 1982; Lewis et al. 2012). Results of this study show that obsidian from the ESRP-VP can be separated into six geochemical groups corresponding to an

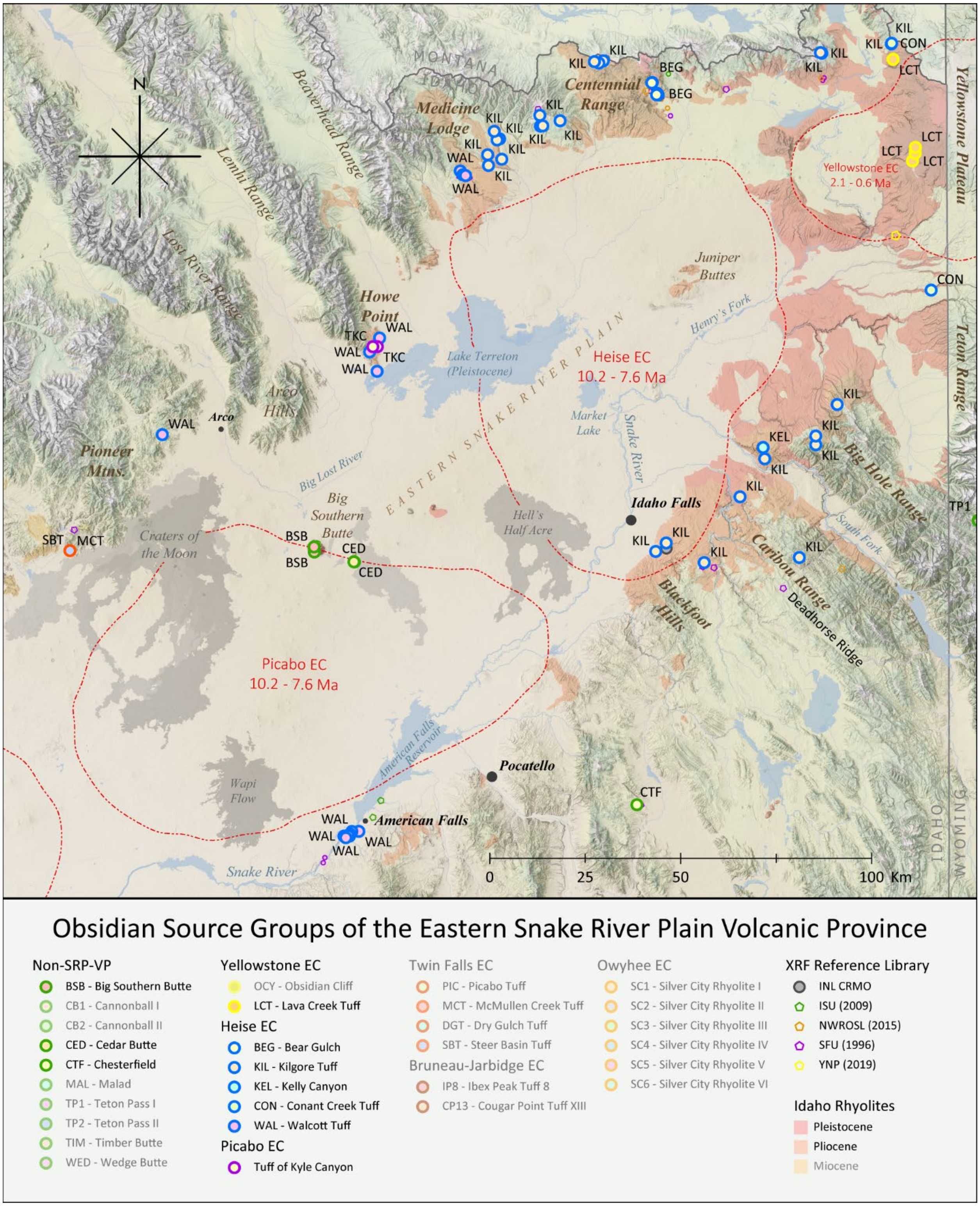

Figure 7: Distribution of sampling locations for obsidian source groups of the eastern Snake River Plain Volcanic Province.

obsidian source group associated with a minor ashflow tuff of the Picabo EC (10.2- 7.6 Ma) at Howe Point, north of the INL. The other six groups are associated with more recent ashflow tuffs, lava flows, and domes of the Heise EC (6.6 - 4.6 Ma) (Anders et al. 2014). ESRP-VP obsidian source groups are more compositionally evolved (having lower concentrations of compatible elements) and diverse than those of the CSRP-VP, reflecting more complex melt histories and longer magmatic residence times in the upper crust (S. S. Hughes and McCurry 2002). Results of this study suggest that they are best discriminated from one another using concentrations of the major elements CaO, MnO, TiO_2, and FeO (Figure 8; Table 6). Use of higher-precision benchtop XRF instruments may permit other labs to distinguish between these groups using the mid-Z elements.

Most source groups of the ESRP-VP have been previously identified and characterized by archaeologists, but only two (the Walcott Tuff and the Conant Creek Tuff) have been linked to their parent geologic units. The Walcott Tuff is a well-utilized source of obsidian first identified along the Snake River below the American Falls reservoir (Bailey 1992; James, Bailey, and D'Auria 1996; Holmer 1997; R. E. Hughes and Pavesic 2005; Skinner 2011b), that has since been reported north of the plain in the Lemhi Range and the Medicine Lodge area (R. E. Hughes 2015; Arkush and Hughes 2018; Keene 2018a). The Conant Creek Tuff is a less utilized source of obsidian found on the northwestern slope of the Teton Range near the Idaho/Wyoming border (Bailey 1992; Holmer 1997; Park 2010; MacDonald, Horton, and Surovell 2019).

Links between other ESRP-VP obsidian source groups and their parent geologic units have not been established, contributing to confusion over source names and their geographic distributions (Holmer 1997; Black 2015). We identify the Kilgore Tuff as the parent ignimbrite of the "Packsaddle" and "Deadhorse Ridge" source groups. Obsidian referred to as the "Packsaddle" group by ISU and GRL has been reported at several sampling locations over a wide area encompassing the Centennial Range, the northern Big Hole Range, and the Caribou Range (Bailey 1992; Black 2015; Arkush and Hughes 2018; Keene 2018a). We were unable to relocate NWROSL's source locale at "Deadhorse Ridge" (Skinner 2011b; Black 2015), but the Kilgore Tuff is the only ignimbrite known to outcrop at higher elevations in the Caribou Range (L. A. Morgan and McIntosh 2005).

There is greater consensus on the location and extent of the "Bear Gulch" and "Kelly Canyon" source areas. Deposits of "Bear Gulch" obsidian are known to occur near West Camas Creek in the Centennial Mountains north of Kilgore, ID (G. A. Wright, Chaya, and McDonald 1990; Bailey 1992; Willingham 1995; James, Bailey, and D'Auria 1996; Holmer 1997; Raley 2011; Skinner 2011b). "Kelly Canyon" obsidian is found at the base of the Kelly Canyon ski resort in the Heise Hills west of Idaho Falls (Holmer 1997; Moore 2009; Skinner 2011b; Black 2015).

The Picabo eruptive center

While hotspot volcanism produced an abundance of obsidian-bearing ignimbrites from the Twin Falls and Heise ECs, until recently there were no known sources of obsidian associated with the Picabo EC (10.2 – 7.6 Ma). In this section, we report a previously unrecognized obsidian source group from the Tuff of Kyle Canyon (9.28 ± 0.01 Ma), a minor ashflow tuff from the Picabo EC (Anders et al. 2014). This group was identified by chance following analysis of samples from four locations near Howe Point (the southern tip of the Lemhi Range; Figure 7) that we had assumed would correspond to the Walcott Tuff obsidian source group based on previous work in this area (Arkush and Hughes 2018). Compositional analyses via XRF soon revealed however that two groups were present: one matching Walcott Tuff obsidian from American Falls, and a second group with much higher concentrations of compatible elements that did not match other reference groups in our database. Geologic maps of the southern Lemhi Range (Kuntz et al., 1994, 2003) indicate that sampling locations for the newly defined group are associated with the Tuff of Kyle Canyon rather than the Walcott Tuff.

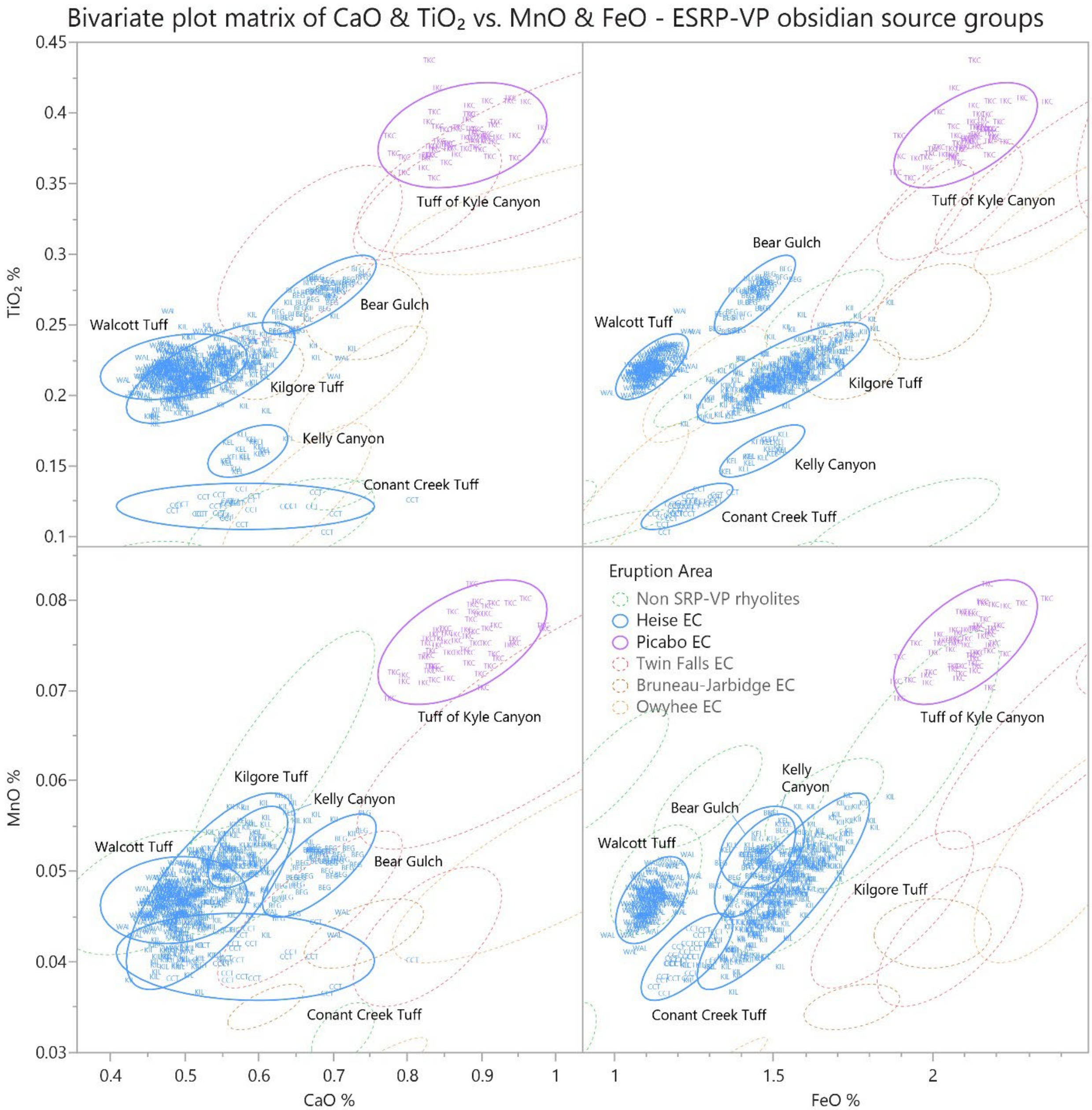

Figure 8: Bivariate plot matrix of CaO and FeO vs. MnO and TiO_2 for obsidian source groups of the Eastern Snake River Plain Volcanic Province.

The Picabo EC is fifth in the sequence of rhyolitic volcanic fields that created the Snake River Plain with passage of the North American Plate over the Yellowstone hotspot (Pierce and Morgan 1992; Drew et al. 2013; Anders et al. 2019). Rhyolitic ignimbrites from the Picabo EC (10.2 – 7.6 Ma) overlap temporally with those of the Twin Falls EC (10.6 – 8.6 Ma) (Anders et al. 2014) and spatially with those of the Heise EC (6.6 – 4.6 Ma) (Drew et al. 2013; Anders et al. 2014; 2019). Most ignimbrites of the Picabo EC are also rather poorly exposed compared to those of neighboring volcanic fields. As a result, few large-volume ignimbrites have been attributed to the Picabo EC (Pierce and Morgan 1992; Perkins and Nash 2002), leading some to question its validity (Nash and Perkins 2012, 9). Over the past decade, geologists have identified several ignimbrites of the Picabo EC and evaluated potential correlates across the plain through a combination of isotopic and trace-element geochemistry, mineral compositions, and paleomagnetism (Drew et al. 2013; 2016; Anders et al. 2014; 2019). Major eruptive units include Arbon Valley Tuff A (10.41 ± 0.01 Ma), Arbon Valley Tuff B (10.22 ± 0.01 Ma), the Tuff of Little Chokecherry Canyon (9.46 ± 0.01 Ma), the Tuff of Kyle Canyon (9.28 ± 0.01 Ma), the Tuff of the Lost River Sinks (8.87 ± 0.16 Ma), and the Tuff of American Falls (7.58 ± 0.01 Ma). The scale and frequency of eruptions at the Picabo EC appear to have declined following the eruption of the Arbon Valley Tuffs. Subsequent ignimbrites were lower in volume and do not outcrop both north and south of the plain (Anders et al. 2014). Surficial outcrops of the Tuff of Kyle Canyon have only been identified at Howe Point in the Lemhi Range (Kuntz et al. 1994; 2003) and in the Arco Hills to the west (Anders et al. 2014), suggesting it is the product of a relatively small eruption on the northern side of the plain.

Tuff of Kyle Canyon

After discovering that two compositional groups of obsidian were present at Howe Point, we first compared the new, non-Walcott group to other reference groups in our database. The group is compositionally distinct from all others of the SRP, but it has concentrations of compatible elements more consistent with obsidian source groups of the Twin Falls EC than the Heise EC, suggesting that it came from an older SRP ignimbrite. Geologic maps of the southern Lemhi range indicate that a few ignimbrites are present at Howe Point that predate the Heise EC: the Arbon Valley Tuff, the Tuff of the Lost River Sinks, and the Tuff of Kyle Canyon (Kuntz et al., 1994, 2003). Sampling locations for the new group were within a drainage partially mapped as the Tuff of Kyle Canyon. To our knowledge, major and trace element data for the Tuff of Kyle Canyon have not been previously reported. We confirmed that this was the source of the new compositional group by testing an additional 16 samples of obsidian collected directly from a ridgeline outcrop identified as the Tuff of Kyle Canyon in a large-scale geologic map (Kuntz et al., 2003).

Compared to source groups of the Heise EC, Tuff of Kyle Canyon obsidian has high concentrations of compatible elements such as FeO, MnO, TiO_2, Zr, and Sr, perhaps reflecting a greater mid-crustal component in its source magma (Drew et al. 2013). Its composition overlaps that of the McMullen Creek and Steer Basin Tuffs on many elements, but it can be separated from the Twin Falls EC groups through bivariate comparisons of FeO, MnO, and TiO_2. Tuff of Kyle Canyon obsidian does not group with or fall on a compositional gradient with Picabo Tuff obsidian, supporting the proposition that the two are derived from separate eruptive cycles (Anders et al. 2014; 2019). Obsidian from the Tuff of Kyle Canyon is the sole group derived from the Picabo EC in our reference database.

The Tuff of Kyle Canyon (9.28 ± 0.01 Ma) is a dark red to purplish brown, densely welded, crystal-poor ashflow tuff composed of two cooling units: a lower, meter-thick ashfall unit with a thin basal vitrophyre, and a 50-meter-thick devitrified upper unit of platy welded tuff (Kuntz et al. 1994; 2003; Anders et al. 2014; 2019). Known exposures are confined to outcrops on the northern edge of the plain in the Arco Hills and in Kyle Canyon at the southern tip of the Lemhi Range (Anders et al. 2019). At present, it has not been correlated with other ignimbrites of the region. Anders et al. (2014, 2019) observe that the Tuff of Kyle Canyon is about the same age as the Idavada "oldest" ignimbrite of the Lake Hills (9.22 ± 0.18 Ma) (Michalek 2009), but they may differ mineralogically (Anders et al. 2014, 2895; 2019, 15). If obsidian occurs in association with the Lake Hills ignimbrites, further investigation would be needed to evaluate the hypothesis that the two are related. There is no indication that the Tuff of Kyle Canyon correlates to any ignimbrite south of the plain.

The Tuff of Kyle Canyon is a poor source of tool-stone compared to nearby exposures of the Walcott Tuff. Visits to most outcrops mapped as the Tuff of Kyle Canyon near Howe Point (Kuntz et al. 2003) failed to yield any obsidian, but it is available in a few abundant but localized deposits of small (4-8 cm) black and red pyroclasts on the upper surface of the tuff. Some pyroclasts have eroded into nearby drainages where they co-occur with secondary deposits of Walcott Tuff obsidian, which is also present in both red and black varieties at Howe Point. Apart from average clast size, the two source groups are visually indistinguishable. Tuff of Kyle Canyon obsidian may have been procured on occasion, however inadvertently, by visitors to the much richer deposits of Walcott Tuff obsidian available nearby.

The Heise eruptive center

The Heise EC produced at least five geochemically distinct obsidian source groups of varying quality, abundance, and spatial extent. Three groups are associated with geographically extensive ignimbrites that outcrop discontinuously on the periphery of the plain: the Walcott Tuff, the Conant Creek Tuff, and the Kilgore Tuff. Obsidian of the Walcott Tuff corresponds to the "American Falls" and "Snake River" source groups (Holmer 1997, tbl. 4; Arkush and Hughes 2018), as discussed above. Secondary deposits of obsidian found in Conant Creek and at Grassy Lake, WY are likewise known to derive from the Conant Creek Tuff, which outcrops on the north and western slopes of the Teton Range (MacDonald, Horton, and Surovell 2019). But the most widespread, abundant, and compositionally variable group is from the Kilgore Tuff. This group has been previously identified under several other names in the archaeological literature, including "Packsaddle" and "Deadhorse Ridge" (Bailey 1992; James, Bailey, and D'Auria 1996; Holmer 1997; Skinner 2011b). Two Heise EC source groups are from more localized deposits derived from smaller-scale eruptive events. The heavily utilized "Bear Gulch" source group is found along West Camas Creek in the Centennial Range near the Montana border (G. A. Wright, Chaya, and McDonald 1990; Bailey 1992; Willingham 1995; James, Bailey, and D'Auria 1996; Holmer 1997; Raley 2011; Skinner 2011b). The "Kelly Canyon" source group is from the Kelly Canyon Rhyolite, an intrusive dome outcropping at the base of the Kelly Canyon ski resort in the Heise Hills (Phillips et al. 2016).

