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RESEARCH ARTICLE

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Elemental, isotopic, and geochronological variability in Mogollon-Datil volcanic province archaeological obsidian, southwestern USA: Solving issues of intersource discrimination

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Abstract

Solving issues of intersource discrimination in archaeological obsidian is a recurring problem in geoarchaeological investigation, particularly since the number of known sources of archaeological obsidian worldwide has grown nearly exponentially in the last few decades, and the complexity of archaeological questions asked has grown equally so. These two parallel aspects of archaeological investigation have required more exacting understanding of the geological relationship between sources and the more accurate analysis of these sources of archaeological obsidian. This is particularly the case in the North American Southwest where the frequency of archaeological investigation is some of the highest in the world, and the theory and method used to interpret that record has become increasingly nuanced. Here, we attempt to unravel the elemental similarity of archaeological obsidian in the Mogollon-Datil volcanic province of southwestern New Mexico where some of the most important and extensively distributed sources are located and the elemental similarity between the sources is great even though the distance between the sources is large. Uniting elemental, isotopic, and geochronological analyses as an intensive pilot study, we unpack this complexity to provide greater understanding of these important sources of archaeological obsidian.

KEYWORDS

$^{40}Ar/^{39}Ar$ geochronology, Mogollon-Datil volcanic province, Sr, Pb and Nd isotopes, obsidian provenance

1 | INTRODUCTION

Since the 1980s, investigations of sources of archaeological obsidian in the Mogollon-Datil volcanic province of southwestern New Mexico have revealed at least five sources and source groups: Antelope Creek, Mule Mountains, North Sawmill Creek, all part of the Mule Creek obsidian complex; Gwynn/Ewe Canyon in the Mogollon Highlands; and Nutt Mountain in Sierra County. Some of this material, such as the Antelope Creek locality at Mule Creek, provided obsidian to prehistoric knappers from Paleoindian to historic times throughout the North American Southwest (Shackley, 2005; Figures 1 and 2), herein Southwest. Frustrating the discrimination of these sources for archaeological purposes is very similar elemental composition relative to other Southwestern sources that are as much as 150 km distant, thus equally complicating inferences of exchange, group interaction, social identity, and migration (Duff, Moss, Windes, Kantner, & Shackley, 2012; Hamilton et al., 2013; Mills et al., 2013a, 2013a; Shackley, 2005; Taliafero, Schriever, & Shackley, 2010b). This is an important issue for archaeology since X-ray fluorescence (XRF) spectrometry with relatively limited precision for many highly discriminating elements (i.e., rare earth elements) is the dominant analytical technique used in North America due mainly to the need for nondestructive analyses and significantly lower cost than other analytical methods (Shackley, 2008, 2011; see especially Glascock, 2011).

Here, we summarize the elemental, isotopic, and geochronological exploratory research into successful discrimination of these important Southwestern sources of archaeological obsidian in order to provide a database and strategy to deal with this problem, one that is present in other volcanic provinces worldwide (e.g., Argote-Espino, Solé, López-Garcia, & Stepone, 2011; Brown, Reid, & Negash, 2009; Chataigner & Gratuze, 2014; Glascock, 2011; Morgan, Renne, Taylor, & WoldeGabriel, 2009; Poidevin, 1998; Poupeau et al., 2010; Sahle, Morgan, Braun, Atnafu, & Hutchings, 2014; Shackley & Sahle, 2017; Vogel, Nomade, Negash, & Renne, 2006; Weisler & Woodhead, 1995). In order to provide clarity beyond XRF, we have acquired Sr, Pb, and Nd isotopic data along with $^{40}Ar/^{39}Ar$ ages from sample splits for these