The Heise EC (6.6 – 4.6 Ma) is the sixth and final rhyolitic volcanic field preceding the Yellowstone EC (2.0 -0.6 Ma) along the Yellowstone hotspot track (L. A. Morgan and McIntosh 2005; Pierce and Morgan 2009; Anders et al. 2014). At the onset of the Pliocene Epoch, the Yellowstone mantle plume began to encounter thicker (>35 km) crust of the Archaean craton below what is now the ESRP (S. S. Hughes and McCurry 2002). Silicic magmas continued to form at the crust/mantle boundary, but then slowly rose to the upper crust where they coalesced in relatively shallow reservoirs, resulting in the formation of an uplifted caldera plateau analogous to present-day Yellowstone (L. A. Morgan, Doherty, and Leeman 1984; Pierce and Morgan 1992; S. S. Hughes and McCurry 2002; L. A. Morgan and McIntosh 2005). This transition away from the deeply sourced, higher-temperature (950-1050º C) fissure eruptions of the CSRP-VP to lower-temperature (850-950º C) caldera eruptions from shallow reservoirs yielded ignimbrites that are both more compositionally diverse and evolved than those of the CSRP-VP (S. S. Hughes and McCurry 2002; Ellis et al. 2017). A few factors could account for these changes in composition: (a) greater magmatic contributions from the continental craton; (b) cooling and crystal fractionation accompanying the ascent of magma bodies through the crust; and (c) near-surface recycling of buried ignimbrites from previous eruptions (S. S. Hughes and McCurry 2002; Bindeman et al. 2007; Ellis et al. 2017; Jean et al. 2018). The net effect of these complex melt histories is that ignimbrites (and obsidians) of the Heise EC are more compositionally distinct from one another and those of other earlier eruptive centers of the SRP-VP, despite broad similarities in magmatic origin.

In the wake of the Yellowstone hotspot, subsidence of the Heise calderas and secondary mafic volcanism resulted in the burial of intra-caldera deposits beneath up to two kilometers of Quaternary basalt and alluvium. Our knowledge of the Heise eruptive sequence is thus drawn from a combination of borehole data (Anders et al. 2014; Ellis et al. 2017; Jean et al. 2018) and outflow deposits that remain exposed on the margins of the plain (L. A. Morgan, Doherty, and Leeman 1984; Pierce and Morgan 1992; 2009; L. A. Morgan and McIntosh 2005). Efforts to correlate these deposits across the plain began somewhat earlier than comparable studies of ignimbrites of the CSRP (Embree, McBroome, and Doherty 1982; Hackett and Morgan 1988; L. A. Morgan 1988; 1992; L. A. Morgan and McIntosh 2005). As a result, the timing,

Table 6: Major and trace-element composition of obsidian source groups from the Eastern Snake River Plain Volcanic Province.

Element		**Picabo Tuff** (n = 32) x̄	± 1s	**Walcott Tuff** (n = 29) x̄	± 1s	**Conant Creek Tuff** (n = 256) x̄	± 1s	**Kelly Canyon Rhyolite** (n = 30) x̄	± 1s	**Kilgore Tuff** (n = 175) x̄	± 1s	**Bear Gulch** n = (27) x̄	± 1s
K_2O	%	5.41	0.24	5.19	0.23	4.99	0.24	5.10	0.21	5.25	0.21	5.60	0.16
CaO	%	0.88	0.07	0.49	0.05	0.59	0.08	0.58	0.02	0.54	0.05	0.68	0.03
TiO_2	%	0.38	0.02	0.22	0.01	0.13	0.01	0.16	0.01	0.22	0.02	0.27	0.01
MnO	%	0.08	0.00	0.05	0.00	0.04	0.00	0.05	0.00	0.05	0.00	0.05	0.00
FeO	%	2.11	0.12	1.13	0.06	1.24	0.07	1.46	0.06	1.53	0.12	1.44	0.05
V*	ppm	110	6	86	5	64	4	81	5	89	9	73	5
Cr*	ppm	60	6	48	6	51	7	60	6	54	7	45	6
Zn	ppm	67	6	55	7	74	7	87	6	61	6	51	6
Rb	ppm	171	6	177	6	168	7	166	6	168	6	168	4
Sr	ppm	51	9	22	6	17	7	15	6	17	6	41	10
Y	ppm	62	9	54	10	66	10	73	8	57	11	39	10
Zr	ppm	493	40	215	21	177	17	243	20	306	40	281	21
Nb	ppm	51	8	47	6	58	8	62	7	53	8	56	10
Ba	ppm	1132	65	948	61	597	40	777	54	913	88	728	59
Pb*	ppm	27	3	26	3	27	4	24	3	26	3	24	3
Alternate source names		**Picabo Hills**		American Falls Snake River **Walcott**		Buggy Springs **Conant Creek**		**Kelly Canyon**		Argument Ridge Bear Gulch B Deadhorse Ridge **Packsaddle** Packsaddle Creek		Big Table Mountain Camas Dry Creek Centennial FMY 90 West Camas Creek	
Potential correlate tuffs		Picabo Tuff B (TH)		Blue Creek Tuff (HP)		Elkhorn Spr. (HH) Wolverine Cr. (BF)				Tuff of Heise (HH) Tuff of Spencer (CM)		Rhyolite of Seel Creek? (CM)	
*Factory calibrated		TH = Timmerman Hills; PR = Pioneer Range; HP = Howe Point; ML = Medicine Lodge; CR = Centennial Range; TR = Teton Range; BH = Big Hole Range; HH = Heise Hills; BF = Blackfoot Range; AF = American Falls											

eruptive volume, and surficial extent of major units in the Heise eruptive sequence are somewhat better understood[d].

[d] Surficial exposures of Heise EC ignimbrites have been mapped in several areas around the ESRP, including along the Snake River below American Falls (Stearns and Isotoff 1956; Trimble and Carr 1961a; 1961b; Carr and Trimble 1976), the Fort Hall Reservation (Hladkey et al. 1992; Link and Stanford 1999), the Blackfoot Hills east of Idaho Falls (Mansfield, Lang, and Merit 1952; Phillips and Welhan 2013; Phillips, Moore, and Feeney 2016), the Heise escarpment (Phillips et al. 2016), the Big Hole

The first major ignimbrite of the Heise EC is the Blacktail Creek Tuff (6.62 ± 0.03 Ma), followed by the Walcott Tuff (6.27 ± 0.04), the Conant Creek Tuff (5.51 ± 0.13), and the Kilgore Tuff (4.45 ± 0.05 Ma) (L. A. Morgan and McIntosh 2005). The Blacktail Creek Tuff was among the most voluminous of the Heise eruptions, but it is less exposed than later units. The Walcott Tuff outcrops on the western side of the Heise EC both north and south of the plain. The Conant Creek Tuff outcrops on the eastern margin of the plain below the Teton Range. It has been geochemically correlated with the Tuff of Elkhorn Springs and the Tuff of Wolverine Creek, also on east side of the plain. Overlying these units, the Kilgore Tuff is the most recent and best exposed among ignimbrites of the Heise EC, outcropping throughout the hills and mountains around the eastern plain. Between major eruptions, smaller volume events associated with caldera uplift and subsidence produced more localized rhyolite tuffs, lava flows, and intrusive domes on caldera margins (L. A. Morgan and McIntosh 2005; Watts, Bindeman, and Schmitt 2011; Ellis et al. 2017). Relevant examples include the Rhyolite of Kelly Canyon (Phillips et al. 2016) and the undescribed obsidian-bearing tuff at Bear Gulch (C. J. Benson 1986; Lane et al. 2019). At the center of Heise EC, caldera fill deposits are exposed at a resurgent dome at Juniper Buttes (Kuntz, 1979; Bindeman et al., 2007; Watts, Bindeman, & Schmitt, 2011).

Five obsidian source groups defined in this study may be attributed to the Heise EC based on geochemical similarity to ignimbrite glass compositions reported by Ellis et al. (2017) and spatial association of sampling locations with mapped geologic units. Three of the source groups may be attributed to major ignimbrites of the Heise eruptive sequence. The other two are associated with exposures of far less extensive tuffs and rhyolite lavas that erupted between larger events. As a group, ignimbrites of the Heise EC are lower in FeO, MnO, TiO_2, and CaO than those of the CSRP-VP (Figure 8; Tables 5 and 6), reflecting the trend toward more evolved compositions among Pliocene ignimbrites of the ESRP-VP (S. S. Hughes and McCurry 2002; Ellis et al. 2017). Obsidian of the Kilgore Tuff exhibits the widest range of compositional variability and is intermediate in composition compared to other source groups of the Heise EC. Walcott Tuff obsidian is within the Kilgore Tuff's range of variation for most elements, but it is more homogenous and lower in Fe2O3, CaO, and Rb. Obsidian of the Conant Creek Tuff exhibits slightly higher concentrations of CaO and Y, and lower concentrations of TiO_2, MnO, and Ba. The Tuff of Wolverine Creek is compositionally indistinguishable from the Conant Creek Tuff (Ellis et al. 2017), but the unit does not appear to bear clasts of obsidian larger than one cm in diameter. Comparative geochemical data are unavailable for the "Bear Gulch" or Rhyolite of Kelly Canyon obsidian source groups. These are attributed to the Heise EC based on spatial association with mapped geologic units (Witkind 1982; Phillips et al. 2016), and compositional affinity with glass compositions reported for major ignimbrites of the Heise EC (Ellis et al. 2017). "Bear Gulch" is a highly utilized but localized source of obsidian underlying the Kilgore Tuff in the Centennial Range. It is higher CaO, TiO_2 and Sr than other source groups of the Heise EC. The Rhyolite of Kelly Canyon is a small, poorly utilized source of obsidian underlying the Conant Creek Tuff. It is similar to the Conant Creek Tuff, but less evolved in composition (higher MnO, FeO, and TiO_2). Obsidian associated with the Rhyolite of Juniper Buttes is higher in Rb and lower in MnO, FeO and Zn.

Walcott Tuff

The Walcott Tuff (6.27 ± 0.01) was first described along the Snake River between American Falls and the Lake Walcott reservoir near the southern margin of the SRP (Stearns and Isotoff 1956; Carr and Trimble 1961; Anders et al. 2014). It has since been recognized as the second major, regionally extensive rhyolitic ignimbrite of the Heise eruptive sequence (L. A. Morgan 1992; L. A. Morgan and McIntosh 2005; Anders

Range (Price 2009; Price and Rodgers 2009; Phillips, Garwood, and Embree 2013), the western Teton Range (Richmond 1973; Christiansen and Love 1978), the Centennial Mountains (Rember and Bennett 1979; Witkind 1982), the Beaverhead Range and Medicine Lodge area (Skipp, Protska, and Schleicher 1979; Hodges 2006), the Lemhi Range (Kuntz et al. 1994; 2003), and the Pioneer Range (Kuntz and Kork 1978; Skipp, Kuntz, and Morgan 1990; Skipp et al. 2009). Composite regional geologic maps of the eastern plain have been prepared by Scott (1982) and Lewis et al. (2012).

et al. 2014) and the geologic source of the “American Falls” and “Snake River” obsidian source groups (R. E. Hughes and Pavesic 2005; R. E. Hughes 2007b; Arkush and Hughes 2018).

Two depositional members of the Walcott Tuff are recognized in the American Falls area. The lower member is a three-meter-thick precursor deposit of unwelded, finely bedded, white to light gray pumice and ash. The upper member is a five-meter-thick, densely welded ashflow tuff that grades upward from a glassy but spherulitic black vitrophyre to a purple-gray, devitrified, lithophysal tuff capped by an incipiently welded, brick-red upper vitrophyre (Stearns and Isotoff 1956; Carr and Trimble 1961). Between the American Falls dam and the Lake Walcott reservoir, the Snake River runs west for several miles along the contact between the upper surface of the Walcott Tuff and overlying strata of Pleistocene basalt (Stearns and Isotoff 1956). The sole exposure of Walcott Tuff on the northern bank of the river is immediately below the American Falls dam, where an abundance of large spherulites (up to 3 cm in diameter) and a “subconchoidal” fracture pattern (Trimble and Carr 1961b) render the basal vitrophyre insufficiently glassy to serve as a true toolstone. The most abundant source of tool-quality Walcott obsidian is at Ferry Hollow, a deep draw two km downstream from the dam on the southern bank of the Snake River. Here, obsidian occurs in clasts the size of typewriters (~ 30 cm) eroding from the basal vitrophyre, and as smaller clasts (5 – 15 cm) in a meter-thick breccia deposit overlying the upper vitrophyre. Downstream from Ferry Hollow, 5 – 10 cm water-worn clasts of obsidian can be found on either bank of the river for about 15 km. Most are found among gravel bars deposited by the Bonneville Flood (17.4 ka) several meters above the present river channel (Trimble and Carr 1961b; Janecke and Oaks 2011a; 2011b).

The Walcott Tuff outcrops in several other exposures along the southern margin of the plain between American Falls and the Blackfoot Hills on the Fort Hall Reservation (Trimble and Carr 1961a; Carr and Trimble 1976; Hladkey et al. 1992). North of the plain, it has been correlated with the Blue Creek Tuff (Skipp, Protska, and Schleicher 1979; Embree, McBroome, and Doherty 1982) based on isotopic age, trace-element geochemistry, paleomagnetic orientation, and stratigraphic position (Morgan, 1988, 1992; Morgan & McIntosh, 2005; Anders et al., 2014). The most accessible exposure of Walcott Tuff north of the plain is at Howe Point on the southern tip of the Lemhi Range, overlooking the Lost River Sinks (Kuntz et al., 1994, 2003). Other exposures have been mapped in the southern Pioneer Mountains to the west (Skipp et al. 2009) and in the Medicine Lodge area to the east (Skipp, Protska, and Schleicher 1979). All exposures of the Walcott Tuff are interpreted as outflow deposits from the edge of a now-collapsed caldera underlying later basalts and alluvium of the ESRP (Embree, McBroome, & Doherty, 1982; Hackett & Morgan, 1988; Morgan & McIntosh, 2005).

Tool-quality obsidian is not universally present in association with the Walcott Tuff. Outside of the American Falls area, exposures of the Walcott Tuff on the southern margin of the plain visited for this study are insufficiently glassy or are limited to the more densely spherulitic or lithophysal horizons. Further fieldwork is needed to determine whether tool-quality obsidian is present in association with outcrops of the Walcott Tuff mapped on the Fort Hall Reservation (Carr and Trimble 1976; Hladkey et al. 1992; Link and Stanford 1999). North of the plain, we collected tool-quality obsidian from exposures of the Walcott Tuff in the Pioneer Range west of Arco, at Howe Point, and near Deep Creek in the Medicine Lodge area. At Howe Point, black and red pyroclasts of obsidian 10 to 15 cm in diameter occur near the contact between the upper and lower members of the tuff. In the southern Pioneer Range and along Deep Creek obsidian occurs in sparse to dense lenses of black pyroclasts 10 to 15 cm in diameter. Walcott Tuff obsidian at Howe Point has been previously sampled by GRL and ISU (Black 2015; Arkush and Hughes 2018). The exposure near Deep Creek in the Medicine Lodge area has been previously sampled by GRL, ISU, SFU (Bailey 1992; Black 2015; Arkush and Hughes 2018). SFU, ISU, GRL, and NWROSL have all reported obsidian source locales in the American Falls area (Bailey 1992; James, Bailey, and D’Auria 1996; Skinner 2011b; Black 2015; Arkush and Hughes 2018). Walcott Tuff obsidian found on the northern margin of the plain is compositionally indistinguishable from obsidian from the American Falls area, but the red variety of Walcott obsidian does not appear to occur south of the plain. At all locations, fractured surfaces of Walcott Tuff obsidian are sub-glassy with white phenocrysts of feldspar and gray spherulites up to one millimeter in diameter.

Conant Creek Tuff

Apart from the Walcott Tuff, the Conant Creek Tuff is the only major, regionally extensive ignimbrite that has been previously recognized as a source of obsidian from the ESRP-VP (Park 2010; MacDonald, Horton, and Surovell 2019). Obsidian of the Conant Creek Tuff is comparable in quality, workability, and appearance to that of the Walcott Tuff. Fractured surfaces reveal a sub-glassy, almost matte texture with sparse phenocrysts of feldspar typical of SRP-VP source groups classified as “ignimbrites” by past Idaho archaeologists. In contrast to the Walcott Tuff however, past archaeological provenance studies suggest that the Conant Creek Tuff was all but ignored as a source of toolstone throughout the Precontact Period (Holmer 1997; Plager 2001; Marler 2009; Scheiber and Finley 2011; Fowler 2014).

The Conant Creek Tuff (5.51 ± 0.07 Ma) was first described and mapped by Christiansen and Love (1978) on the northern flanks of the Teton Range in western Wyoming (40Ar/39Ar date from Morgan & McIntosh, 2005). Type and reference sections suggest a cooling unit composed of four horizons typical of ESRP-VP ignimbrites : (1) a thin (0.5 m), nonwelded, white, massive to crudely bedded ashflow tuff; grading into (2) an incipiently welded, glassy, friable ashflow tuff (1 m); overlain by (3) a black, densely welded, obsidian vitrophyre that breaks into conspicuous vertical columns and “conchoidally fractured blocks as much as 60 cm in diameter” (1-2 m); grading into (4) a thicker (10 - 120 m) lithoidal horizon of brown to pink-gray, densely welded, devitrified tuff with abundant 1 - 5 mm spherical lithophysae.

The Conant Creek Tuff is the product of a relatively low-volume eruption that occurred near the eastern margin of the upper SRP. It was originally thought to outcrop both at the headwaters of Conant and Boone Creeks on the western side of the Teton range, and at Signal Mountain and Pilgrim Mountain east of the Tetons near Jackson Hole, WY (Christiansen et al. 1978; Christiansen and Love 1978). More recent investigations have revealed that (1) ignimbrite outcrops that were thought to represent the Conant Creek Tuff east of the Tetons are in fact distal outflow deposits of the Kilgore Tuff (4.X Ma) (Morgan, 1992; Morgan & McIntosh, 2005); and (2) that the Conant Creek Tuff may correlate with both the Tuff of Elkhorn Springs and the Wolverine Creek Tuff on the eastern margin of the SRP to the south (L. A. Morgan and McIntosh 2005; Bindeman et al. 2007; Szymanowski et al. 2015; 2016). The Tuff of Elkhorn Springs (5.48 ± 0.07 Ma) is a densely welded ashflow tuff that outcrops below the Kilgore Tuff at the Heise Cliffs west of the Big Hole Range; it is correlated with the Conant Creek Tuff based on similarities in 40Ar/39Ar age, magnetic polarity, and geochemical composition (Morgan, 1992; Morgan & McIntosh, 2005). The Wolverine Creek Tuff (5.59 ± 0.05 Ma) is a thick (16 - 60 m), unwelded, finely bedded airfall tuff exposed in pumice quarries in the foothills east of Idaho Falls (Morgan & McIntosh, 2005; Phillips & Welhan, 2013; Phillips, Moore, & Feeney, 2016). It stratigraphically underlies the Elkhorn Springs exposure of the Conant Creek Tuff at the Heise Cliffs but is of similar age and identical in geochemical composition, suggesting a common magmatic origin (Szymanowski et al. 2015; 2016; Phillips et al. 2016). Sparse, gravel-sized (< 1 cm) clasts of obsidian are common among bedded deposits of the Wolverine Creek Tuff (Szymanowski et al. 2015; Phillips et al. 2016; Phillips, Moore, and Feeney 2016), but these are of insufficient size to serve as toolstone.

The principal sampling location of Conant Creek Tuff obsidian represented in the CRMO reference collection is at Buggy Springs along Conant Creek, immediately west of the Idaho/Wyoming border. Along Conant Creek, obsidian is present among gravels in the streambed as occasional well-rounded cobbles five to seven cm in diameter. The Buggy Springs locale was previously sampled by SFU and ISU (Bailey 1992; Black 2015). Deposits of Conant Creek Tuff obsidian have also been reported by GRL at Grassy Lake to the north between Yellowstone and Teton National Parks (MacDonald, Horton, and

Surovell 2019). Both locations represent secondary deposits of obsidian eroded from exposures of the Conant Creek Tuff outcropping along streams of the northern Teton range at elevations of 7,000 to 8,500 feet (Christiansen et al. 1978). In addition to this locale, a few small clasts of obsidian matching the Conant Creek Tuff source group were found among obsidian of the Kilgore Tuff in a steep mountain drainage north of Reas Pass in the Centennial Range, near the Idaho/Montana/Wyoming border. Further fieldwork is needed to characterize the extent of primary obsidian deposits associated with the Conant Creek Tuff in the Teton Range, the eastern Centennial Range, and the Big Hole Mountains.

Kelly Canyon Rhyolite

Between major ignimbrite-forming eruptions of the Heise eruptive sequence, smaller-scale eruptions of rhyolitic lavas and tuffs occurred in association with episodes of tectonic subsidence near caldera margins (Morgan & McIntosh, 2005). In general, these units are not as well-mapped or described as the more extensive ignimbrites, but named examples include the Rhyolite of Hawley Spring (7.5 ± 0.04 Ma), the Rhyolite of Lidy Hot Springs (6.2 ± 0.05 Ma), the Rhyolite of Kelly Canyon (5.7 ± 0.1 Ma), and the Rhyolite of Sheridan Reservoir (4.0 ± 0.4 Ma) (Morgan & McIntosh, 2005). The Rhyolite of Kelly Canyon is one of the only minor rhyolites of the Heise EC known to bear substantial deposits of tool quality obsidian.

The Rhyolite of Kelly Canyon outcrops exclusively in the Heise Hills north of the South Fork of the Snake River. It is stratigraphically overlain by the Wolverine Creek Tuff and underlain by the Blacktail Creek Tuff (Phillips et al. 2016). Morgan and McIntosh (2005) argue that it is the product of a precursor eruption that occurred near the boundary of the Conant Creek Tuff caldera. While fairly localized compared to major ignimbrites of the SRP-VP, the Rhyolite of Kelly Canyon forms cliffs up to 300 m thick in the Heise area (Phillips et al. 2016). Most exposures are brown, crystal-poor, devitrified and massive, with incipient flow-banding and closely-spaced joints, but a few outcrops are dominated by gray perlite with remnant marekanites of black and orange obsidian (Phillips et al. 2016).

The most accessible exposure of Kelly Canyon obsidian is a prominent roadcut at the base of the Kelly Canyon Ski Resort. This locale served as the source of Kelly Canyon reference material in the CRMO database, as well as previous reference collections reported by SFU and ISU (Bailey 1992; James, Bailey, and D'Auria 1996; Black 2015). Compared to other obsidian source groups of the SRP-VP, Kelly Canyon obsidian is exceptionally glassy, but clasts larger than five cm in diameter are rare and it tends to yield an abundance of fine slivers upon fracture that can detract from its workability. Very few artifacts have been attributed to this source group in previous archaeological provenance studies in the region (Plager 2001; Marler 2009; Scheiber and Finley 2011; Fowler 2014).

Kilgore Tuff

The Kilgore Tuff is the most recent (4.45 ± 0.05 Ma) and voluminous (1,800 km3) of the major ignimbrites of the Heise EC (Morgan & McIntosh, 2005; Bindeman et al., 2007; Watts, Bindeman, & Schmitt, 2011). It is also the most abundant and extensive obsidian source group of the SRP-VP. Nearly 30 individual source locales of Kilgore Tuff obsidian are represented in the CRMO reference collection, and these represent a small fraction of locales where it outcrops on the landscape. Yet like the Conant Creek Tuff, past archaeological provenance research conducted in southern Idaho has shown that this group was rarely utilized as a source of toolstone (Holmer 1997; Plager 2001; Marler 2009; Scheiber and Finley 2011; Fowler 2014).

Surface exposures of the Kilgore Tuff vary greatly in thickness, morphology, and geochemical composition (Hackett & Morgan, 1988; Morgan, 1988; Morgan & McIntosh, 2005). On the southern margin of the plain, exposures range from 11 to 30 m thick, and form compound cooling units composed of alternating zones of massive to platy devitrified tuff and well-developed lithophysal horizons. On the northern margin of the plain, exposures form simple cooling units of devitrified platy or well-developed lithophysal horizons that range from four m thick in the Lemhi Range to 120 m thick in the Centennial Range north of Kilgore. On both margins of the plain, the base of the tuff consists of a thin, incipiently welded co-ignimbritic ash that grades upward into a basal vitrophyre of densely welded black to red vitric shards (L. A. Morgan 1988; L. A. Morgan, Doherty, and Leeman 1984). In some locales, the basal vitrophyre manifests as a lens of glassy black pyroclasts 10 to 30 cm in diameter underlying the upper devitrified or lithoidal horizons.

As the most recent large-volume ignimbrite of the Heise eruptive sequence, the Kilgore Tuff is well exposed throughout the hills on the margins of the ESRP. Early work by Morgan (1988) demonstrated that it correlates with the former Tuff of Spencer in the Centennial Mountains (Skipp, Protska, and Schleicher 1979), and with the former Tuff of Heise in the Heise Hills (Embree, McBroome, and Doherty 1982), based on paleo-magnetometry, 40Ar/39Ar geochronology, and geochemistry. Surficial outcrops of the Kilgore Tuff have been mapped or documented in the southern Lemhi Range (Kuntz et al., 1994), in the Centennial Mountains from the Medicine Lodge area to Reas Pass (Skipp, Protska, and Schleicher 1979; Skipp, Kuntz, and Morgan 1990), on the flanks of the Teton Range (Morgan, 1992), at the Heise Hills and the Big Hole Range (Phillips, Garwood, and Embree 2013; Phillips et al. 2016), in the Caribou Mountains near Palisades Reservoir (Embree, McBroome, and Doherty 1982), and in the Blackfoot Range east of Idaho Falls (Phillips and Welhan 2013; Phillips, Moore, and Feeney 2016). Exposures of the Kilgore Tuff in the center of the ESRP at Juniper Buttes suggest that this area represents a resurgent dome of the Kilgore Caldera (Kuntz 1979; L. A. Morgan and McIntosh 2005).

Morgan and McIntosh (2005) argue that the Kilgore Tuff erupted from at least three vent source areas: two on the northern margin of the plain near Lidy Hot Springs and Spencer/Kilgore; and one on the southern margin of the plain near Heise. Evidence for this interpretation includes abrupt lateral changes in ignimbrite thickness and the size of lithic clasts, magnetic fabric analyses, and local Bouguer gravity lows (Morgan, 1988; Morgan & McIntosh, 2005). Low δ18O and diverse U-Pb zircon ages suggest the Kilgore Tuff formed in part through remelting of hydrothermally altered intracaldera deposits of earlier ignimbrites of the Heise EC (Bindeman et al. 2007; Watts, Bindeman, and Schmitt 2011; Drew et al. 2013). These complex mechanisms of magma formation, eruption, and emplacement may also explain the high variability in geochemical composition of Kilgore Tuff obsidian relative to other source groups of the ESRP-VP (Figure 8; Table 6).

Most exposures of the Kilgore Tuff are underlain by a meter-thick black basal vitrophyre, but in some areas, this is condensed to a thin horizon of black, glassy pyroclasts (e.g., Henry Creek, Bonneville County, ID). In other areas (e.g. Bone Road, Bonneville County, ID) obsidian occurs as float among ashy sediments in the absence of an overlying lithoidal zone. Pyroclasts are typically subangular to subrounded with minimal cortex development and range in size between locales from less than 10 cm to over 30 cm in diameter on average. Fractured surfaces are comparable in appearance to Walcott Tuff obsidian, but with a higher quantity of phenocrysts and fewer spherulites. It is generally black, but a pale gray variety outcrops at least two locales in the Big Hole Mountains (Moody Swamp and Radio Relay Ridge). A majority of Kilgore Tuff obsidian source locales represented in the CRMO reference collection have been previously reported by SFU and/or ISU (Bailey 1992; James, Bailey, and D'Auria 1996; Black 2015). Efforts to relocate NWROSL's sampling location at Deadhorse Ridge in the Caribou Range were unsuccessful, despite multiple attempts. All other sampling locations in the Caribou Range yielded obsidian corresponding to the Kilgore Tuff group. Most exposures of Kilgore Tuff obsidian in the Centennial, Big Hole and Caribou ranges occur at higher elevations (6500' to 8500'), but it also outcrops at lower elevations (5000' - 5500') in the hills east of Idaho Falls.

Bear Gulch

"Bear Gulch" is perhaps the most well-utilized and widely traded obsidian source group of the ESRP-VP. The group was first identified by researchers at the Field Museum through geochemical analysis of obsidian artifacts interred as grave goods at Hopewell sites in the upper Midwest (Griffin, Gordus, and Wright 1969; Hatch et al. 1990; R. E. Hughes 1992). The source of these artifacts was not initially known, but their compositional similarity to material from Obsidian Cliff, WY led Field Museum archaeologists to suspect an origin near Yellowstone NP. For this reason, the group was known simply as "FMY-90". Other names for the group came to include "Big Table Mountain," "Centennial," "West Camas Creek," "Camas Dry Creek," and "Bear Gulch" (among others) after the source area was identified in the late 1970s (Holmer, 1997: Table 4). While the group bears a clear compositional affinity to other obsidian source groups of the Heise EC and ESRP-VP (Figure 8; Table 6), the geologic context of the source area is poorly understood.

In contrast to other major source groups of the Heise EC, deposits of Bear Gulch obsidian are limited to a relatively small (28 km^2), contiguous area northeast of West Camas Creek in the Centennial Mountains near Kilgore, ID (Sims 1979; Willingham 1995; Raley 2011). Deposits of abundant subangular to subrounded pyroclasts of obsidian 15 to 30 cm in diameter occur throughout Bear Gulch and among the alluvium of upper West Camas Creek. Pyroclasts are composed of densely sintered fragments of black vitric ash, yielding a distinctly matte to sub-glassy but uniform fractured surface that, in contrast to other Heise EC source groups, is entirely free of spherulites and phenocrysts. SFU, ISU, NWROSL, and GRL have all reported sampling locations of Bear Gulch obsidian along West Camas Creek north of Kilgore (James, Bailey, and D'Auria 1996; R. E. Hughes 2007b; Skinner 2011b; Black 2015).

Unfortunately, the geology of the Centennial Mountains has received little attention compared to other areas of southern Idaho, and the eruptive unit that Bear Gulch obsidian is derived from has not been formally described or mapped by geologists. Preliminary surficial geology maps are available for the portions of the Centennial Range to the east (Witkind 1982) and for the Medicine Lodge area to the west (Skipp, Protska, and Schleicher 1979), but these are over 40 years old and do not encompass the West Camas Creek area north of Kilgore. Morgan et al. (1984) reported a series of localized rhyolite flows in the Kilgore area, but these are not mapped or described in detail. The best available source of information on the geology of Bear Gulch comes from efforts to characterize the Kilgore gold prospect (C. J. Benson 1986; Lane et al. 2019), an area two km from Bear Gulch on the opposite (southwest) side of West Camas Creek. Data from these studies suggest that gold mineralization at the Kilgore prospect is related to hydrothermal alteration of a series of localized rhyolites associated with ring-fracture volcanism at the edge of the Kilgore caldera (C. J. Benson 1986; Lane et al. 2019). Whole-rock geochemical data reported for the Rhyolite of Steel Creek, an undated rhyolite dome underlying the Kilgore Tuff (C. J. Benson 1986, tbl. 1), is a relatively close match for Bear Gulch obsidian, but this association is tentative. Geologic maps and stratigraphic profiles prepared for the Kilgore Prospect area do not encompass or describe the rich obsidian deposits located northeast of West Camas Creek at Bear Gulch.

The prevalence of Bear Gulch obsidian in regional artifact assemblages (Holmer 1997; Plager 2001; Fowler 2014), evidence for long-distance trade of the material (Griffin, Gordus, and Wright 1969; Hatch et al. 1990; R. E. Hughes 1992; 2007a), and findings from archaeological surveys of the Centennial Mountains (Sims 1979; Willingham 1995; Raley 2011) underscore the importance of Bear Gulch as a lithic resource area. The compositional similarity of Bear Gulch obsidian to material of the Walcott and Kilgore Tuffs indicates that it is the product of the Heise EC, but current evidence suggests it is derived from a relatively localized rhyolite dome associated with ring-fracture volcanism near a source vent of the Kilgore caldera.

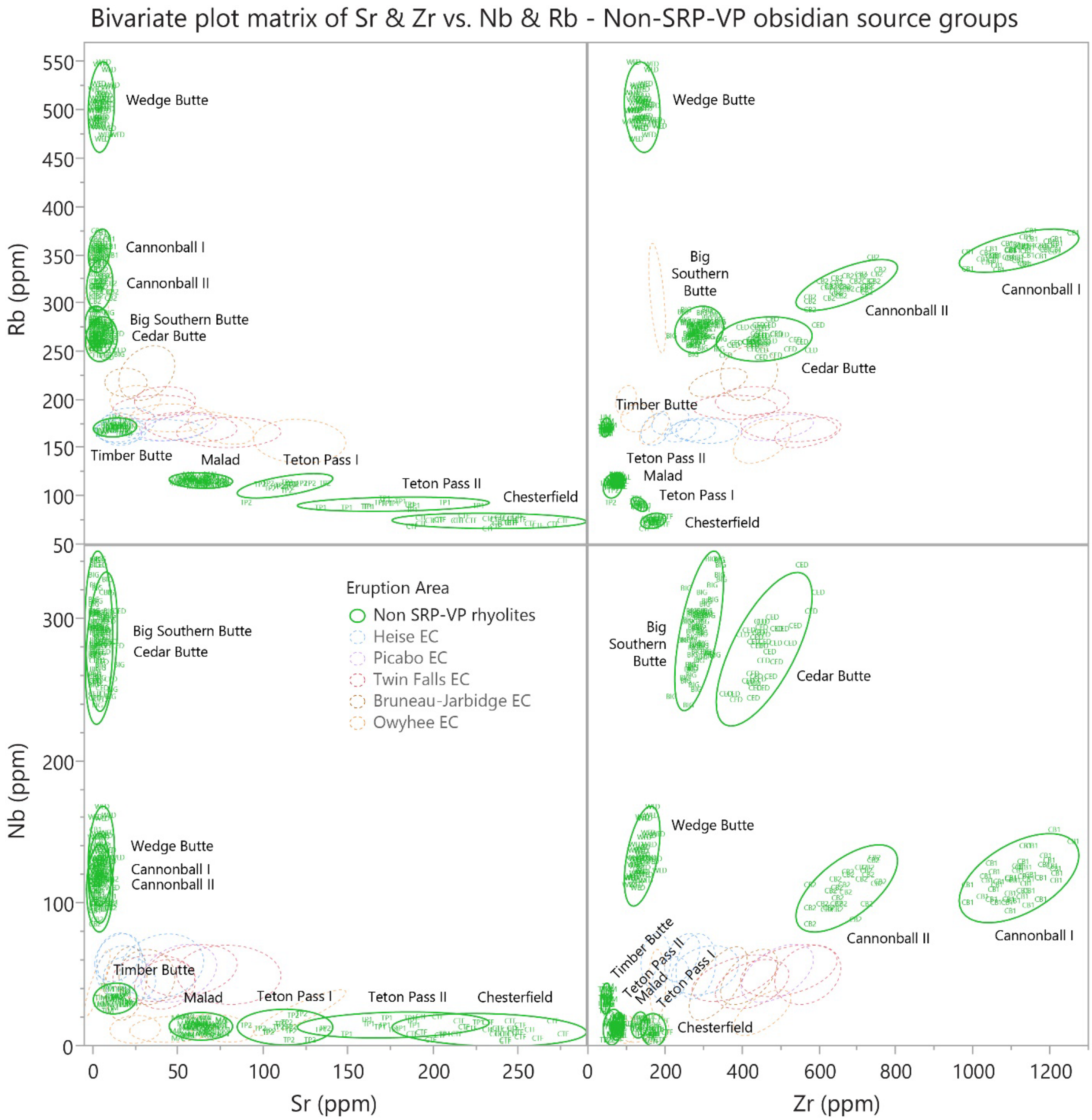

Figure 9: Bivariate plot matrix of Sr and Zr vs. Nb and Rb for Non-SRP-VP rhyolite domes and tuffs.

Non-SRP-VP rhyolite domes and tuffs

Several southern Idaho obsidian source areas are unrelated to the hotspot magmatism and rhyolitic super-eruptions of the SRP-VP. While some cover areas greater than 50 km^2, they are far more localized than those associated with major ignimbrites of the Twin Falls and Heise ECs. These include “Timber Butte,” “Cannonball Mountain,” “Wedge Butte,” “Big Southern Butte,” “Cedar Butte,” “Malad,” “Chesterfield” and “Teton Pass” (Figures 2, 5, and 7). Each of these source areas is the product of a discrete eruptive event with a unique geochemical signature. Multiple geochemical groups are present at both Cannonball Mountain and Teton Pass, but otherwise there is a clean correspondence between geochemical source groups and geographic source areas.

southern Idaho obsidian source groups unaffiliated with SRP-VP have seemingly little in common beyond the fact that they are not derived from the SRP-VP. Those that have been dated range in age from 14.5 Ma (Timber Butte) to 0.3 Ma (Big Southern Butte), with the older rhyolites to the west and younger rhyolites to the east (Armstrong, Leeman, and Malde 1975; Clemens and Wood 1991; Kuntz and Kork 1978). Some groups are from prominent rhyolite lava domes (e.g., Timber Butte and Big Southern Butte), while others are associated with rhyolite tuffs (e.g., Cannonball Mountain and perhaps Malad). And yet, geochemical differences between the groups are patterned geographically (Figure 6; Table 7). Obsidian source groups from younger rhyolite domes on the Snake River Plain (Big Southern Butte, Cedar Butte, and Wedge Butte) have high Rb:Sr ratios, high Nb, low to moderate Ti and Zr, and low Ba. By contrast, non-SRP-VP sources southeast of the plain (Malad, Chesterfield, and Teton Pass) have low Rb:Sr ratios, high Ba and Ti, and low Zr, Nb, and Y. North of the plain, Timber Butte obsidian has very low Sr, Y, Zr, Nb, and Ba, high Mn and moderately high Rb, while Cannonball Mountain obsidian has high Ti, Mn, Zn, Rb, and Zr, and low Sr and Ba.