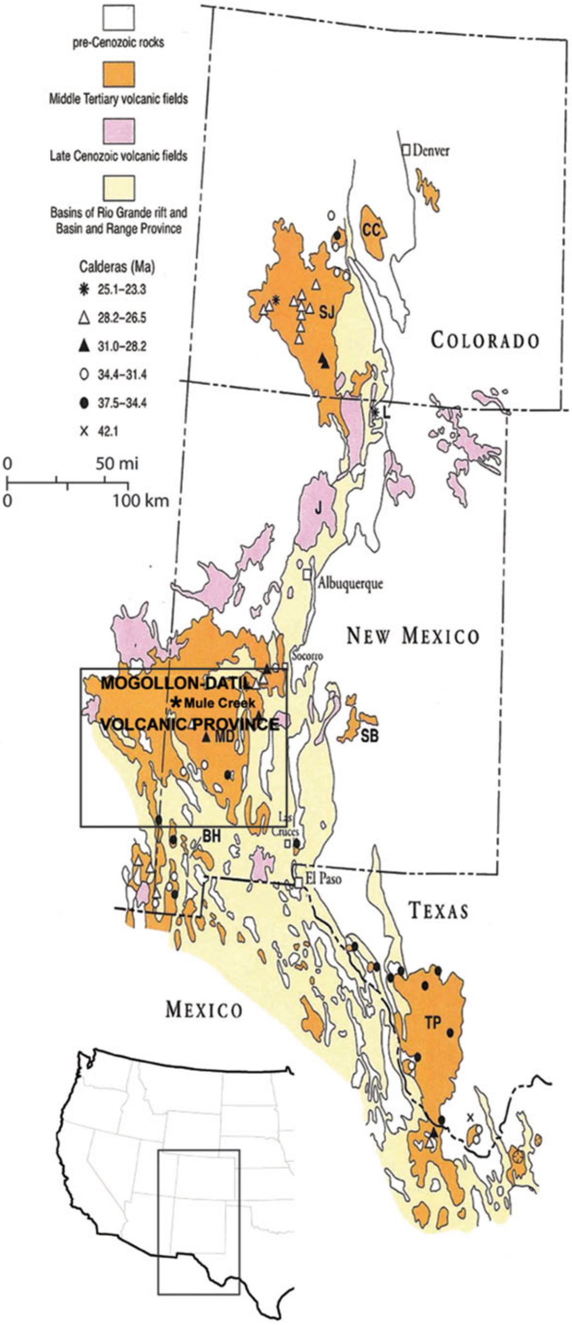

FIGURE 1 Cenozoic volcanism in the southwestern USA including the Mogollon-Datil volcanic province (adapted from Chapin et al., 2004). MD = Mogollon-Datil; SJ = San Juan; TP = Trans-Pecos. The others are not relevant here. Figure 2 located in square. Courtesy of New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NewMexico [Color figure can be viewed at wileyonlinelibrary.com]

sources (see Supplementary Document 1 for laboratory and instrumental methods for XRF, the isotopic analysis, and $^{40}Ar/^{39}Ar$ dating). While some of the sources have been dated by K-Ar in the past, the new $^{40}Ar/^{39}Ar$ ages provide greater precision and clarity in understanding eruptive histories and intersource relationships, particularly for the Mule Creek sources as well as geological and geoarchaeological interpretation of the region as a whole.

2 | THE MOGOLLON-DATIL VOLCANIC PROVINCE

The Mogollon-Datil volcanic province is part of a discontinuous belt of middle Cenozoic volcanism that runs from the Sierra Madre Occidental in west Mexico, through the Trans-Pecos volcanic field in west Texas, and northward to the San Juan volcanic field in southwestern Colorado (Figure 1). Geological studies of this very large volcanic province began in the 1930s, but in the last decade have essentially ceased as geological interest grew in other theoretical areas away from studies of crustal extension, particularly for the high-silica fluid depleted rhyolites that produced obsidian (*c.f.*Elston, 2001, 2008).

This region, which is on the boundary between the Basin and Range complex to the west and southwest, and the southeastern edge of the Colorado Plateau, exhibits a silicic geology that is somewhat distinctive; from the decidedly peraluminous glass of Cow Canyon with relatively high strontium values to the distinct chemical variability of the Mule Creek glasses (Elston, 1984; Ratté, Marvin, Naeser, & Bikerman, 1984; Rhodes & Smith, 1972; Shackley, 1988; Shackley, 1995; Shackley, 2005). The province has been named Mogollon-Datil for its location and major floristic association (Elston, 1965; Elston, Rhodes, Coney, & Deal, 1976).