Smaller rhyolite domes and tuffs of southern Idaho have received considerably less attention from geologists than the major ignimbrites of the SRP-VP (but see Leeman 1982b; McCurry et al. 1999, 2008, 2015; Spear and King 1982). In most cases however, the geologic context of the source is unambiguous – Big Southern Butte obsidian is from Big Southern Butte; Timber Butte obsidian is from Timber Butte, etc. We see little need to revise or revisit the source names for groups derived from localized, non-SRP-VP rhyolite domes, flows, or tuffs. Indeed, some have not been mapped or documented in any detail beyond that available in the archaeological literature (i.e. Chesterfield and Teton Pass). The following sections outline the location, extent, and relative composition of each of the non-SRP-VP obsidian source groups sampled in this study, with reference to available information on the silicic geology of each area.

Timber Butte

Timber Butte is located 65 km north of Boise, Idaho west of the Payette River near the town of Gardena and the western contact between the Idaho Batholith and the Columbia River Basalt Group. It is the oldest (14.5 +- 0.6 Ma) obsidian-bearing rhyolite dome in southern Idaho (Clemens and Wood 1991), and the most well-utilized source of obsidian in the western and central areas of the state (Holmer 1997; Plager 2001; Fowler 2014).

Timber Butte is an intrusive rhyolite dome formed through partial melting of the shallow granitic crust of the Idaho Batholith due to upwelling of the parental magma of the Columbia River Basalt Group (Clemens 1990; Clemens and Wood 1991). It has moderately high concentrations of K_2O, CaO, and Rb, high concentrations MnO, and low concentrations of FeO and TiO_2. Compared to obsidian source groups from other non-SRP-VP rhyolite domes and tuffs, it has distinctly low concentrations of Sr, Y, Nb, Zr, and Ba (Figure 9; Table 7). It is compositionally similar to the obsidian source groups of the Silver City Rhyolites and formed under similar conditions prior to formation of the western Snake River Plain and separation of the Owyhee uplands from the Boise Mountains around 11.5 - 8 Ma (Wood and Clemens 2002).

Table 7: Major and trace-element composition of obsidian source groups from Non-SRP-VP rhyolite domes and dikes.

		Timber Butte (n = 27)		Cannonball I (n = 49)		Cannonball II (n = 30)		Wedge Butte (n = 43)		Big Southern Butte (n = 77)	
		$\bar{x}$	± 1s	$\bar{x}$	± 1s	$\bar{x}$	± 1s	$\bar{x}$	± 1s	$\bar{x}$	± 1s
K_2O	%	4.12	0.10	5.19	0.21	5.50	0.32	4.61	0.27	4.78	0.41
CaO	%	0.65	0.02	0.25	0.02	0.24	0.02	0.55	0.04	0.45	0.05
TiO_2	%	0.02	0.00	0.16	0.01	0.26	0.01	0.02	0.01	0.07	0.02
MnO	%	0.11	0.00	0.08	0.00	0.12	0.00	0.05	0.00	0.05	0.00
FeO	%	0.49	0.02	3.06	0.09	4.25	0.18	1.13	0.06	1.54	0.09
V*	ppm	6	2	56	3	61	4	16	2	25	3
Cr*	ppm	4	4	84	7	90	10	26	5	39	7
Zn	ppm	53	3	209	11	236	14	124	9	239	14
Rb	ppm	171	4	354	9	319	11	503	19	272	10
Sr	ppm	13	5	4	3	4	3	5	3	4	3
Y	ppm	34	6	101	15	98	15	176	19	207	25
Zr	ppm	47	5	1120	64	672	53	142	21	289	26
Nb	ppm	33	4	117	13	110	12	133	14	292	23
Ba	ppm	112	33	90	30	101	36	96	27	108	45
Pb*	ppm	33	3	62	5	61	4	72	4	87	6

		Cedar Butte (n = 41)		Malad (n = 51)		Teton Pass I (n = 15)		Teton Pass II (n = 16)		Chesterfield (n = 30)	
		$\bar{x}$	± 1s	$\bar{x}$	± 1s	$\bar{x}$	± 1s	$\bar{x}$	± 1s	$\bar{x}$	± 1s
K_2O	%	5.23	0.32	4.30	0.12	3.44	0.21	3.79	0.20	3.18	0.13
CaO	%	0.63	0.05	0.71	0.02	1.54	0.06	1.18	0.05	1.84	0.07
TiO_2	%	0.11	0.02	0.13	0.00	0.20	0.01	0.11	0.01	0.26	0.01
MnO	%	0.06	0.01	0.03	0.00	0.06	0.00	0.06	0.00	0.06	0.00
FeO	%	1.88	0.15	0.88	0.03	1.30	0.07	1.00	0.10	1.66	0.08
V*	ppm	43	7	105	4	84	5	79	4	106	5
Cr*	ppm	65	11	28	5	29	6	23	6	33	5
Zn	ppm	225	18	30	3	40	4	41	6	41	4
Rb	ppm	260	12	116	3	91	3	111	6	74	3
Sr	ppm	5	4	63	8	185	41	112	11	233	23
Y	ppm	230	31	26	6	22	3	21	5	18	5
Zr	ppm	456	54	76	8	140	27	65	10	170	13
Nb	ppm	278	22	14	4	15	4	13	5	11	5
Ba	ppm	131	40	1467	59	1046	63	1192	47	1334	59
Pb*	ppm	79	7	31	3	25	3	30	3	23	2

The Rhyolite of Timber Butte consists of two members: a lower, glassy rhyolite with common flow-shearing and normal magnetic polarity; and an upper, stony to vesicular flow-banded rhyolite with reverse polarity (Clemens and Wood 1991). Obsidian of Timber Butte may be found eroding from talus slopes of the lower member on the northern and western slopes of the butte in abundant, 10 to 40 cm diameter, angular clasts of exceptionally glassy material (Corn 2006). The source is well-characterized and has been sampled by all major archaeological XRF labs with Idaho obsidian reference collections (James, Bailey, and D'Auria 1996; Skinner 2011b; Black 2015).

Cannonball Mountain I & II

Cannonball Mountain is located in the Soldier Mountains north of the Camas Prairie near Fairfield, Idaho. The southern flanks of the mountain are blanketed in a mid-Miocene rhyolite tuff designated the Tuff of Cannonball Mountain by Lewis (1990). It is host to two geochemically distinct obsidian source groups: Cannonball I and Cannonball II. Neither group is well-represented in syntheses of southern Idaho obsidian source use (Holmer 1997; Plager 2001; Fowler 2014), despite the proximity of the source area to the Camas Prairie.

The Tuff of Cannonball Mountain (10.2 ± 0.3 Ma) is an alkali rhyolite tuff exposed on the southern flanks of the Soldier Mountains (Lewis 1990, 50–52). It is up to 300 m thick and covers an area of about 35 km^2 between Sampson Creek and Elk Creek overlooking the extensional graben of the Camas Prairie. Two members of the Rhyolite of Cannonball Mountain are mapped in the Fairfield 30' x 60' quadrangle (Garwood et al. 2014). The upper member is a light gray porphyritic to vesicular tuff with common pyroclasts of obsidian occurring as float in ashy colluvial soils (Lewis 1990, 50–52). The lower member contains abundant flattened glassy fragments of perlitic glass and is confined to a small (< 1 km^2) area along Elk Creek (Garwood et al. 2014, 15). Obsidian of both the Cannonball I and Cannonball II source groups outcrop in areas mapped as the upper member of the tuff. The Cannonball I source group outcrops at elevations less than 7000'. The Cannonball II source group outcrops at elevations of 7000' to 7400'.

As an alkali rhyolite, the Tuff of Cannonball Mountain is compositionally unique among Miocene rhyolites of southern Idaho (Lewis 1990, tbl. 3). Cannonball Mountain obsidian has high concentrations of K_2O, MnO and FeO, low concentrations of CaO, high Rb:Sr ratios, and high concentrations of Zr. The Cannonball II group has higher concentrations of compatible elements (FeO, TiO_2, MnO, and Zr) than Cannonball I (Figure 9; Table 7). SFU and NWROSL report sampling locations at lower-elevation portions of the mountain that likely correspond to the Cannonball I source group (Bailey 1992; Skinner 2011b). ISU reports sampling locations at elevations corresponding to both Cannonball I and Cannonball II (Black 2015). Pyroclasts of both groups are black, glassy, devoid of phenocrysts, 5 to 15 cm in diameter, and visually indistinguishable.

Wedge Butte

Wedge Butte (3.06 ± 0.04 Ma) is a small rhyolite dome (230 m tall by 3 km^2) east of Magic Reservoir near Shoshone, ID (Armstrong, Leeman, & Malde, 1975; Othberg et al., 2007). It is host to small (3 - 4 cm) clasts of visually-distinctive snowflake obsidian, but past Provenance studies have shown that it was not a well-utilized source of southern Idaho obsidian (Holmer 1997; Plager 2001; Fowler 2014).

Wedge Butte is the largest of three minor rhyolite domes mapped as the Rhyolite of Wedge Butte (3.0 - 3.5 Ma) east of the Magic Reservoir eruptive center (3-6 Ma), a buried caldera separating the Mt. Bennet and Picabo Hills east of the Camas Prairie (Leeman, 1982; Honjo et al., 1986; Othberg et al., 2007). Wedge Butte is a pink to gray rhyolite dome with abundant phenocrysts of quartz, sanidine, and plagioclase. The dome has pronounced vertical radial joints that weather to form concentric ridges visible in aerial imagery (Othberg et al., 2007; Garwood et al., 2014).

Major and trace-element geochemistry of the Rhyolite of Wedge Butte has not been previously reported. Wedge Butte obsidian is unique among southern Idaho obsidian source groups, but most similar to that of Big Southern Butte and Cedar Butte. It is similarly high in K_2O and low in CaO, but has lower concentrations of FeO, exceptionally high Rb:Sr ratios, and lower concentrations of Zr and Nb. Wedge Butte obsidian has been previously sampled by SFU, ISU, and NWROSL (James, Bailey, and D'Auria 1996; Skinner 2011b; Black 2015). Obsidian has not been identified in association with the other two rhyolite domes mapped as the Rhyolite of Wedge Butte.

Big Southern Butte

Big Southern Butte is a 760 m rhyolite dome complex on the eastern Snake River Plain between Blackfoot and Arco, ID. It is the largest and youngest (300 ± 20 Ka) of several peralkaline rhyolite domes (e.g. East Butte) and cryptodomes (e.g. Middle Butte) extruded through Quaternary basalts near the axial high of the plain (Armstrong, Leeman, and Malde 1975; McCurry et al. 2008). It is also a well-utilized source of southern Idaho obsidian (Holmer 1997; Plager 2001; Scheiber and Finley 2011; Fowler 2014).

Big Southern Butte formed through the eruption of two coalesced rhyolite domes capped by a 350 m thick slab of Quaternary basalt (Kuntz and Kork 1978; Spear and King 1982). Eruption began as an intrusive, laccolithic cryptodome beneath overlying basalts at the intersection of an extensional rift zone and the axial volcanic zone of the ESRP. Continued magma input led to failure of the basaltic roof, followed first by the eruption of the eastern dome, uplift and displacement of the basalt slab to the north, then eruption of a second, overlapping dome to the west (Spear and King 1982). The eastern dome is a tan/lavender aphanitic rhyolite lava that grades upward into a white granular rhyolite lava and flow breccia with zones of tan rhyolite with laminar interlayers of spherulitic obsidian. The western dome is a white, granular rhyolite lava with minor flow-banding capped by several meters of flow breccia and obsidian (Kuntz and Kork 1978). Whole rock K-Ar dates for the two domes overlap (309 ± 10 and 294 ± 15 Ka) and they are nearly identical in composition (McCurry et al. 2008).

Quaternary peralkaline rhyolite domes of the ESRP, such as Big Southern Butte, are more silica and potassium-rich than the earlier Miocene and Pliocene rhyolite tuffs of the SRP-VP (McCurry, Hackett, and Hayden 1999; McCurry et al. 2008). To account for these findings, McCurry et al. (2008; Whittaker et al., 2008) hypothesize that they formed through extreme fractionation of mantle-derived basalt, with minimal contributions of continental crust (McCurry et al. 2008; Whitaker et al. 2008). Results of this study are consistent with these interpretations. Big Southern Butte obsidian is rich in K_2O, relatively depleted in CaO, TiO_2, MnO, and FeO, low Sr, moderate Rb and Zr, and high Zn, Y, and Nb (Figure 9; Table 7). It is compositionally similar to, but distinct from, obsidian from Cedar Butte and Wedge Butte. SFU, ISU, NWROSL, and GRL report obsidian sampling locations at Big Southern Butte (James, Bailey, and D'Auria 1996; R. E. Hughes 2007b; Skinner 2011b; Black 2015).

Cedar Butte

Cedar Butte (400 ± 29 Ka) is a broad, compositionally zoned shield volcano 20 km east of Big Southern Butte. It measures a modest 120 m high, but covers an area exceeding 20 km^2 (Hayden 1992; McCurry, Hackett, and Hayden 1999). No artifacts have been identified as corresponding to the Cedar Butte obsidian source group in regional archaeological provenance studies (Holmer 1997; Plager 2001; Scheiber and Finley 2011; Fowler 2014), but Cedar Butte was not identified as a source locale until 2008 (Marler 2009, fig. 3).

Cedar Butte erupted in several stages of increasingly mafic composition (Hayden 1992; McCurry, Hackett, and Hayden 1999). The earliest eruption is a pink to buff-colored high-silica rhyolitic lava with common flow banding capped by dense to pumiceous flow breccia bearing abundant, 5 to 10 cm clasts of black, glassy obsidian. Later stages of eruption were higher volume, lower viscosity flows of trachydacite, trachyandesite, and basaltic trachyandesite. Obsidian-bearing rhyolite flows at Cedar Butte are largely obscured by later eruptions, but remain exposed at a 0.5 km^2 area south of the primary source vent (Hayden 1992, fig. 5).

Like Big Southern Butte, eruption of Cedar Butte was driven by extensional decompression and magmatic upwelling along the ESRP axial volcanic zone (Spear and King 1982; McCurry, Hackett, and Hayden 1999). The compositional evolution of Cedar Butte lavas from peralkaline rhyolites to rocks of progressively more mafic compositions provides one of the principal lines of evidence for extreme fractionation of olivine tholeiite melts (McCurry et al. 2008; Whitaker et al. 2008). Obsidian of Cedar Butte is thus compositionally very similar to that of Big Southern Butte, but is less evolved and may be distinguished by greater concentrations of CaO, TiO_2, MnO, FeO, and Zr (Figure 9; Table 7). To our knowledge, ISU is the sole archaeological XRF lab that has previously reported obsidian sampling locations at Cedar Butte (Black 2015).

Malad

The "Malad" source group is a highly utilized and extensively traded source of obsidian located 30 km north of Malad, Idaho (Thompson 2004). It outcrops as angular pyroclasts of banded black to clear obsidian in pumice deposits at the base of a rhyolite dome complex erupted from the Hawkins Basin Volcanic Center (Pope, Blair, and Link 2001; Pope 2002). The source area covers over 50 km^2 of uneven wooded terrain, agricultural fields, and pumice/perlite mines between the Hawkins Creek basin of Bannock County, ID and the Wright Creek basin of Oneida County, ID. This places it at the hydrographic boundary between the Snake River Plain watershed and the northern Great Basin.

The Hawkins Basin Volcanic Center produced a series of Upper Miocene rhyolite and dacite flows that have been grouped under the Salt Lake Formation (Pope, Blair, and Link 2001; Pope 2002). The Salt Lake Formation refers to a complex of tuffaceous Middle Miocene to Lower Pliocene lacustrine and fluvial strata deposited in extensional grabens in the northern Great Basin near the Utah/Idaho border (Long et al. 2006). It is equivalent to the more ash-rich Starlight Formation in valleys south of the Snake River Plain in southern Idaho (Carr and Trimble 1976). Eight Upper Miocene rhyolite units erupted from the Hawkins Basin volcanic center (Pope, Blair, and Link 2001; Pope 2002). The earliest of these is a 60 m thick, massive to weakly flow banded, non-biotite bearing rhyolite flow partially blanketed in obsidian cobbles. To the south, a >30 m thick deposit of layered to massive rhyolite pumice with clasts of obsidian, non-biotite bearing devitrified rhyolite, and occasional pumice block breccia is exposed in the pit-walls of several perlite mines. These units are overlain by a biotite-bearing rhyolite flow dated to 6.63 ± 0.04 Ma (Pope, Blair, and Link 2001; Pope 2002). Preliminary mapping of the Malad 30' x 60' quadrangle suggests that obsidian-bearing pumice deposits and rhyolite flows of the Hawkins Basin volcanic center extend beyond the Wakley Peak quadrangle to the west and north (Long and Link 2007). Equivalent units have not been identified or mapped among Salt Lake Formation sediments in valleys to the east or west (Long et al. 2006).

Rhyolites of the Hawkins Basin Volcanic Center are silica-rich (77-79%) and compositionally more evolved than ignimbrite tuffs of the SRP-VP. Pope (2002, pp. 85–92) suggests that silicic magmatism at the Hawkins Basin Volcanic Center is thus unrelated to the SRP-VP, despite the overlap in timing with the Picabo and Heise ECs. Malad obsidian is also compositionally distinct from younger rhyolite domes of the SRP (i.e., Big Southern Butte and Cedar Butte; Figure 9; Table 7). It has comparatively moderate concentrations of K_2O, CaO, TiO_2, low concentrations of Fe0, low Rb:Sr ratios, low concentrations of Y, Zr, and Nb, and high concentrations of Ba. Malad is a well characterized obsidian source area that has been sampled by most major archaeological XRF labs operating in North America (James, Bailey, and D'Auria 1996; Skinner 2011b; Black 2015; R. E. Hughes 2015).

Chesterfield

The "Chesterfield" obsidian source group is a small, poorly utilized source area west of the ghost town of Chesterfield in the upper Portneuf Basin (Holmer 1997). Obsidian outcrops for less than a km in a roadcut above a shallow, unnamed drainage between Toponce Creek and King Creek. Clasts are angular to subangular, small (3 - 5 cm in diameter) but moderately abundant, glassy, free of phenocrysts, and of indeterminate origin. The aerial extent of the deposit is likewise unclear. The drainage bisects a broad, gently sloping terrace mapped simply as the Salt Lake Formation (Link and Stanford 1999). Relative to other southern Idaho obsidian source groups, Chesterfield obsidian has aberrantly low concentrations of K_2O, high concentrations of CaO and TiO_2, very low Rb:Sr ratios, low Y, Nb, and Zr, and high Ba (Figure 9; Table 7). Its composition is most akin to that of the Teton Pass source groups, but with higher concentrations of CaO, TiO_2, FeO, and lower Rb:Sr ratios. The Chesterfield source locale has been previously sampled by ISU (Black 2015).

Teton Pass I & II

Two compositionally distinct but related source groups (Teton Pass I and II) outcrop at Teton Pass near the Idaho/Wyoming border between Victor, ID and Wilson, WY. Teton Pass I and II were well-utilized source groups in southwestern Wyoming (Finley, Boyle, and Harvey 2015) and were locally important on the upper South Fork of the Snake in southern Idaho (Marler 2009), but they constitute a minor percentage of obsidian artifacts on the Snake River Plain (Fowler 2014; Holmer 1997; Marler 2009; Plager 2001; Scheiber and Finley 2011).

The surficial geology of Teton Pass is dominated by heavily faulted and uplifted blocks of limestone, sandstone, and shale (Schroeder 1969). Teton Pass obsidian is associated with a few narrow rhyolite flows and vents exposed in isolated outcrops on the eastern side of the pass. The group known as Teton Pass I outcrops at higher elevations two km south of the pass. The Teton Pass II group outcrops closer to the valley floor on the Wyoming side of the border in a roadcut near Crecent H Ranch. Both groups outcrop in moderate abundance as small (3 - 6 cm) subangular clasts of exceptionally glassy, translucent black material. Their surficial extent is unclear due to steep wooded terrain and residential development. Geologic mapping of the area suggests that parent rhyolites may be largely obscured by glacial till (Schroeder 1969).

As noted above, the composition of Teton Pass I and II obsidian is oddly similar to Chesterfield obsidian. Most notably, the three groups form a compositional gradient on CaO, TiO_2, Rb, and Sr (Figure 9; Table 7). Of the three groups, Chesterfield has the highest concentrations of CaO and TiO_2 and the lowest Rb:Sr ratios. Teton Pass II has the lowest concentrations of CaO and TiO_2 and the highest Rb:Sr ratios. Teton Pass I is intermediate in composition between the other two groups. These trends are somewhat surprising given the distance between the two locales (>110 km), but Teton Pass and the upper Portneuf Basin share similar bedrock geology (Link and Stanford 1999; Schroeder 1969). Source locales at Teton Pass/Crescent H have been reported by ISU, GRL, and NWROSL (Black 2015; MacDonald 2014; Skinner 2011d).

Discussion

At first glance, the geographic distribution of Idaho obsidian source locales appears to present an ideal source-scape for the examination of raw material conveyance and forager mobility. Obsidian outcrops in a nearly continuous chain of deposits on the perimeter of the central and eastern Snake River Plain (Figure 2). Yet, as we have seen, there is often a poor correspondence between geochemical source groups and geographic source areas in southern Idaho, posing a unique set of challenges for archaeological provenance research in the region.

Of the 28 obsidian source groups defined in this study, only about half outcrop within relatively localized (<100 km^2), contiguous areas (Figure 2). These include all of the Non-SRP-VP rhyolite domes and tuffs (Timber Butte, Cannonball Mountain, Wedge Butte, Big Southern Butte, Cedar Butte, Malad, Chesterfield, and Teton Pass), plus Bear Gulch and Kelly Canyon of the Heise EC. Other groups outcrop in vast, overlapping, and sometimes discontinuous source areas. Those of the Owyhee EC are found in an uneven patchwork of often intermixed deposits over a large (~700 km^2) but contiguous area. Greater challenges are posed by source groups associated with regionally extensive ignimbrites of the SRP-VP. Five groups of the CSRP-VP (Cougar Point Tuff XIII, Ibex Peak Tuff 8, Steer Basin Tuff, Dry Gulch Tuff, and McMullen Creek Tuff) co-occur within a 5,500 km^2 area south of the Snake River Plain in an area spanning the Idaho, Nevada, and Utah borders. Two of these (McMullen Creek Tuff and Steer Basin Tuff) have also been found among gravels of an ancient alluvial system north of the plain. Groups from the ESRP-VP (the Walcott Tuff and Kilgore Tuff) outcrop over larger, even more discontinuous areas. Some groups defined in this study are only known from one or two sampling locations, but may outcrop in additional locales given their association with large-volume ignimbrite tuffs. These include the Conant Creek Tuff of the Heise EC, the Tuff of Kyle Canyon of the Picabo EC, the Picabo Tuff of the Twin Falls EC, and Ibex Peak Tuff 8 of the Bruneau-Jarbidge EC.

Past obsidian provenance research in southern Idaho has shown that a majority of obsidian artifacts were produced with material obtained from a few heavily-utilized obsidian source groups (Holmer 1997; Plager 2001; Marler 2009; Scheiber and Finley 2011; Fowler 2014). Drawing on data compiled for nearly 4,300 artifacts collected from sites across southern Idaho, Fowler (2014) reports that 87% could be attributed to just six sources: Timber Butte (30%), Malad (19%), Bear Gulch (10%), Big Southern Butte (9%), the Walcott Tuff (8%), "Browns Bench" (7%) and Owyhee (4%). These results require some reconsideration in light of the present work. The most geologically extensive Idaho source groups (the Kilgore Tuff, Steer Basin Tuff, and Walcott Tuff) are either absent from this list or reported in surprisingly low percentages given their abundance and wide distribution on the landscape. Some of this may be due to inconsistencies in source nomenclature, but it is notable that the four most well-utilized source groups are all from fairly localized, contiguous source areas. This has important implications for our understanding of lithic procurement and reduction strategies as they relate to other aspects of Precontact subsistence and mobility in the region.

In the context of the present study, the strong preference for material from a small subset of source areas cannot be readily explained by differences in material abundance, accessibility, average clast size or deposit extent. This suggests that throughout the Precontact Period, toolstone procurement was not an activity that was simply embedded in or ancillary to broader patterns of subsistence and mobility (Binford 1979). Some raw materials were clearly more sought after than others. These would have likely been obtained through direct procurement via logistic forays, perhaps with some level of intragroup or intergroup exchange (Speth et al. 2013; Newlander 2018; 2012). A similar pattern of lithic resource use has been observed on the nearby Yellowstone Plateau (MacDonald, Horton, and Surovell 2019), where a strong preference for material from Obsidian Cliff and Bear Gulch over other available source materials is best explained by differences in material quality. Higher quality obsidian from Obsidian Cliff and Bear Gulch was heavily-utilized and transported for great distances, while lower quality Cougar Creek obsidian was used rarely and discarded within short distances of the source. In a lithic-rich source-scape, resource abundance permits and predicts more selective strategies of source acquisition (MacDonald, Horton, and Surovell 2019), such as direct procurement and exchange (Newlander 2012). Lower-ranked materials might be procured and used for expedient tasks in the course of other subsistence activities; but would be readily discarded given the knowledge that equivalent materials would be widely available elsewhere. A similar, dual strategy of source selection and conveyance may have been employed throughout the wider region, including southern Idaho. If so, data on the differential conveyance of high vs. low-ranked obsidian source groups may provide insight into alternative strategies of procurement, mobility, and trade.

The challenge in southern Idaho, of course, is how to best measure and evaluate patterns of material conveyance given the broad geographic distribution of many SRP-VP source areas. Traditional measures of material transport, such as distance fall-off curves, are clearly problematic for geographically extensive or discontinuous source areas. One option might be to measure the distance to the nearest known outcrop of the geologic unit associated with a given source group, but the quality and scale of geologic mapping is often uneven in Idaho, and obsidian is not universally present in association with most parent geologic units. The approach that we have taken is to map the distribution of sampling locations for each group as multi-point features relative to a generalized map of regional silicic geology (Figures 2, 5, and 7). This is an imperfect solution given the overlapping extent of source areas in the Cassia Hills and elsewhere, but we hope that it provides a fairly transparent representation of the data informing our view of regional source distributions. For provenance studies of artifacts from individual sites or smaller study areas, we suggest that estimates of source distance would be best computed as the minimum distance to viable source locale; meaning the linear distance to the nearest source locale where sizable (> 3 cm) clasts of toolstone-quality material are reliably available. After all, if distance fall-off models for both direct procurement and down-the-line exchange would predict an exponential decline in material transport with distance from a given source area (Hodder and Orton 1976, 145), the nearest of two or more plausible source locales is exponentially more likely to represent the true source of the material. For regional studies of toolstone conveyance, we would advocate an approach similar to that taken by Plager (2001, 82), who mapped obsidian conveyance as isoline intervals indicating the percentage of artifacts from each source within one-degree quadrats spanning the study area. The advantage of this approach is that it maps the distribution of sourced artifacts independently of the geographic distribution of raw materials. Other forms of density map would accomplish the same ends.

Conclusions

Results of this study build upon previous assessments of the Idaho obsidian source-scape by contextualizing regional source distributions in terms of newly available information from the geologic literature. Archaeologists have long been aware of the extent and relative distribution of the "Browns Bench" and "Butte Valley A" source groups (Hughes and Smith 1993) and corrections to information on the distribution of Walcott Tuff obsidian have recently been reported (Hughes and Arkush 2018; Hughes 2015). We have attempted to reconcile discrepancies in regional source nomenclature and the mapped distribution of Idaho obsidian source locales by clarifying how geochemical groups relate to source areas. Through this work, we have defined a few previously unrecognized source groups, such as the Tuff of Kyle Canyon and the Dry Gulch Tuff, and have recorded a number of new source locales for previously established groups. In addition, we have identified parent geologic units for most major source groups of the SRP-VP, such as the Steer Basin and Kilgore Tuffs, to clarify the depositional context and potential extent of obsidian source areas derived from these geologic units. We sincerely hope that this will enhance archaeologists' understanding of regional source distributions rather than further muddy an already confusing body of source nomenclature. The need for further work in some areas should be apparent.

We conclude with three broad suggestions for future research on the obsidian source-scape of southern Idaho and the SRP-VP:

(1) First, this study has not addressed the spatial distribution of obsidian source groups of the Yellowstone EC, the most recent volcanic field of the Yellowstone/Snake River Plain Volcanic Province. Several obsidian source locales have been reported within the Yellowstone Caldera (MacDonald, Horton, and Surovell 2019; Park 2010), but it is not clear whether these represent unique geochemical groups or whether some are associated with larger ignimbrite tuffs that form much of the caldera plateau. There is also a need for further obsidian sampling in the Mt. Bennett Hills, where geologists have identified ignimbrites that may correlate to obsidian-bearing tuffs found south of the plain, as well as areas corresponding to Bruneau-Jarbidge and Twin Falls EC source areas sampled by Page and Bacon (2106) in northern Nevada and Utah. Additional sampling in the Silver City Range would clarify the location, extent, and geologic context of primary deposits for the six geochemical groups found in that area.

(2) Second, our understanding of the Idaho obsidian source-scape would be improved through incorporation of data on the distribution of procurement locales identified through archaeological survey. Sampling locations reported in this study represent a small fraction of locales where obsidian is available on the landscape, and some would not have been viable sources of toolstone in the past (e.g., pebble-sized clasts or material exposed in modern roadcuts). Information on the distribution of true procurement sites would clarify which locales within geographically extensive source areas were utilized as sources of raw material. More detailed study of procurement and reduction strategies evident at such sites would also complement data obtained through provenance research by providing a view to how toolstone procurement and selection strategies factored into larger patterns of subsistence and mobility (e.g. Shott 2015; 2018).

(3) Finally, there is some need to revisit past findings on patterns of obsidian conveyance in southern Idaho and adjacent regions. The more comprehensive obsidian provenance studies conducted in southern Idaho have relied to greater or lesser degrees on syntheses of results from previous, smaller studies that were compiled from a largely unpublished body of research (Scheiber and Finley 2011; Fowler 2014; Plager 2001; Holmer 1997). On the whole, patterns of obsidian conveyance documented in these studies are consistent for well-utilized and better-characterized source areas such as Timber Butte, Malad, and Big Southern Butte. But many artifacts are

attributed to source locales such as “Deep Creek” and “Camas Prairie” that are now recognized as individual source locales from much more extensive, discontinuous source areas. Some reassessment of this body of data is warranted in light of the present study, as well as recent advancements in methods of trace-element analysis and source attribution. This is not to suggest that this body of work is no longer of value. Pioneering work by Holmer (1997) and Plager (2001) inspired the present study, and continues to inform our view of how patterns of obsidian procurement and transport relate to other aspects of forager behavior on the Snake River Plain.

References Cited

Ambroz, Jessica A., Glascock Glascock Michael D., and Craig E. Skinner. 2001. "Chemical Differentiation of Obsidian within the Glass Buttes Complex, Oregon." *Journal of Archaeological Science* 28: 741–46.

Anders, Mark H., Victor J. DiVenere, Sidney R. Hemming, and Joel Gombiner. 2019. "40Ar/39Ar and Paleomagnetic Constraints on the Age and Areal Extent of the Picabo Volcanic Field: Implications for the Yellowstone Hotspot." *Geosphere* 15 (3): 716–35.

Anders, Mark H., David W. Rodgers, Sidney R. Hemming, Janet Saltzman, Victor J. DiVenere, Jonathan T. Hagstrum, Glenn F. Embree, and Robert C. Walter. 2014. "A Fixed Sublithospheric Source for the Late Neogene Track of the Yellowstone Hotspot: Implications of the Heise and Picabo Volcanic Fields." *Journal of Geophysical Research: Solid Earth* 119 (4): 2871–2906.

Andrews, Graham D. M., Michael J. Branney, Bill C. Bonnichsen, and Michael McCurry. 2008. "Rhyolitic Ignimbrites in the Rogerson Graben, Southern Snake River Plain Volcanic Province: Volcanic Stratigraphy, Eruption History and Basin Evolution." *Bulletin of Volcanology* 70 (3): 269–91.

Argote-Espino, Denisse, Jesús Solé, Pedro López-García, and Osvaldo Sterpone. 2012. "Obsidian Subsource Identification in the Sierra de Pachuca and Otumba Volcanic Regions, Central Mexico, by ICP-MS and DBSCAN Statistical Analysis." *Geoarchaeology* 27 (1): 48–62.

Arkush, Brooke, and Richard Hughes. 2018. "An Investigation of Prehistoric Volcanic Glass Use in the Birch Creek Valley of Eastern Idaho." *Journal of California and Great Basin Anthropology* 38 (September): 75–86.

Armstrong, Richard Lee, William Leeman, and Harold E. Malde. 1975. "K-Ar Dating, Quaternary and Neogene Volcanic Rocks of the Snake River Plain, Idaho." *American Journal of Science* 275 (3): 225–51. https://doi.org/10.2475/ajs.275.3.225.

Asher, R. R. 1968. "Geology and Mineral Resources of a Portion of the Silver City Region, Owyhee County, Idaho." Technical report 138. Pamphlet. Moscow, ID: Idaho Bureau of Mines and Geology.

Bailey, Jeff. 1992. "X-Ray Fluorescence Characterization of Volcanic Glass Artifacts from Wilson Butte Cave, Idaho." Master's thesis, Calgary, AL: Department of Anthropology, University of Alberta.

Barberena, Ramiro, María V. Fernández, Agustina A. Rughini, Karen Borrazzo, Raven Garvey, Gustavo Lucero, Claudia Della Negra, Guadalupe Romero Villanueva, Víctor Durán, and Valeria Cortegoso. 2019. "Deconstructing a Complex Obsidian 'Source-scape': A Geoarchaeological and Geochemical Approach in Northwestern Patagonia." *Geoarchaeology* 34 (1): 30–41.

Barrientos, Gustavo, Luciana Catella, and Fernando Oliva. 2015. "The Spatial Structure of Lithic Landscapes: The Late Holocene Record of East-Central Argentina as a Case Study." *Journal of Archaeological Method and Theory* 22 (4): 1151–92.

Baxter, Paul W., Thomas J. Connolly, and Craig E. Skinner. 2015. "Obsidian Use in the Willamette Valley and Adjacent Western Cascades of Oregon." In *Toolstone Geography of the Pacific Northwest*, 218–23. Burnaby, BC: Archaeology Press, Simon Fraser University.

Benson, Christopher J. 1986. "Geology of the Kilgore Prospect Area, Clark County, Idaho." Master's thesis, Phoenix, AZ: Department of Geology, Arizona State University.

Benson, Thomas R., Gail A. Mahood, and Marty Grove. 2017. "Geology and 40Ar/39Ar Geochronology of the Middle Miocene McDermitt Volcanic Field, Oregon and Nevada: Silicic Volcanism Associated with Propagating Flood Basalt Dikes at Initiation of the Yellowstone Hotspot." *GSA Bulletin* 129 (9–10): 1027–51. https://doi.org/10.1130/B31642.1.

Bergantz, George W. 1995. "Changing Techniques and Paradigms for the Evaluation of Magmatic Processes." *Journal of Geophysical Research: Solid Earth* 100 (B9): 17603–13.

Bindeman, Ilya N., Kathryn E. Watts, Axel K. Schmitt, Lisa A. Morgan, and Pat W.C. Shanks. 2007. "Voluminous Low Δ18O Magmas in the Late Miocene Heise Volcanic Field, Idaho: Implications for the Fate of Yellowstone Hotspot Calderas." *Geology* 35 (11): 1019–22.