Lavas and tuffs erupted from andesitic to silicic volcanoes, domes, and calderas coalesced to form the Mogollon-Datil volcanic province in southwestern New Mexico between ≈20 and 40 Ma (Chapin, Wilks, & McIntosh, 2004; Elston, 1984; Elston, 2008; McIntosh et al., 1991; McIntosh, Chapin, Ratté, & Sutter, 1992; Ratté et al., 1984). This feature, which includes the mountainous terrain of the Gila Wilderness, covers about 40,000 km^2. Initially, andesite volcanism occurred across this region 40 to 36 Ma. Later, both basaltic and andesitic events and silicic calderas formed between 36 and 20 Ma. Many of these eruptive events were very large ignimbrite (tuff) events, some of them silicic and responsible for the production of obsidian through rapid quenching at the margins and/or pyroclastic cooling (Elston, 1984, 2001, 2008). During the latter part of the sequence, silicic rhyolite dome complexes were formed as well, sometimes as ring events at the margins of calderas as at the Bursum caldera's Gwynn/Ewe Canyon obsidian source in the Mogollon Mountains and possibly Mule Creek, creating the very old, but still artifact quality obsidian (17.67-31.74 Ma) in this important archaeological region (Elston, 2001; Elston, 2008; Ratté, 2004; Shackley, 2005; see Table 1). The province is composed, in part, of two caldera complexes that were active at about the same time. The oldest eruptions of the southern complex occurred in the Organ Mountains near Las Cruces, New Mexico, about 36 Ma. Volcanic activity migrated from the Organ Mountains toward the northwest 220 km, in part producing the Nutt Mountain rhyolite and obsidian (31.74 ± 0.13 Ma) ending with the eruption of the 28 Ma Bursum caldera located northwest of Silver City, New Mexico (Figure 2). The Bursum caldera is responsible for the Gwynn/Ewe Canyons obsidian dated now to 28.13 ± 0.02 Ma (Table 1).

Caldera formation in the northern portion of the province started near Socorro, New Mexico, about 32 Ma and migrated toward the southwest, presumably including the Mule Creek complex

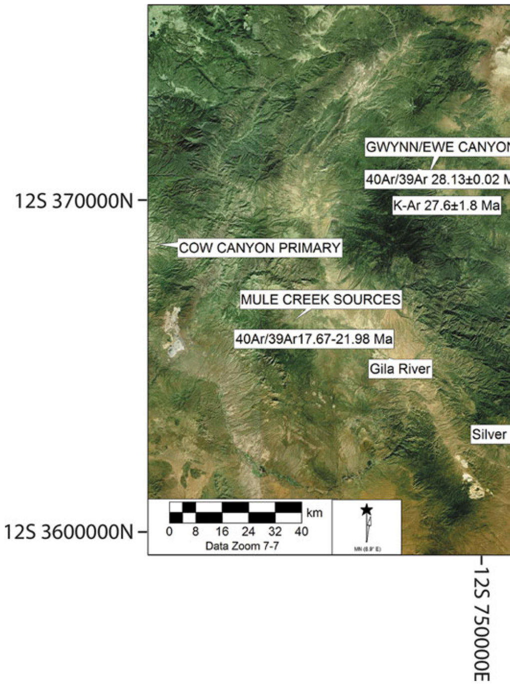

FIGURE 2 Satellite aerial image of the approximate location of Mogollon-Datil obsidian sources and ^{40}Ar/^{39}Ar ages discussed here. Cow Canyon and McDaniel Tank, although Mogollon-Datil obsidian sources, have not been dated, and given the high Sr concentrations making them easy to discriminate are not included in this study [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 ^{40}Ar/^{39}Ar data for Mogollon-Datil obsidians (see Supplemental Table 3 for raw data)