Binford, Lewis R. 1979. "Organization and Formation Processes: Looking at Curated Technologies." *Journal of Anthropological Research* 35 (3): 255–73.
Black, Marielle Loryn Pedro. 2014. "Using X-Ray Fluorescence Spectrometry to Assess Variance in Obsidian Source Distribution in Southern Idaho." Master's thesis, Boise, Idaho: Department of Anthropology, Boise State University. https://scholarworks.boisestate.edu/cgi/viewcontent.cgi?article=1854&context=td.
———. 2015. "Using X-Ray Fluorescence Spectrometry to Assess Variance in Obsidian Source Distributon in Southern Idaho." *Idaho Archaeologist* 38 (1): 17–67.
Bonnichsen, Bill C. 1982a. "Chemical Compositon of the Cougar Point Tuff and Rhyolite Lava Flows from the Bruneau-Jarbidge Eruptive Center, Owyhee County, Idaho." Technical report 82–1. Moscow, ID: Idaho Geological Survey, University of Idaho.
———. 1982b. "The Bruneau-Jarbidge Eruptive Center, Southwestern Idaho." In *Cenozoic Geology of Idaho*, edited by Bill C. Bonnichsen and Roy M. Breckenridge, 237–54. Idaho Bureau of Mines and Geology Bulletin 26. Moscow, ID: Idaho Bureau of Mines and Geology.
———. 1983. "Epithermal Gold and Silver Deposits, Silver City-De Lamar District, Idaho." Moscow, ID: Idaho Geological Survey, University of Idaho.
Bonnichsen, Bill C., and Roy M. Breckenridge. 1982. *Cenozoic Geology of Idaho*. Idaho Bureau of Mines and Geology Bulletin 26. Idaho Bureau of Mines and Geology.
Bonnichsen, Bill C., and Gary P. Citron. 1982. "The Cougar Point Tuff, Southwestern Idaho and Vicinity." In *Cenozoic Geology of Idaho*, edited by Bill C. Bonnichsen and Roy M. Breckenridge, 255–81. Idaho Bureau of Mines and Geology Bulletin 26. Moscow, ID: Idaho Bureau of Mines and Geology.
Bonnichsen, Bill C., and Martha M. Godchaux. 2006. "Geologic Map of the Murphy 30 x 60 Quadrangle, Ada, Canyon, Elmore, and Owyhee Counties, Idaho." Idaho Geological Survey.
Bonnichsen, Bill C., and Margaret D. Jenks. 1995a. "Geologic Map of the Cowan Reservoir Quadrangle, Owyhee County, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.
———. 1995b. "Geologic Map of the Triguero Lake Quadrangle, Owyhee County, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.
Bonnichsen, Bill C., William P. Leeman, Norio Honjo, William C. McIntosh, and Martha M. Godchaux. 2008. "Miocene Silicic Volcanism in Southwestern Idaho: Geochronology, Geochemistry, and Evolution of the Central Snake River Plain." *Bulletin of Volcanology* 70 (3): 315–42.
Bonnichsen, Bill C., Craig M. White, and Michael McCurry, eds. 2002. *Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province*. Idaho Geological Survey Bulletin 30. Moscow, ID: Idaho Geological Survey.
Bowers, Alfred W., and C. N. Savage. 1962. "Primitive Man on Browns Bench: His Environment and His Record." 14. Information Circular. Idaho Bureau of Mines and Geology.
Branney, Michael J., Bill C. Bonnichsen, Graham D. M. Andrews, Ben S. Ellis, Tiffany L. Barry, and Michael McCurry. 2008. "'Snake River (SR)-Type'Volcanism at the Yellowstone Hotspot Track: Distinctive Products from Unusual, High-Temperature Silicic Super-Eruptions." *Bulletin of Volcanology* 70 (3): 293–314.
Branney, Michael J., and Peter Kokelaar. 2002. *Pyroclastic Density Currents and the Sedimentation of Ignimbrites*. Geological Society Memoir 27. London, UK: The Geological Society.
Brown, Francis H., Charles Reid, and Agazi Negash. 2009. "Possible Isotopic Fractionation of Argon in Source Obsidians and Archeological Artifacts from Kulkuletti, Ethiopia." *Journal of Archaeological Science* 36 (10): 2119–24.
Camp, Victor E., and Martin E. Ross. 2004. "Mantle Dynamics and Genesis of Mafic Magmatism in the Intermontane Pacific Northwest." *Journal of Geophysical Research: Solid Earth* 109 (B8).
Camp, Victor E., and R. E. Wells. 2021. "The Case for a Long-Lived and Robust Yellowstone Hotspot." *GSA Today* 31 (1): 4–10.
Cann, Johnson Robin, and Colin Renfrew. 1964. "The Characterization of Obsidian and Its Application to the Mediterranean Region." *Proceedings of the Prehistoric Society* 30: 111–33.

Carr, Wilfred J., and Donald E. Trimble. 1961. "Geology of the American Falls Quadrangle, Idaho." Geological Survey Bulletin 1121-G. Contributions to General Geology. Reston, VA: United States Geological Survey.

———. 1976. "Geologic Map and Section of the Rockland and Arbon Quadrangles, Power County, Idaho." Geologic Map. Bulletin 1399. Reston, VA: United States Geological Survey.

Cashman, Katharine V., and George W. Bergantz. 1991. "Magmatic Processes." *Reviews of Geophysics* 29: 500–512.

Cashman, Katharine V., R. Stephen J. Sparks, and Jonathan D. Blundy. 2017. "Vertically Extensive and Unstable Magmatic Systems: A Unified View of Igneous Processes." *Science* 355 (6331).

Cathey, Henrietta E., and Barbara P. Nash. 2004. "The Cougar Point Tuff: Implications for Thermochemical Zonation and Longevity of High-Temperature, Large-Volume Silicic Magmas of the Miocene Yellowstone Hotspot." *Journal of Petrology* 45 (1): 27–58.

Christiansen, Robert L. 2001. "The Quaternary and Pliocene Yellowstone Plateau Volcanic Field of Wyoming, Idaho, and Montana." Professional Paper 729-G. Reston, VA: United States Geological Survey.

Christiansen, Robert L., H. Richard Blank Jr., J. D. Love, and John C. Reed Jr. 1978. "Geologic Map of the Grassy Lake Reservoir Quadrangle, Yellowstone National Park and Vicinity, Wyoming." Geologic Map. Reston, VA: United States Geological Survey.

Christiansen, Robert L., and J. D. Love. 1978. "The Pliocene Conant Creek Tuff in the Northn Part Fo the Teton Range and Jackson Hole, Wyoming." Geological Survey Bulletin 1435–C. Contributions to Stratigraphy. Reston, VA: United States Geological Survey.

Clemens, Drew M. 1990. "Volcanic Stratigraphy and Geochemistry of Timber Butte, Valley and Gem Counties, West-Central Idaho." Senior honors thesis, Boise, Idaho: Boise State University.

Clemens, Drew M., and Spencer H. Wood. 1991. "K-Ar Age of Silicic Volcanic Rocks within the Lower Columbia River Basalt Group at Timber Butte, Boise and Gem Counties, West-Central Idaho." *Isochron West* 57.

Coats, Robert Roy. 1964. "Geology of the Jarbidge Quadrangle, Nevada-Idaho." Geological Survey Bulletin 1141–M. Contributions to General Geology. Washington D.C.: United States Geological Survey.

Connolly, Thomas J., Craig E. Skinner, and Paul W. Baxter. 2015. "Ancient Trade Routes for Obsidian Cliffs and Newberry Volcano Toolstone in the Pacific Northwest." In *Toolstone Geography of the Pacific Northwest*, 180–92. Burnaby, BC: Archaeology Press, Simon Fraser University.

Corn, Tyronne L. 2006. "Timber Butte Obsidian Source Survey: Geology, Prehistory, Chemical Sourcing, and Debitage Analysis." Master's thesis, Moscow, Idaho: Department of Anthropology, University of Idaho.

Craig, Nathan, Robert J. Speakman, Rachel S. Popelka-Filcoff, Michael D. Glascock, J. David Robertson, M. Steven Shackley, and Mark S. Aldenderfer. 2007. "Comparison of XRF and PXRF for Analysis of Archaeological Obsidian from Southern Peru." *Journal of Archaeological Science* 34 (12): 2012–24.

Drew, Dana L., Ilya N. Bindeman, Matthew W. Loewen, and Paul J. Wallace. 2016. "Initiation of Large-Volume Silicic Centers in the Yellowstone Hotspot Track: Insights from H2O-and F-Rich Quartz-Hosted Rhyolitic Melt Inclusions in the Arbon Valley Tuff of the Snake River Plain." *Contributions to Mineralogy and Petrology* 171 (1): 1–20.

Drew, Dana L., Ilya N. Bindeman, Kathryn E. Watts, Axel K. Schmitt, Bin Fu, and Michael McCurry. 2013. "Crustal-Scale Recycling in Caldera Complexes and Rift Zones along the Yellowstone Hotspot Track: O and Hf Isotopic Evidence in Diverse Zircons from Voluminous Rhyolites of the Picabo Volcanic Field, Idaho." *Earth and Planetary Science Letters* 381: 63–77.

Ekren, Einar B., David H. McIntyre, and Earl H. Bennett. 1984. "High-Temperature, Large-Volume, Lavalike Ash-Flow Tuffs without Calderas in Southwestern Idaho." 1272. Geological Survey Professional Paper. United States Geological Survey.

Ekren, Einar B., David H. McIntyre, Earl H. Bennett, and H. E. Malde. 1981. "Geologic Map of Owyhee County, Idaho, West of Longitude 1160." United States Geological Survey.

Ellis, Ben S. 2009. "Rhyolitic Explosive Eruptions of The Central Snake River Plain, Idaho: Investigations of The Lower Cassia Mountains Succession and Surrounding Areas." Doctoral dissertation, Leicester, UK: Department of Geology, University of Leicester.

Ellis, Ben S., Tiffany Barry, Michael J. Branney, John A. Wolff, Ilya Bindeman, Rob Wilson, and Bill C. Bonnichsen. 2010. "Petrologic Constraints on the Development of a Large-Volume, High Temperature, Silicic Magma System: The Twin Falls Eruptive Centre, Central Snake River Plain." *Lithos* 120 (3–4): 475–89.

Ellis, Ben S., and Michael J. Branney. 2010. "Silicic Phreatomagmatism in the Snake River Plain: The Deadeye Member." *Bulletin of Volcanology* 72 (10): 1241–57.

Ellis, Ben S., Michael J. Branney, Tiffany L. Barry, D. Barfod, Ilya N. Bindeman, John A. Wolff, and Bill C. Bonnichsen. 2012. "Geochemical Correlation of Three Large-Volume Ignimbrites from the Yellowstone Hotspot Track, Idaho, USA." *Bulletin of Volcanology* 74 (1): 261–77.

Ellis, Ben S., Mark D. Schmitz, and M. Hill. 2019. "Reconstructing a Snake River Plain 'Super-Eruption'via Compositional Fingerprinting and High-Precision U/Pb Zircon Geochronology." *Contributions to Mineralogy and Petrology* 174 (12): 1–16.

Ellis, Ben S., Dawid Szymanowski, Jörn-Frederik Wotzlaw, Axel K. Schmitt, Ilya N. Bindeman, Juliana Troch, Chris Harris, Olivier Bachmann, and Marcel Guillong. 2017. "Post-Caldera Volcanism at the Heise Volcanic Field: Implications for Petrogenetic Models." *Journal of Petrology* 58 (1): 115–36.

Ellis, Ben S., J. A. Wolff, S. Boroughs, D. F. Mark, William Starkel, and Bill C. Bonnichsen. 2013. "Rhyolitic Volcanism of the Central Snake River Plain: A Review." *Bulletin of Volcanology* 75 (8): 1–19.

Embree, Glenn F., Lisa A. McBroome, and David J. Doherty. 1982. "Preliminary Stratigraphic Framework of the Pliocene and Miocene Rhyolite, Eastern Snake River Plain, Idaho." In *Cenozoic Geology of Idaho*, edited by Bill C. Bonnichsen, 26:333–43. Idaho Bureau of Mines and Geology Bulletin.

Ericson, Jonathon E., and Michael D. Glascock. 2004. "Subsource Characterization: Obsidian Utilization of Subsources of the Coso Volcanic Field, Coso Junction, California, USA." *Geoarchaeology: An International Journal* 19 (8): 779–805.

ESRI. 2021. "ArcGIS Pro." Esri Inc. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.

Faure, Gunter. 1997. *Principles and Applications of Geochemistry*. Vol. 625. Prentice Hall Upper Saddle River, NJ.

Finley, Judson B., Maureen P. Boyle, and David C. Harvey. 2015. "Obsidian Conveyance in the Mountain World of the Numa." *Plains Anthropologist* 60 (November): 375–91.

Finn, David R., Robert S. Coe, Ethan Brown, Michael Branney, Marc Reichow, Thomas Knott, Michael Storey, and Bill Bonnichsen. 2016. "Distinguishing and Correlating Deposits from Large Ignimbrite Eruptions Using Paleomagnetism: The Cougar Point Tuffs (Mid-Miocene), Southern Snake River Plain, Idaho, USA." *Journal of Geophysical Research: Solid Earth* 121 (9): 6293–6314.

Fowler, Benjamin L. 2014. "Obsidian Toolstone Conveyance: Southern Idaho Forager Mobility." Master's thesis, Logan, Utah: Department of Anthropology, Utah State University.

Frahm, Ellery. 2012. "Evaluation of Archaeological Sourcing Techniques: Reconsidering and Re-Deriving Hughes' Four-Fold Assessment Scheme." *Geoarchaeology* 27 (2): 166–74.

———. 2013. "Is Obsidian Sourcing about Geochemistry or Archaeology? A Reply to Speakman and Shackley." *Journal of Archaeological Science* 40 (2): 1444–48.

———. 2014. "What Constitutes an Obsidian 'Source'?: Landscape and Geochemical Considerations and Their Archaeological Implications." In *Twenty-Five Years on the CuttingEdge of Obsidian Studies: Selected Readings from the IAOS Bulletin*, edited by Carolyn D. Dillian. International Association for Obsidian Studies.

https://www.academia.edu/1228383/Chapter_8_What_Constitutes_an_Obsidian_Source_Landscape_and_Geochemical_Considerations_and_their_Archaeological_Implications.
Frahm, Ellery, and Joshua M. Feinberg. 2015. "Reassessing Obsidian Field Relationships at Glass Buttes, Oregon." *Journal of Archaeological Science: Reports* 2: 654–65.
Frison, George C., Gary A. Wright, James B. Griffin, and Adon A. Gordus. 1968. "Neutron Activation Analysis of Obsidian: An Example of Its Relevance to Northwestern Plains Archaeology." *Plains Anthropologist* 13 (41): 209–17. https://doi.org/10.1080/2052546.1968.11908471.
Gallagher, Joseph G. 1979. "The Archeology of the Sheepeater Battleground and Redfish Overhang Sites: Settlement Model for Central Idaho." 5. Cultural Resource Report. Intermountain Region: USDA Forest Service.
Gardner, James E., Fabian B. Wadsworth, Edward W. Llewellin, James M. Watkins, and Jason P. Coumans. 2019. "Experimental Constraints on the Texture and Origin of Obsidian Pyroclasts." *Bulletin of Volcanology* 81 (22): 1–15.
Garwood, Dean L., John D. Kauffman, and Kurt L. Othberg. 2011. "Geologic Map of the Picabo Quadrangle, Blaine County, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.
Garwood, Dean L., John D. Kauffman, Kurt L. Othberg, and Reed S. Lewis. 2014. "Geologic Map of the Fairfield 30 x 60 Minute Quadrangle, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.
Gillerman, Virginia S., Dennis M. Feeney, Andrew S. Canada, and Keegan L. Schmidt. 2021. "Geologic Map of the DeLamar and Swisher Mountain Quadrangles, Owyhee County, Idaho." Idaho Geological Survey.
Glascock, Michael D. 1992. "Characterization of Archaeological Ceramics at MURR by Neutron Activation Analysis and Multivariate Statistics." In *Chemical Characterization of Ceramic Pastes in Archaeology*, edited by Hector Neff, 11–25. Monographs in World Archaeology 7. Madison, WI: Prehistory Press.
———. 2002. "Obsidian Provenance Research in the Americas." *Accounts of Chemical Research* 35 (8): 611–17.
———. 2011. "Comparison and Contrast between XRF and NAA: Used for Characterization of Obsidian Sources in Central Mexico." In *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology*, edited by M. Steven Shackley, 161–92. New York, NY: Springer.
Glascock, Michael D., and Hector Neff. 2003. "Neutron Activation Analysis and Provenance Research in Archaeology." *Measurement Science and Technology* 14 (9): 1516–26. https://doi.org/10.1088/0957-0233/14/9/304.
Gordus, Adon A., Gary A. Wright, and James B. Griffin. 1968. "Obsidian Sources Characterized by Neutron-Activation Analysis." *Science* 161 (3839): 382–84.
Green, James P. 1982. "XRF Trace Element Analysis and Hydration Measurement of Archaeological and Source Obsidians from the Northeastern Great Basin." Paper presented at the 18th Biennial Meeting of the Great Basin Anthropological Conference, Reno, NV.
Griffin, James B., Adon A. Gordus, and Gary A. Wright. 1969. "Identification of the Sources of Hopewellian Obsidian in the Middle West." *American Antiquity* 34 (1): 1–14.
Hackett, William R., and Lisa A. Morgan. 1988. "Explosive Basaltic and Rhyolitic Volcanism of the Eastern Snake River Plain, Idaho." *Guidebook to the Geology of Central and Southern Idaho: Idaho Geological Survey Bulletin* 27: 283–301.
Harbottle, Garman. 1982. "Chemical Characterization in Archaeology." In *Contexts Fro Prehistoric Exchange*, edited by Jonathan E. Ericson and Timothy K. Earle, 13–51. New York, NY: Academic Press.
Harris, Kathryn. 2014. "Human Landscape Use on the Snake River Plain, Idaho." In *Lithics in the West: Using Lithic Analysis to Solve Archaeological Problems in Western North America*, edited by Douglas H. MacDonald, William Andrefsky, Jr., and Pei-Lin Yu, 161–72. Missoula, MT: University of Montana Press.

Hasten, Zachary Eugene Levi. 2012. “Mid-Miocene Magmatism in the Owyhee Mountains, ID: Origin and Petrogenesis of Volcanic Rocks in the Silver City District.” Master’s thesis, Manhatten, KS: Department of Geology, Kansas State University.

Hatch, James W., Joseph W. Michels, Christopher M. Stevenson, Barry E. Scheetz, and Richard A. Geidel. 1990. “Hopewell Obsidian Studies: Behavioral Implications of Recent Sourcing and Dating Research.” *American Antiquity* 55 (3): 461–79.

Hayden, Karl P. 1992. “The Geology and Petrology of Cedar Butte, Bingham County, Idaho.” Master’s thesis, Pocatello, ID: Department of Geology, Idaho State University.

Henrikson, L. Suzann. 2008. “Going with the Flow: The Impact of Holocene Fissure Eruptions on Obsidian Source Use in Southeastern Idaho.” *Journal of California and Great Basin Anthropology* 28 (2): 153–65.

Hladkey, Frank R., Karl S. Kellog, Steven S. Oriel, Paul K. Link, Jack W. Nielson, and Roger E. Amerman. 1992. “Geologic Map of the Eastern Part of the Fort Hall Indian Reservation, Bannock, Bingham, and Caribou Counties, Idaho.” Geologic Map. Miscellaneous Investigations Series, Map I-2006. United States Geological Survey.

Hodder, Ian, and Clive Orton. 1976. *Spatial Analysis in Archaeology*. Cambridge, UK: Cambridge University Press.

Hodges, Mary K. V. 2006. “Tertiary Stratigraphy of the Idaho Medicine Lodge Valley, Clark County, Idaho.” Master’s thesis, Pocatello, ID: Department of Geosciences, Idaho State University.

Holmer, Richard N. 1997. “Volcanic Glass Utilization in Eastern Idaho.” *Tebiwa* 26 (2): 186–204.

Honjo, Norio, K. R. McElwee, R. A. Duncan, and W. P. Leeman. 1986. “K-Ar Ages of Volcanic Rocks from the Magic Reservoir Eruptive Center, Snake River Plain, Idaho.” *Isochron West* 46: 15–19.

Hughes, Richard E. 1982. “Age and Exploitation of Obsidian from the Medicine Lake Highland, California.” *Journal of Archaeological Science* 9 (2): 173–85. https://doi.org/10.1016/0305-4403(82)90048-6.

———. 1984. “Obsidian Studies in the Great Basin: Problems and Prospects.” In *Obsidian Studies in the Great Basin*, edited by Richard E. Hughes, 1–20. Contributions of the University of California Archaeological Research Facility, Berkely 45. Berkely, CA: University of California, Berkely.

———. 1988. “The Coso Volcanic Field Reexamined: Implications for Obsidian Sourcing and Hydration Dating Research.” *Geoarchaeology* 3 (4): 253–65. https://doi.org/10.1002/gea.3340030402.

———. 1992. “Another Look at Hopewell Obsidian Studies.” *American Antiquity* 57 (3): 515–23.

———. 1998. “On Reliability, Validity, and Scale in Obsidian Sourcing Research.” In *Unit Issues in Archaeology: Measuring Time, Space, and Material*, edited by Ann Felice Ramenofsky and Anastasia Steffen, 103–14. Foundations of Archaeological Inquiry. Salt Lake City, Utah: The University of Utah Press.

———. 2007a. “The Geologic Sources for Obsidian Artifacts from Minnesota Archaeological Sites.” *The Minnesota Archaeologist* 66: 16.

———. 2007b. “Major Revision of Geologic Source Attributions for Obsidian Artifacts from Veratic Rockshelter, Idaho.” *Journal of the Idaho Academy of Science* Volume 43 (January): 10–21.

———. 2015. “Prehistoric Obsidian Conveyance in the Eastern Great Basin: Evidence from Hogup and Danger Caves, Utah.” *Journal of Archaeological Science: Reports* 4 (December): 293–309. https://doi.org/10.1016/j.jasrep.2015.08.033.

Hughes, Richard E., and Max G. Pavesic. 2005. “Proximity and Provenance: A Lesson from the Sterling Cache, Idaho.” *Journal of California and Great Basin Anthropology* 25 (2): 221–25.

Hughes, Richard E., and Robert L. Smith. 1993. “Archaeology, Geology, and Geochemistry in Obsidian Provenance Studies.” In *Effects of Scale on Archaeological and Geoscientific Perspectives*, 79–91. Geological Society of America Special Paper 283. Geological Society of America.

Hughes, Scott S., and Michael McCurry. 2002. “Bulk Major and Trace-Element Evidence for a Time-Space Evolution of Snake River Plain Rhyolites, Idaho.” In *Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province.*, edited by Bill C. Bonnichsen, Michael McCurry, and

Craig M. White, 30:177–94. Idaho Geological Survey Bulletin. Moscow, ID: Idaho Geological Survey.
Hughes, Scott S., Richard P. Smith, William R. Hackett, Steven R. Anderson, and Glenn D. Thackray. 1999. “Mafic Volcanism and Environmental Geology of the Eastern Snake River Plain, Idaho.” In *Guidebook to the Geology of Eastern Idaho*, 143–68. Pocatello, ID: Idaho Museum of Natural History.
James, Malcolm A., Jeff Bailey, and John M. D’Auria. 1996. “A Volcanic Glass Library for the Pacific Northwest: Problems and Prospects.” *Canadian Journal of Archaeology* 20: 93–122.
Janecke, Susanne U., and Robert Q. Oaks. 2011a. “New Insights into the Outlet Conditions of Late Pleistocene Lake Bonneville, Southeastern Idaho, USA.” *Geosphere* 7 (6): 1369–91.
———. 2011b. “Reinterpreted History of Latest Pleistocene Lake Bonneville: Geologic Setting of Threshold Failure, Bonneville Flood, Deltas of the Bear River, and Outlets for Two Provo Shorelines, Southeastern Idaho, USA.”
Jean, Marlon M., Eric H. Christiansen, Duane E. Champion, Scott K. Vetter, William M. Phillips, Stephan Schuth, and John W. Shervais. 2018. “Caldera Life-Cycles of the Yellowstone Hotspot Track: Death and Rebirth of the Heise Caldera.” *Journal of Petrology* 59 (8): 1643–70.
Jones, George, Charlotte Beck, Eric Jones, and Richard E. Hughes. 2003. “Lithic Source Use and Paleoarchaic Foraging Territories in the Great Basin.” *American Antiquity* 68 (January): 5–38. https://doi.org/10.2307/3557031.
Jones, George T., and Charlotte Beck. 1990. “An Obsidian Hydration Chronology of Late Pleistocene-Early Holocene Surface Assemblages from Butte Valley, Nevada.” *Journal of California and Great Basin Anthropology* 12 (1): 84–100.
Kauffman, John D., Kurt L. Othberg, and Dean L. Garwood. 2010. “Geologic Map of the McHan Reservoir Quadrangle, Camas and Gooding Counties, Idaho.” Geologic Map. Moscow, ID: Idaho Geological Survey.
Keene, Joshua L. 2018a. “A Diachronic Perspective on Great Basin Projectile Point Morphology from Veratic Rockshelter, Idaho.” *Quaternary International* 466: 299–317.
———. 2018b. “A Diachronic Perspective on Great Basin Projectile Point Morphology from Veratic Rockshelter, Idaho.” *Quaternary International* 466: 299–317.
Knight, Charles LF, Heng Hu, Michael D. Glascock, and Stephen A. Nelson. 2017. “Obsidian Sub-Sources at the Zaragoza-Oyameles Quarry in Puebla, Mexico: Similarities with Altotonga and Their Distribution throughout Mesoamerica.” *Latin American Antiquity* 28 (1): 46–65.
Knott, Thomas R., Michael J. Branney, Marc K. Reichow, David R. Finn, Robert S. Coe, Michael Storey, Dan Barfod, and Michael McCurry. 2016. “Mid-Miocene Record of Large-Scale Snake River–Type Explosive Volcanism and Associated Subsidence on the Yellowstone Hotspot Track: The Cassia Formation of Idaho, USA.” *Bulletin* 128 (7–8): 1121–46.
Knott, Thomas R., Michael J. Branney, Marc K. Reichow, David R. Finn, Simon Tapster, and Robert S. Coe. 2020. “Discovery of Two New Super-Eruptions from the Yellowstone Hotspot Track (USA): Is the Yellowstone Hotspot Waning?” *Geology* 48 (9): 934–38.
Knott, Thomas R., Marc K. Reichow, Michael J. Branney, David R. Finn, Robert S. Coe, Michael Storey, and Bill Bonnichsen. 2016. “Rheomorphic Ignimbrites of the Rogerson Formation, Central Snake River Plain, USA: Record of Mid-Miocene Rhyolitic Explosive Eruptions and Associated Crustal Subsidence along the Yellowstone Hotspot Track.” *Bulletin of Volcanology* 78 (4): 1–25.
Kuntz, Mel A. 1979. “Geologic Map of the Juniper Buttes Area, Eastern Snake River Plain.” Miscellaneous Investigations Series, Map I-1115. United States Geological Survey.
Kuntz, Mel A., Jeffrey K. Geslin, Linda E. Mark, Mary K. V. Hodges, Mary E. Kauffman, Duane E. Champion, Marvin R. Lanphere, et al. 2003. “Geologic Map of the Northern and Central Parts of the Idaho National Engineering and Environmental Laboratory, Eastern Idaho.” Geologic Map. Moscow, ID: Idaho Geological Survey.
Kuntz, Mel A., and John O. Kork. 1978. “Geology of the Arco-Big Southern Butte Area, Eastern Snake River Plain, and Volcanic Hazards to the Radioactive Waste Management Complex, and Other

Waste Storage and Reactor Facilities at the Idaho National Engineering Laboratory, Idaho." US Geological Survey,.

Kuntz, Mel A., Betty A. Skipp, Duane E. Champion, Philip B. Gans, D. Paco Van Sistine, and Scott R. Snyders. 2007. "Geologic Map of the Craters of the Moon 30' x 60' Quadrangle, Idaho." Geologic Map. Scientific Investigations Map 2969. Reston, VA: United States Geological Survey.

Kuntz, Mel A., Betty A. Skipp, Marvin A. Lanphere, William E. Scott, Kenneth L. Pierce, G. Brent Dalrymple, Duane E. Champion, et al. 1994. "Geologic Map of the Idaho National Engineering Laboratory and Adjoining Areas, Eastern Idaho." Geologic Map. Miscellaneous Investigations Series, Map I-2330. Reston, VA: United States Geological Survey.

Lane, Terre, Todd Harvey, David Rowe, and J.J. Brown. 2019. "Independent Technical Report and Economic Assessment, Kilgore Project, Clark County, Idaho, USA." Technical report. Global Research Engineering, prepared for Otis Gold Corp.

Le Maitre, Roger W., A. Streckeisen, B. Zanettin, M. J. Le Bas, B. Bonin, and P. Bateman. 2005. *Igneous Rocks: A Classification and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks*. Cambridge University Press.

Leeman, William P. 1982a. "Development of the Snake River Plain-Yellowstone Plateau Province, Idaho and Wyoming: An Overview and Petrologic Model." In *Cenozoic Geology of Idaho*, edited by Bill C. Bonnichsen and R. M. Breckenridge, 155–77. Idaho Bureau of Mines and Geology Bulletin 26. Idaho Bureau of Mines and Geology.

———. 1982b. "Geology of the Magic Reservoir Area, Snake River Plain, Idaho." In *Cenozoic Geology of Idaho*, edited by Bill C. Bonnichsen and Roy M. Breckenridge, 26:369–76. Idaho Bureau of Mines and Geology Bulletin. Moscow, ID: Idaho Bureau of Mines and Geology.

Lewis, Reed S. 1990. "Geology, Geochemistry, and Mineral Potential of Cretaceous and Tertiary Plutons in the Eastern Part of the Soldier Mountains, Idaho." Doctoral Dissertation, Corvallis, OR: Department of Geology, Oregon State University.

Lewis, Reed S., Paul K. Link, Loudon R. Stanford, and Sean P. Long. 2012. "Geologic Map of Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.

Link, Paul K., and Loudon R. Stanford. 1999. "Geologic Map Compilation of the Pocatello 30 x 60 Minute Quadrangle, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.

Long, Sean P., and Paul K. Link. 2007. "Geologic Map Compilation of the Malad City 30 x 60 Minute Quadrangle, Idaho." Idaho Geological Survey.

Long, Sean P., Paul K. Link, Susanne U. Janecke, Michael E. Perkins, and C. Mark Fanning. 2006. "Multiple Phases of Tertiary Extension and Synextensional Deposition of the Miocene–Pliocene Salt Lake Formation in an Evolving Supradetachment Basin, Malad Range, Southeast Idaho, USA." *Rocky Mountain Geology* 41 (1): 1–27.

MacDonald, Douglas H. 2014. "Deciphering Point-of-Origin for Prehistoric Hunter-Gatherers at Yellowstone Lake, Wyoming: A Case Study in Lithic Technology and Settlement Pattern Studies." In *Lithics in the West: Using Lithic Analysis to Solve Archaeological Problems in Western North America*, edited by Douglas H. MacDonald, William Andrefsky, Jr., and Pei-Lin Yu, 142–60. Missoula, MT: University of Montana Press.

MacDonald, Douglas H., Elizabeth A. Horton, and Todd A. Surovell. 2019. "Cougar Creek: Quantitative Assessment of Obsidian Use in the Greater Yellowstone Ecosystem." *American Antiquity* 84 (1): 158–78. https://doi.org/10.1017/aaq.2018.76.

Manley, Curtis R., and William C. McIntosh. 2002. "The Juniper Mountain Volcanic Center, Owyhee County, Southwestern Idaho: Age Relations and Physical Volcanology." In *Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province*, edited by Bill C. Bonnichsen, Craig M. White, and Michael McCurry, 205–27. Idaho Geological Survey Bulletin 30. Idaho Geological Survey.

Mansfield, G.R., W.B. Lang, and J.W. Merit. 1952. “Geologic Map of the Ammon and Paradise Valley Quadrangles, Idaho.” Geologic Map. Professional Paper. United States Geological Survey.
Mapel, William J., and William J. Hail. 1959. “Tertiary Geology of the Goose Creek District, Cassia County, Idaho, Box Elder County, Utah, and Elko, Nevade.” 1055-H. Geological Survey Bulletin. Reston, VA: United States Geological Survey.
Marler, Clayton F. 2009. “Report on Trace Element Analysis of INL Obsidian Artifacts.” Idaho Falls, ID: Idaho National Laboratory Cultural Resources Management Office.
McCurry, Michael, William R. Hackett, and Karl Hayden. 1999. “Cedar Butte and Cogenetic Quaternary Rhyolite Domes of the Eastern Snake River Plain.” *Guidebook to the Geology of Eastern Idaho: Idaho Museum of Natural History*, 169–79.
McCurry, Michael, Karl P. Hayden, Lee H. Morse, and Stan Mertzman. 2008. “Genesis of Post-Hotspot, A-Type Rhyolite of the Eastern Snake River Plain Volcanic Field by Extreme Fractional Crystallization of Olivine Tholeiite.” *Bulletin of Volcanology* 70: 361–83.
McCurry, Michael, David M. Pearson, John Welhan, Shannon K. Natwotniak, and Meghan Fisher. 2015. “Origin and Potential Geothermal Significance of China Hat and Other Late Pleistocene Topaz Rhyolite Lava Domes of the Blackfoot Volcanic Field, SE Idaho.” *Geothermal Resources Council Transactions* 39: 35–47.
McMillan, Rhy, Marghaleray Amini, and Dominique Weis. 2019. “Splitting Obsidian: Assessing a Multiproxy Approach for Sourcing Obsidian Artifacts in British Columbia.” *Journal of Archaeological Science: Reports* 28: 102040.
Michalek, Milana. 2009. “Age and Amount of Crustal Flexure in the Lake Hills, South-Central Idaho, and Implications for the Subsidence of the Eastern Snake River Plain.” Master’s thesis, Pocatello, ID: Department of Geology, Idaho State University.
Minc, Leah D., and Johannes Sterba. 2017. “Instrumental Neutron Activation Analysis (INAA) in the Study of Archaeological Ceramics.” *The Oxford Handbook of Archaeological Ceramic Analysis*, 424–46.
Monnereau, L. R., Ben S. Ellis, D. Szymanowski, O. Bachmann, and M. Guillong. 2021. “Obsidian Pyroclasts in the Yellowstone-Snake River Plain Ignimbrites Are Dominantly Juvenile in Origin.” *Bulletin of Volcanology* 83 (4): 27. https://doi.org/10.1007/s00445-021-01448-1.
Moore, Joe. 2009. “Great Basin Tool-Stone Sources: The NDOT Obsidian and Tool-Stone Sourcing Project: 2002 Progress Report.” Carson City, NV: Nevada Department of Transportation.
Morgan, Leah E., Paul R. Renne, R. E. Taylor, and Giday WoldeGabriel. 2009. “Archaeological Age Constraints from Extrusion Ages of Obsidian: Examples from the Middle Awash, Ethiopia.” *Quaternary Geochronology* 4 (3): 193–203.
Morgan, Lisa A. 1988. “Explosive Rhyolitic Volcanism on the Eastern Snake River Plain.” Doctoral dissertation, Honolulu, HI: Department of Geoloy and Geophysics, University of Hawaii.
———. 1992. “Stratigraphic Relations and Paleomagnetic and Geochemical Correlations of Ignimbrites of the Heise Volcanic Field, Eastern Snake River Plain, Eastern Idaho and Western Wyoming.” In *Regional Geology of Eastern Idaho and Western Wyoming*, edited by Paul K. Link, Mel A. Kuntz, and Lucian B. Piatt. Vol. 179. GSA Memoirs. Geological Society of America.
Morgan, Lisa A., David J. Doherty, and William P. Leeman. 1984. “Ignimbrites of the Eastern Snake River Plain: Evidence for Major Caldera-Forming Eruptions.” *Journal of Geophysical Research: Solid Earth* 89 (B10): 8665–78.
Morgan, Lisa A., and William C. McIntosh. 2005. “Timing and Development of the Heise Volcanic Field, Snake River Plain, Idaho, Western USA.” *Geological Society of America Bulletin* 117 (3–4): 288–306.
Mytton, James W., Paul L. Williams, and William A. Morgan. 1990. “Geologic Map of the Stricker 4 Quadrangle, Cassia County, Idaho.” Geologic Map. Miscellaneous Investigations Series, Map I-2052. Reston, VA: United States Geological Survey.
Nash, Barbara P., and Michael E. Perkins. 2012. “Neogene Fallout Tuffs from the Yellowstone Hotspot in the Columbia Plateau Region, Oregon, Washington and Idaho, USA.” *PLOS ONE* 7 (10): e44205.

Neff, Hector. 1998. “Units in Chemistry-Based Ceramic.” In *Unit Issues in Archaeology: Measuring Time, Space, and Material*, edited by Ann Felice Ramenofsky and Anastasia Steffen, 115–27. Salt Lake City, UT: University of Utah Press.

———. 2002. “Quantitative Techniques for Analyzing Ceramic Compositional Data.” In *Ceramic Production and Circulation in the Greater Southwest: Source Determination by INAA and Complementary Mineralogical Investigations*, 15–36. Monograph 44. The Cotsen Institute of Archaeology at UCLA Los Angeles.

Nelson, Jr., Fred W. 1984. “X-Ray Fluorescence Analysis of Some Western North American Obsidians.” In *Obsidian Studies in the Great Basin*, edited by Richard E. Hughes, 27–62. Contributions of the University of California Archaeological Research Facility, Berkely. Berkely, CA: University of California, Berkely.

Newlander, Khori. 2012. “Exchange, Embedded Procurement, and Hunter-Gatherer Mobility: A Case Study from the North American Great Basin.” Doctoral Dissertation, Ann Arbor, MI: Department of Anthropology, University of Michigan.

———. 2018. “Imagining the Cultural Landscapes of Paleoindians.” *Journal of Archaeological Science: Reports* 19 (June): 836–45. https://doi.org/10.1016/j.jasrep.2017.11.035.

Newlander, Khori, Nathan Goodale, George T. Jones, and David G. Bailey. 2015. “Empirical Study of the Effect of Count Time on the Precision and Accuracy of PXRF Data.” *Journal of Archaeological Science: Reports* 3: 534–48.

Oakley, William L. 2006. “Geologic Map of the Davis Mountain 7.5-Minute Quadrangle, Camas and Gooding Counties, Idaho: Stratigraphic Relations of Miocene Rhyolites.” Master’s thesis, Department of Geology, Idaho State University.

Oakley, William L., and P. K. Link. 2006. “Geologic Map of the Davis Mountain Quadrangle, Gooding and Camas Counties, Idaho.” Idaho Geological Survey.

Othberg, K. L., and J. D. Kauffman. 2010. “Geologic Map of the Fairfield Quadrangle.”

Othberg, Kurt L., and John D. Kauffman. 2009. “Geologic Map of the Spring Creek Reservoir Quadrangle, Camas County, Idaho.” Geologic Map. Moscow, ID: Idaho Geological Survey.

Othberg, Kurt L., John D. Kauffman, Jesse S. Bird, and Jane S. Freed. 2007. “Geologic Map of the Shoshone Ice Cave Quadrangle, Blaine, Lincoln, and Camas Counties, Idaho.” Idaho Geological Survey.

Ozbun, Terry L. 2017. “Toolstone Geography and the Larger Lithic Landscape.” In *Toolstone Geography in the Pacific Northwest*, edited by Terry L. Ozbun and Ron L. Adams. Archaeology Press, Simon Fraser University.

Page, David, and Steve Bacon. 2016. “Browns Bench Predictive Modeling, Resampling, and Geochemcial Characterization across Portions of Idaho, Nevada, and Utah.” Technical report. Reno, NV: Desert Research Institute.