Field No.	Source Name	Material Dated	Age Ma	$\pm 2\sigma$	UTM ZONE	UTM-E	UTM-N	Previous K-Ar Dates (Marvin et al., 1987)
101308-1	Antelope Cr East	Obsidian	19.56	0.04	12S	686342	3672801	17.7 ± 0.6 Ma
092713	Antelope Cr West	Obsidian	19.433	0.013	12S	682964	3673061	n/a
081495-1	Mule Mountains	Obsidian	21.98	0.02	12S	698127	3665529	17.7 ± 1.9 Ma
MC/NS-1	North Sawmill Cr	obsidian	17.67	0.02	12S	686447	3664070	n/a
061193-1	Gwynn/Ewe Canyon	obsidian	28.13	0.02	12S	729214	3710762	27.6 ± 1.8 Ma
101208	Nutt Mtn	obsidian	31.74	0.13	13S	276185	3616787	n/a

(17.67–21.98 Ma), one of the most important sources of archaeological obsidian in the Southwest from Paleoindian to the historic periods (≈14 ka to A.D. 1540; Hamilton et al., 2013; Mills et al., 2013a, Mills et al., 2013b; Ratté, 2004; Shackley, 2005). The elemental and isotopic similarity among some of these obsidian sources is likely the result of near contemporaneous events over the very large area during the latter stages of volcanism in the province that sampled similar upper crustal magma, in this case granite plutons (Elston, 2008; Shackley, 2005; see Supplemental Tables 1 & 2).

3 | SOURCES OF MOGOLLON-DATIL ARCHAEOLOGICAL OBSIDIAN

As mentioned above, most of the sources of archaeological obsidian in the Mogollon-Datil region have been known to archaeologists and geologists for decades (Findlow & Bolognese, 1982; Hughes, 1988; Shackley, 1988; Stevenson & McCurry, 1990; Church, 2000; Shackley, 1992; Shackley, 1995; Shackley, 1998; Shackley, 2005; Ratté, 2004; Hamilton et al., 2013; Mills et al., 2013b; Taliafero et al., 2010). Sources geographically unknown until recently such as Nutt Mountain in Sierra County are considered "minor" sources and were essentially undetectable, in part due to the compositional similarity between the sources. In the case of Nutt Mountain, there is a close elemental similarity to the Mule Mountains source at the Mule Creek obsidian complex and the Gwynn/Ewe Canyons source in the Mogollon Mountains. The elemental similarity of these sources is a major driver of this research (Figures 3 and 4).

The Mule Creek sources have been of special concern to archaeology beginning in the 1980s, mainly due to their presence in sites throughout the Southwest, and more recently the investigation of long-distance migration and social networks from and to sites in the Mule Creek area from the Classic Mimbres to the Late Classic, a period from about A.D. 1100 to the mid 1300s (Stevenson & McCurry, 1990; Shackley, 1988; Taliafero et al., 2010; 2013a Mills et al., 2013a, 2013b). Recent geoarchaeological field schools sponsored by the Keck Foundation and the University of California, Berkeley, have included the Mogollon-Datil sources as part of summer fieldwork due to the need to understand and discriminate the sources in order to address more

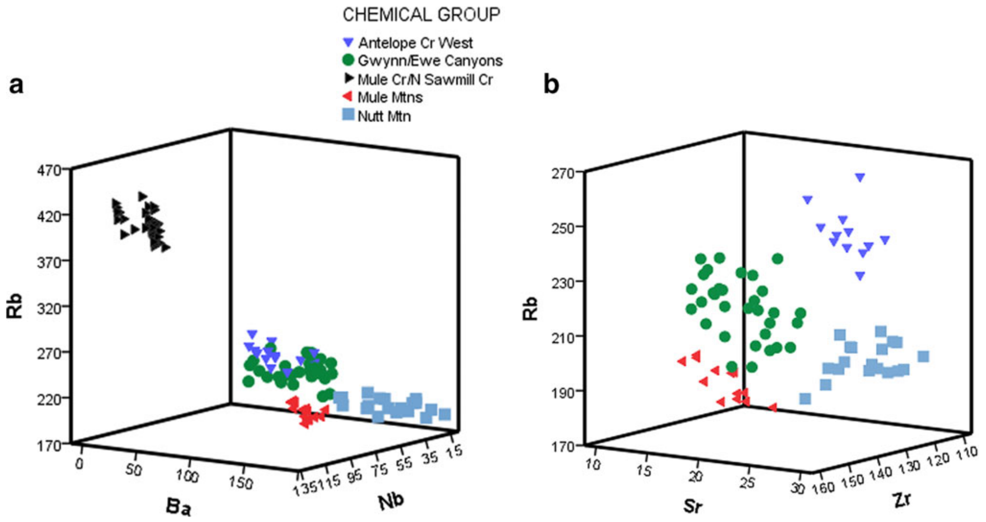

FIGURE 3 (A, left): Ba, Rb, Nb three-dimensional plot of all the Mogollon-Datil obsidian sources discriminating high Rb North Sawmill Creek source and indicating the similarity of the other sources in these trace elements. (B, right): Sr, Rb, Zr three-dimensional plot of the Mogollon-Datil obsidian sources minus N. Sawmill Creek. Note that the most commonly used source in prehistory, Antelope Creek West, is easily discriminated with these elements. Mule Mountains and Nutt Mountain similarly discriminate. See Figure 4 for more clarity [Color figure can be viewed at wileyonlinelibrary.com]

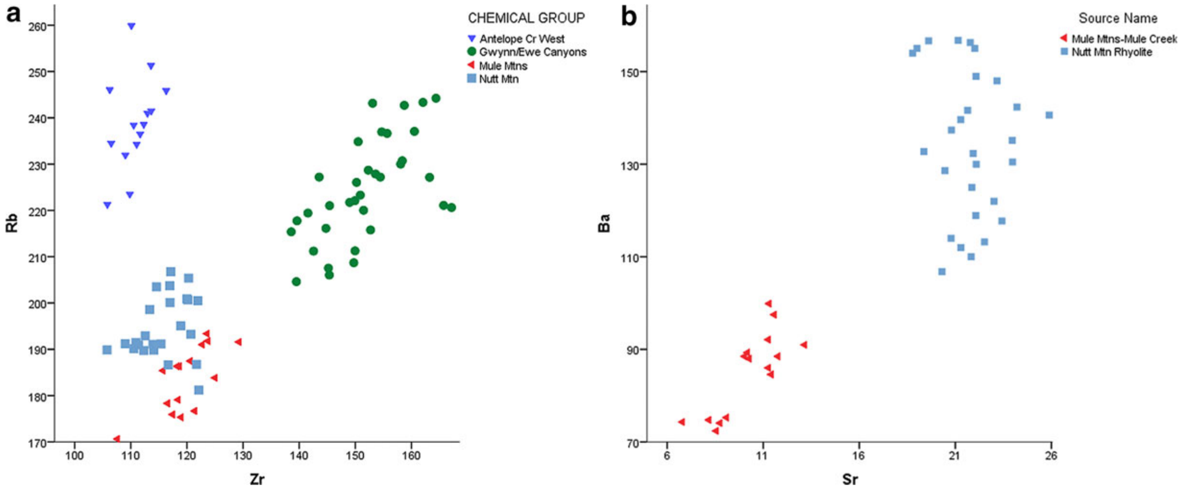

FIGURE 4 (A, left) Zr versus Rb bivariate plot of the Mogollon-Datil sources minus high Rb North Sawmill Creek. Here, Gwynn-Ewe Canyon and Antelope Creek West are easily discriminated, but Mule Mountains and Nutt Mountain are not. (B, right): Ba versus Sr bivariate plot providing better discrimination between Mule Mountains and Nutt Mountain. While these two large ion lithophile incompatibles tend to move into solid phase at about the same time and thus have a linear relationship, here they easily solve the discrimination problem, although the elemental separation of the Sr values in only about 5 ppm, and nearly overlapping in Ba. Using energy-dispersive XRF, it is important to derive low detection limits for Sr and Ba when attempting to discriminate these two sources (see also Figure 3) [Color figure can be viewed at wileyonlinelibrary.com]

nuanced 21st century archaeological issues mentioned above (Duff et al., 2012; Mills et al., 2013a, 2013a; Taliafero et al., 2010b; see also Joyce, 2011).