Page, David, and Daron Duke. 2015. “Toolstone Sourcing, Lithic Resource Use, and Paleoarchaic Mobility in the Western Bonneville Basin.” In *The Paleoarchaic Occupation of the Old River Bed Delta*, edited by David B. Madsen, Dave N. Schmitt, and David Page, 209–35. University of Utah Anthropological Papers 128. Salt Lake City, UT: The University of Utah Press.

Pansze Jr., Arthur J. 1975. “Geology and Ore Deposits of the Silver City - De Lamar - Flint Region, Owyhee County, Idaho.” Technical report 161. Pamphlet. Moscow, ID: Idaho Bureau of Mines and Geology.

Park, Robin J. 2010. “A Culture of Convenience: Obsidian Source Selection in Yellowstone National Park.” Master’s thesis, Saskatoon, SK: Department of Anthropology, University of Saskatchewan.

Parker, Jennifer L. 1996. “Physical Volcanology and Geochemistry of the Tuff of Wooden Shoe Butte, Cassia Mountains, Idaho.” Master’s thesis, Pocatello, ID: Department of Geology, Idaho State University.

Perkins, Michael E., Francis H. Brown, William P. Nash, William McIntosh, and S. K. Williams. 1998. "Sequence, Age, and Source of Silicic Fallout Tuffs in Middle to Late Miocene Basins of the Northern Basin and Range Province." *Geological Society of America Bulletin* 110 (3): 344–60.

Perkins, Michael E., and Barbara P. Nash. 2002. "Explosive Silicic Volcanism of the Yellowstone Hotspot: The Ash Fall Tuff Record." *Geological Society of America Bulletin* 114 (3): 367–81.

Perkins, Michael E., William P. Nash, Francis H. Brown, and Robert J. Fleck. 1995. "Fallout Tuffs of Trapper Creek, Idaho—A Record of Miocene Explosive Volcanism in the Snake River Plain Volcanic Province." *Geological Society of America Bulletin* 107 (12): 1484–1506.

Phillips, William M., Dean L. Garwood, and Glenn F. Embree. 2013. "Geologic Map of the Packsaddle Lake Quadrangle, Teton County, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.

Phillips, William M., Daniel K. Moore, and Dennis M. Feeney. 2016. "Geologic Map of the Poplar Quadrangle, Bonneville County, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.

Phillips, William M., Daniel K. Moore, Dennis M. Feeney, and Glenn F. Embree. 2016. "Geologic Map of the Heise Quadrangle, Bonneville, Jefferson, and Madison Counties, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.

Phillips, William M., and John A. Welhan. 2013. "Geologic Map of the Goshen Quadrangle, Bingham and Bonneville Counties, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.

Pierce, Kenneth L., and Lisa A. Morgan. 1992. "The Track of the Yellowstone Hot Spot: Volcanism, Faulting, and Uplift." In *Regional Geology of Eastern Idaho and Western Wyoming*, edited by Paul K. Link, Mel A. Kuntz, and Piatt, Lucian B. Vol. 179. GSA Memoirs. Geological Society of America.

———. 2009. "Is the Track of the Yellowstone Hotspot Driven by a Deep Mantle Plume? — Review of Volcanism, Faulting, and Uplift in Light of New Data." *Journal of Volcanology and Geothermal Research*, The Track of the Yellowstone Hotspot, 188 (1): 1–25. https://doi.org/10.1016/j.jvolgeores.2009.07.009.

Pierce, Kenneth L., Lisa A. Morgan, and Richard W. Saltus. 2002. "Yellowstone Plume Head: Postulated Tectonic Relations to the Vancouver Slab, Continental Boundaries, and Climate." In *Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province*, 5–33. Idaho Geological Survey Bulletin 30.

Plager, Sharon. 2001. "Patterns in the Distribution of Volcanic Glass across Southern Idaho." Master's thesis, Pocatello, ID: Department of Anthropology, Idaho State University.

Pope, Aaron D. 2002. "Geology of the Wakley Peak, Idaho, 7.5' Quadrangle: Multiple Phases of Late Miocene to Pliocene Extension, and Relations to the Southern Hawkins Basin Volcanic Center." Master's thesis, Pocatello, ID: Department of Geology, Idaho State University.

Pope, Aaron D., James J. Blair, and Paul K. Link. 2001. "Geologic Map of the Wakley Peak Quadrangle, Bannock and Oneida Counties, Idaho." Idaho Geological Survey.

Poupeau, Gérard, François-Xavier Le Bourdonnec, Tristan Carter, Sarah Delerue, M. Steven Shackley, Jean-Alix Barrat, Stéphan Dubernet, Philippe Moretto, Thomas Calligaro, and Marina Milić. 2010. "The Use of SEM-EDS, PIXE and EDXRF for Obsidian Provenance Studies in the Near East: A Case Study from Neolithic Çatalhöyük (Central Anatolia)." *Journal of Archaeological Science* 37 (11): 2705–20.

Price, Kathleen B. 2009. "Geology of the Northern End of the Big Hole Mountains, Madison and Teton County, Idaho." Master's thesis, Pocatello, ID: Department of Geology, Idaho State University.

Price, Kathleen B., and David W. Rodgers. 2009. "Geologic Map of the North End of the Big Hole Mountains, Madison and Teton Counties, Idaho." Geologic Map. Moscow, ID: Idaho Geological Survey.

Raley, Patrick M. 2011. "Obsidian Procurement Area Studies: Excavations at Bear Gulch, Idaho." Master's thesis, Chico, CA: Department of Anthropology, California State University, Chico.

Rap, George "Rip," and Christopher L. Hill. 1998. *Geoarchaeology: The Earth Science Approach to Archaeological Interpretation*. New Haven, CN: Yale University Press.

Reed, William Gilmore. 1985. “An Approach to the Archaeological Identification of Shoshonean Subsistence Territories in Southern Idaho.” Master’s thesis, Department of Anthropology, Idaho State University.

Reid, Kenneth C. 2014. “Through a Glass Darkly: Patterns of Obsidian and Fine Grained Volcanic Toolstone Acquisition on the Southern Plateau.” In *Lithics in the West: Using Lithic Analysis to Solve Archaeological Problems in Western North America*, edited by Douglas H. MacDonald, William Andrefsky, Jr., and Pei-Lin Yu, 97–119. Missoula, MT: University of Montana Press.

Rember, William C., and Earl H. Bennett. 1979. “Geologic Map of the Dubois Quadrangle, Idaho.” Geologic Map. Geologic Map Series. Idaho Department of Lands, Bureau of Mines and Geology.

Richmond, Gerald M. 1973. “Surficial Geologic Map of the Warm River Butte Quadrangle, Yellowstone National Park and Adjoining Area, Idaho and Wyoming.” Geologic Map. Miscellaneous Geologic Investigations. United States Geological Survey.

Rust, A. C., and K. V. Cashman. 2007. “Multiple Origins of Obsidian Pyroclasts and Implications for Changes in the Dynamics of the 1300 BP Eruption of Newberry Volcano, USA.” *Bulletin of Volcanology* 69 (8): 825–45.

Sappington, Robert L. 1981a. “A Progress Report on the Obsidian and Vitrophyre Sourcing Project.” *Idaho Archaeologist* 4: 4–17.

———. 1981b. “Additional Obsidian and Vitrophyre Source Descriptions from Idaho and Adjacent Areas.” *Idaho Archaeologist* 5: 4–8.

———. 1984. “Procurement without Quarry Production: Examples from Southwestern Idaho.” In *Prehistoric Quarries and Lithic Production*, edited by Jonathon E. Ericson and Purdy, Barbara A. New Directions in Archaeology. Cambridge University Press.

SAS Institute Inc. 2021. “JMP.” SAS Institute Inc. https://www.jmp.com.

Scheiber, Laura L., and Judson Byrd Finley. 2011. “Obsidian Source Use in the Greater Yellowstone Area, Wyoming Basin, and Central Rocky Mountains.” *American Antiquity* 76 (2): 372–94. https://doi.org/10.7183/0002-7316.76.2.372.

Schmidt, Dwight L. 1962. “Quaternary Geology of the Bellevue Area in Blaine and Camas Counties, Idaho.” Technical report 62–120. Open-File Report. Reston, VA: United States Geological Survey.

Schroeder, Marvin L. 1969. “Geologic Map of the Teton Pass Quadrangle, Teton County, Wyoming.” Reston, VA: United States Geological Survey. https://pubs.er.usgs.gov/publication/gq793.

Scott, William E. 1982. “Surficial Geologic Map of Rhe Eastern Snake River Plain and Adjacent Areas, 111° to 115° W, Idaho and Wyoming.” Geologic Map. Miscellaneous Investigations Series, Map I-1372. Reston, VA: United States Geological Survey.

Shackley, M. Steven. 1988. “Sources of Archaeological Obsidian in the Southwest: An Archaeological, Petrological, and Geochemical Study.” *American Antiquity* 53 (4): 752–72. https://doi.org/10.2307/281117.

———. 2005. *Obsidian: Geology and Archaeology in the North American Southwest*. Tucson, AZ: The University of Arizona Press.

———, ed. 2011. *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. Springer.

———. 2012. “Portable X-Ray Fluorescence Spectrometry (PXRF): The Good, the Bad, and the Ugly.” *Archaeology Southwest Magazine* 26 (2): 1–8.

Shackley, M. Steven, Leah E. Morgan, and Douglas Pyle. 2017. “Elemental, Isotopic, and Geochronological Variability in Mogollon-Datil Volcanic Province Archaeological Obsidian, Southwestern USA: Solving Issues of Intersource Discrimination.” *Geoarchaeology* 33 (December). https://doi.org/10.1002/gea.21672.

Shott, Michael J. 2015. “Glass Is Heavy, Too: Testing the Field-Processing Model at the Modena Obsidian Quarry, Lincoln County, Southeastern Nevada.” *American Antiquity* 80 (3): 548–70.

———. 2018. “The Costs and Benefits of Technological Organization: Hunter-Gatherer Lithic Industries and Beyond.” In *Lithic Technological Organization and Paleoenvironmental Change*, 321–33. Springer.

Sims, Cort. 1979. “The Centennial Mountains: A Cultural Resource Overview.” Technical report. St. Anthony, Idaho: Targhee National Forest. https://www.academia.edu/2766193/The_Centennial_Mountains_A_Cultural_Resource_Overview.

Skinner, Craig E. 2011a. “Browns Bench Obsidian Source, Idaho, Nevada, and Utah.” Map. Corvallis, OR: Northwest Research Obsidian Studies Laboratory. https://www.sourcecatalog.com/image_maps/map_obsidian_idaho_brownsbench.pdf.

———. 2011b. “Idaho Obsidian Sources (Preliminary).” Map. Corvallis, OR: Northwest Research Obsidian Studies Laboratory. https://www.sourcecatalog.com/id/s_id.html.

———. 2011c. “Southwest Idaho Obsidian Sources with Widespread Geographic Distribution.” Map. Corvallis, OR: Northwest Research Obsidian Studies Laboratory. https://www.sourcecatalog.com/image_maps/map_obsidian_idaho_map1.pdf.

———. 2011d. “Wyoming Obsidian Sources.” Map. Corvallis, OR: Northwest Research Obsidian Studies Laboratory. https://www.sourcecatalog.com/wy/s_wy.html.

Skipp, Betty A., Mel A. Kuntz, and Lisa A. Morgan. 1990. “Geologic Map of the Mackay 4 (Grouse) SE Quadrangle, Butte County, Idaho.” Geologic Map. Reston, VA: United States Geological Survey.

Skipp, Betty A., Harold J. Protska, and David L. Schleicher. 1979. “Preliminary Geologic Map of the Edie Ranch Quadrangle, Clark County, Idaho, and Beaverhead County, Montana.” Geologic Map. Reston, VA: United States Geological Survey.

Skipp, Betty A., Lawrence G. Snider, Susanne U. Janecke, and Mel A. Kuntz. 2009. “Geologic Map of the Arco 30 x 60 Minute Quadrangle, South-Central Idaho.” Geologic Map. Moscow, ID: Idaho Geological Survey.

Speakman, Robert J., and M. Steven Shackley. 2013. “Silo Science and Portable XRF in Archaeology: A Response to Frahm.” *Journal of Archaeological Science* 40 (2): 1435–43.

Spear, Dallas B., and John S. King. 1982. “The Geology of Big Southern Butte, Idaho.” In *Cenozoic Geology of Idaho*, edited by Bill C. Bonnichsen and Roy M. Breckenridge, 26:395–403. Idaho Bureau of Mines and Geology Bulletin. Moscow, ID: Idaho Bureau of Mines and Geology.

Speth, John D., Khori Newlander, Andrew A. White, Ashley K. Lemke, and Lars E. Anderson. 2013. “Early Paleoindian Big-Game Hunting in North America: Provisioning or Politics?” *Quaternary International* 285: 111–39.

Stearns, Harold T., and Andrei Isotoff. 1956. “Stratigraphic Sequence in the Eagle Rock Volcanic Area near American Falls, Idaho.” *Geological Society of America Bulletin* 67 (1): 19–34.

Szymanowski, Dawid, Ben S. Ellis, Olivier Bachmann, Marcel Guillong, and William M. Phillips. 2015. “Bridging Basalts and Rhyolites in the Yellowstone–Snake River Plain Volcanic Province: The Elusive Intermediate Step.” *Earth and Planetary Science Letters* 415: 80–89.

Szymanowski, Dawid, Ben S. Ellis, Jörn-Frederik Wotzlaw, Yannick Buret, Albrecht von Quadt, Irena Peytcheva, Ilya N. Bindeman, and Olivier Bachmann. 2016. “Geochronological and Isotopic Records of Crustal Storage and Assimilation in the Wolverine Creek–Conant Creek System, Heise Eruptive Centre, Snake River Plain.” *Contributions to Mineralogy and Petrology* 171 (12): 1–15.

Thompson, Randy A. 2004. “Trade or Transport: Occurence of Obsidian from the Malad, Idaho Source in the Great Plains.” Master’s thesis, Pocatello, ID: Department of Anthropology, Idaho State University.

Trimble, Donald E., and Wilfred J. Carr. 1961a. “Geologic Map and Section of the American Falls Quadrangle, Idaho.” Geologic Map. Bulletin 1121-G. Reston, VA: United States Geological Survey.

———. 1961b. “Late Quaternary History of the Snake River in the American Falls Region, Idaho.” *Geological Society of America Bulletin* 72 (12): 1739–48.

Tuffen, Hugh, Stephanie Flude, Kim Berlo, Fabian Wadsworth, and Jonathan Castro. 2020. “Obsidian.” In *Encyclopedia of Geology*, edited by David Alderton and Scott A. Elias, Second, 1–6:196–208. Amsterdam, Netherlands: Elsevier.

Watkins, Anni M. 1998. “Geochemistry, Petrography, and Stratigraphy of the Tuff Os Steer Basin, Twin Falls and Cassia Counties, Idaho.” Master’s thesis, Pocatello, ID: Department of Geology, Idaho State University.

Watts, Kathryn E., Ilya N. Bindeman, and Axel K. Schmitt. 2011. “Large-Volume Rhyolite Genesis in Caldera Complexes of the Snake River Plain: Insights from the Kilgore Tuff of the Heise Volcanic Field, Idaho, with Comparison to Yellowstone and Bruneau–Jarbidge Rhyolites.” *Journal of Petrology* 52 (5): 857–90.

Weigand, Phil C., Garman Harbottle, and Edward V. Sayre. 1977. “Turquoise Sources and Source Analysis: Mesoamerica and the Southwestern USA.” In *Exchange Systems in Prehistory*, edited by Timothy K. Earle and Jonathon E. Ericson, 15–34. Elsevier.

Whitaker, Matthew L., Hanna Nekvasil, Donald H. Lindsley, and Michael McCurry. 2008. “Can Crystallization of Olivine Tholeiite Give Rise to Potassic Rhyolites?—An Experimental Investigation.” *Bulletin of Volcanology* 70 (3): 417–34. https://doi.org/10.1007/s00445-007-0146-1.

White, William M. 2015. “Probing the Earth’s Deep Interior through Geochemistry.” *Geochemical Perspectives* 4 (2): 95–251.

Williams, Paul L., Harry R. Covington, and James W. Mytton. 1991. “Geologic Map of the Stricker 2 Quadrangle, Twin Falls and Cassia Counties, Idaho.” Geologic Map. Miscellaneous Investigations Series, Map I-2146. Reston, VA: United States Geological Survey.

Williams, Paul L., James W. Mytton, and Harry R. Covington. 1990. “Geologic Map of the Stricker 1 Quadrangle, Cassia, Twin Falls, and Jerome Counties, Idaho.” Geologic Map. Miscellaneous Investigations Series, Map I-2078. Reston, VA: United States Geological Survey.

Williams, Paul L., James W. Mytton, and William A. Morgan. 1999. “Geologic Map of the Stricker 3 Quadrangle, Idaho and Nevada.” Geologic Map. Miscellaneous Investigations Series, Map I-2633. Reston, VA: United States Geological Survey.

Willingham, Charles G. 1995. “Big Table Mountain: An Obsidian Source in the Centennial Mountains of Eastern Idaho.” *Idaho Archaeologist* 18 (1): 3–7.

Willson, Christopher A. 2005. “X-Ray Fluorescence Analysis of Obsidian Associated with Late Archaic Sites in Southwestern Idaho and Southeastern Oregon, Issues in Addressing Mobility.” Master’s thesis, Department of Anthropology, University of Idaho.

———. 2007. “A Re-Evaluation of X-Ray Fluorescence Data from Idaho and Southeastern Oregon.” *Idaho Archaeologist* 30 (2): 17–26.

Witkind, Irving J. 1982. “Geologic Map of the Centennial Mountains Wilderness Study Area and Contiguous Areas, Idaho and Montana.” Geologic Map. Miscellaneous Field Studies, Map MF-1342-A. Reston, VA: United States Geological Survey.

Wood, Spencer H., and Drew M. Clemens. 2002. “Geologic and Tectonic History of the Western Snake River Plain, Idaho and Oregon.” In *Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province*, 69–103. Idaho Geological Survey Bulletin 30.

Wright, Gary A., Henry Chaya, and James McDonald. 1990. “The Location of the Field Museum Yellowstone (F.M.Y., 90) Group Obsidian Source.” *Plains Anthropologist* 35 (127): 71–74. https://doi.org/10.1080/2052546.1990.11909556.

Wright, Gary A., James B. Griffin, and Adon A. Gordus. 1969. “Preliminary Report on Obsidian Samples from Veratic Rockshelter, Idaho.” *Tebiwa* 12: 27–30.

Wright, Karen E. 1998. “Geochemistry and Petrology of the Tuff of McMullen Creek, Cassia County, Idaho.” Master’s thesis, Pocatello, ID: Department of Geology, Idaho State University.

Wright, Karen E., Michael McCurry, and Scott S. Hughes. 2002. “Petrology and Geochemistry of the Miocene Tuff of McMullen Creek, Central Snake River Plain.” In *Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province.*, edited by Bill C. Bonnichsen, Michael McCurry, and Craig M. White, 30:177–94. Idaho Geological Survey Bulletin. Moscow, ID: Idaho Geological Survey.