3.1 | The Mule Creek lava and ash-flow obsidian complex

Including secondary deposition, the Mule Creek sources are some of the geographically largest obsidian sources in the Southwest. The obsidian is, in part, found in a very extensive late Tertiary (Neogene) ash-flow sheet that covers portions of Greenlee County, Arizona, and Catron and Grants Counties, New Mexico (Ratté, 2004; Figures 2 and 5). The 100+ mm nodule size density at the Antelope Creek West locality reaches hundreds per 5 m^2, especially on the top of the ash hills. Erosion into basins and the San Francisco and Gila River systems has been occurring from the Mule Creek sources since 21.98 ± 0.02 Ma with the Mule Mountains event, and even more so with the volumetrically and numerically superior 19.433 ± 0.013 Ma Antelope Creek West event that is located just above and south of the San Francisco River Canyon (Shackley, 1998, 2005; see Figure 5).

Fieldwork and chemical analyses by Ratté and Brooks (1989) lead them to conclude that the Mule Creek caldera is actually just a graben, although the typical succession from intermediate to silicic volcanism apparently holds. The caldera structure seen originally by Rhodes

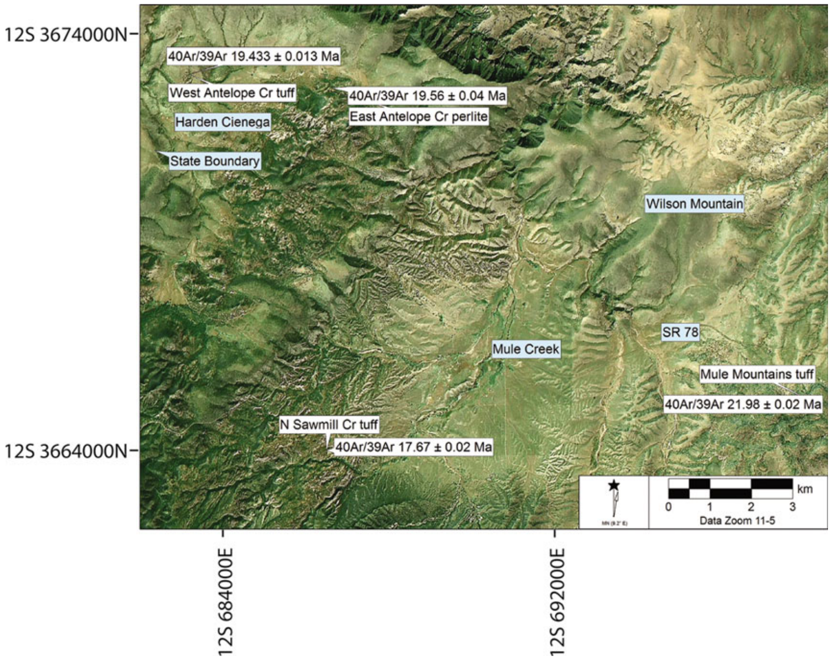

FIGURE 5 Satellite aerial image of the Mule Creek sources and corresponding ^{40}Ar/^{39}Ar ages. State boundary is the Arizona/NewMexico line [Color figure can be viewed at wileyonlinelibrary.com]

and Smith (1972) does seem sensible upon first glance, with a central graben surrounded by what could be interpreted as post-collapse ring eruptions including the structures discussed here: the Mule Mountains dome complex, North Sawmill Creek ash flow, and the Antelope Creek dome complex and ash flows (Figure 5). Elston has discussed the different definitions of calderas and cauldrons, and defined a cauldron from Smith and Bailey (1968) "as a structural term for 'all volcanic subsidence structures'" (Elston, 2001:51). He further observes that "in southwestern New Mexico we see faulted and eroded mid-Tertiary cauldron substructures and at best remnants of original caldera topography" (Elston, 2001:51). Using these criteria, Mule Creek could be considered a cauldron.

The obsidian was originally directly dated at the Antelope Creek locality (Antelope Creek East locality herein) to 17.7 ± 0.6 Ma by K-Ar, and at the Mule Mountain locality at the same statistical age (17.7 ± 1 Ma reported by Ratté and Brooks, 1983, 1989). The ^{40}Ar/^{39}Ar results in this study suggest that the K-Ar dating of obsidian at the Antelope Creek locality (Antelope Creek East here) was inaccurate, with the Antelope Creek locality now dated to 19.56 ± 0.04 Ma and Mule Mountains considerably older at 21.98 ± 0.02 Ma (Table 1). A single obsidian marekanite sampled from the perlitic lava at the Antelope Creek East locality by Ratté was used in the original K-Ar dating, and the marekanite used in this study is from the same locality (Jim Ratté, oral communication 2003, and Ratté, 2004; see sample 101308-1, Supplemental Table 1). Unusual for geological descriptions of the time, the obsidian proper was discussed as an integral part of the regional geology by Ratté and Brooks: Rhyolite of Mule Creek (Miocene). Aphyric, high-silica, alkali-rhyolite domal flows from the Harden Cienega eruptive center along southwestern border of quadrangle [Wilson Mountain 1:24,000 quad, New Mexico; Antelope Creek East locality herein]. Unit ob, commonly at the base of the flows, consists of brown, pumiceous glass that grades upward into gray to black perlitic obsidian and obsidian breccia. Extensive ledges of partly hydrated, perlitic obsidian contain nonhydrated obsidian nodules (marekenites) which, when released by weathering, become the Apache tears that are widespread on the surface and within the Gila conglomerate in this region. Age shown in correlation is from locality about 1 km south of tank in Antelope Creek in Big Lue Mountains quadrangle adjacent to west edge of the Wilson Mountain quadrangle. Thickness of flows is as much as 60 m and unit ob as much as 25 m (Ratté and Brooks, 1989:map text, bold as in original, bracketed comments by Shackley).

Shackley's (1995, 1995, 2005) study of Ratté's original locality (now Antelope Creek East) indicated that all of the marekanites exhibit perlitic cracking and are generally poor media for chipped stone tool production, even though Ratté and Brooks characterized them as "nonhydrated" (see above). Shackley has experimented using bipolar percussion on hundreds of marekanites from this locality since the 1980s and has found only perlitic marekanites, none of them what most stone tool makers would call artifact quality (Shackley, 1988, 2005). Furthermore, there are virtually no bipolar cores or flakes present over the large perlitic dome complex at this locality, suggesting as well, that it was not a major toolstone quarry in prehistory (see Shackley, 2005: 53–55). Given the poor quality of Antelope Creek obsidian, why were so many Antelope Creek artifacts occurring in prehistoric sites in the region for 14,000 years of prehistory? It was a conundrum for decades with no apparent resolution until the Antelope Creek West locality was discovered in 2013, an ash flow tuff deposit with abundant high artifact quality obsidian marekanites up to 100 mm in largest dimension and plentiful reduced cores and flakes throughout the deposit located just northwest of the Antelope Creek East dome complex (Figure 5).

Additionally, the location at the head of Cienega and Antelope Creeks flowing directly into the San Francisco River explained the

TABLE 2 Major, minor oxides and trace elements for the selected Mogollon-Datil obsidians (not normalized to RGM-1). See Supplemental Table 2 for "raw" elemental concentrations

Source/sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	Σ
	%	%	%	%	%	%	%	%	%	%	%	%	%
Mule Cr East 061309-1-6	3.969	0	11.552	77.308	0	5.18	0.625	0.054	0	0	0.06	1.112	99.86
Mule Cr West 092713-1-11	3.746	0	11.513	77.894	0	5.054	0.59	0.052	0.011	0	0.061	0.978	99.899
Mule Mtns 061393-1-4	3.609	0	11.474	77.954	0	5.525	0.454	0.107	0	0.002	0.074	0.705	99.904
N Sawmill Cr 061209-1-1	3.864	0	11.743	77.589	0	4.894	0.593	0.05	0	0.004	0.11	0.929	99.776
Nutt Mtn, Sierra Co. 062013-2	3.43	0	11.393	78.701	0	4.743	0.573	0.072	0.005	0	0.05	0.926	99.893
Gwynn/Ewe Cnyns 092813-2-2-1	3.693	0	12.242	76.906	0	5.13	0.524	0.182	0	0.004	0.072	1.056	99.809
RGM1-S4 (USGS standard)	3.976	0	12.167	74.366	0	5.169	1.497	0.259	0.009	0	0.051	2.288	99.782
	Zn	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th				
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm				
061309-1-6	44	251	17	45	110	25	64	28	29				
092713-1-11	41	238	16	41	111	25	73	28	32				
061393-1-4	41	174	12	25	109	27	57	23	32				
061209-1-1	68	408	8	73	102	110	14	32	41				
062013-2	37	218	13	42	104	22	58	26	28				
092813-2-2-1	48	222	19	28	154	24	61	29	36				
RGM1-S4	43	151	106	24	221	8	763	22	12				

relatively abundant secondary deposits of Antelope Creek obsidian flowing into the Gila River system as much as 100 stream km to the west (Shackley, 1992, 1998, 2005; Figure 3). None of the Antelope Creek obsidian recovered in downstream Gila River alluvium was of the perlitic character seen at Antelope Creek East. Indeed, recent research indicates that they would not survive stream transport for any distance (Shackley, 1992, 1998, 2005, 2012). The elemental composition of the two Antelope Creek localities overlaps significantly, and both differ considerably from the other Mule Creek complex obsidian sources (Figures 3 & 4; Table 2; Supplemental Table 2).

At least four distinct chemical groups are evident in Mule Creek area sources, distinguished by Rb, Sr, Y, Nb, Zr, and Ba, concentration values, and are named after the localities where marekanites have been found in perlitic lava and ignimbrites, originally named by Ratté: Antelope Creek (East and West localities 19+ Ma); Mule Mountains (≈22 Ma); and North Sawmill Creek (17+ Ma), all in New Mexico (Shackley, 2005; Ratté 2008; Figures 3 & 4; Table 1, Supplemental Table 2). Additionally, during the 1994 field season, a fourth subgroup was discovered downstream as secondary deposits in San Francisco River alluvium near Clifton, Arizona, and in older alluvium between U.S. Highway 191 and Eagle Creek in eastern Arizona north of Clifton (Shackley, 2005). This "low zirconium" subgroup was discovered in alluvium upstream from the juncture of the Blue and San Francisco Rivers, but the primary source has not been discovered. It is rare in archaeological contexts in the region, and the elemental data are not reported here (see https://swxrflab.net/mulecr.htm).

The Antelope Creek locality, after Government Mountain, Arizona, and the Jemez Mountains sources in northern New Mexico, was the most significant Southwestern source of obsidian since Paleoindian times, recovered in sites in the region in much greater frequency than any other of the Mogollon-Datil obsidians. Indeed, Antelope Creek obsidian has been recovered as artifacts from western Arizona into Texas, Oklahoma, Kansas, and south well into Mexico (Hamilton et al., 2013; Mills et al., 2013, 2013a; Taliafero et al., 2010b). The Late Classic (A.D. 1300–1400) inhabitants of the Mule Creek area as well as Classic Mimbres (A.D. 1000–1130) appear to have seen this obsidian as a commodity given its distribution over much of the Southwest (Mills et al., 2013a, 2013b; Figure 6). Clovis (Paleoindian) knappers in New Mexico often used the Antelope Creek West obsidian for point production, pointing to the Late Pleistocene significance of the area (Hamilton et al., 2013). Mule Creek, in part due to abundant surface water, high water tables, and relatively low elevation, was an important area for human occupation for 14,000 years as it remains today, particularly in the Late Classic of the late 13th and early 14th centuries A.D. (Mills et al., 2013b, 2013ab).

3.2 | The Gwynn/Ewe Canyon obsidian complex in the Mogollon Mountains

The Gwynn Canyon source data were originally provided by Chris Stevenson (then) of New Mexico State University's Obsidian Hydration Laboratory (Stevenson & McCurry, 1990; see also Hughes, 1988). The specimens for Shackley's original field collection were all procured in Ewe Canyon south of another source area in the Gwynn Canyon area (discovered first; see 2013 collection below; Shackley, 1988, 1995). The nodules (up to 50 mm in diameter) are found mainly in a volcanic-derived alluvium and within the washes. The glass is a high-quality material, but only 15 nodules were available for study from Stevenson (Shackley, 1988). No specific reduction areas were noted by Stevenson, but most nodules were picked up in the Gwynn Canyon bottom. The 15 original nodules studied all have waterworn black cortex and

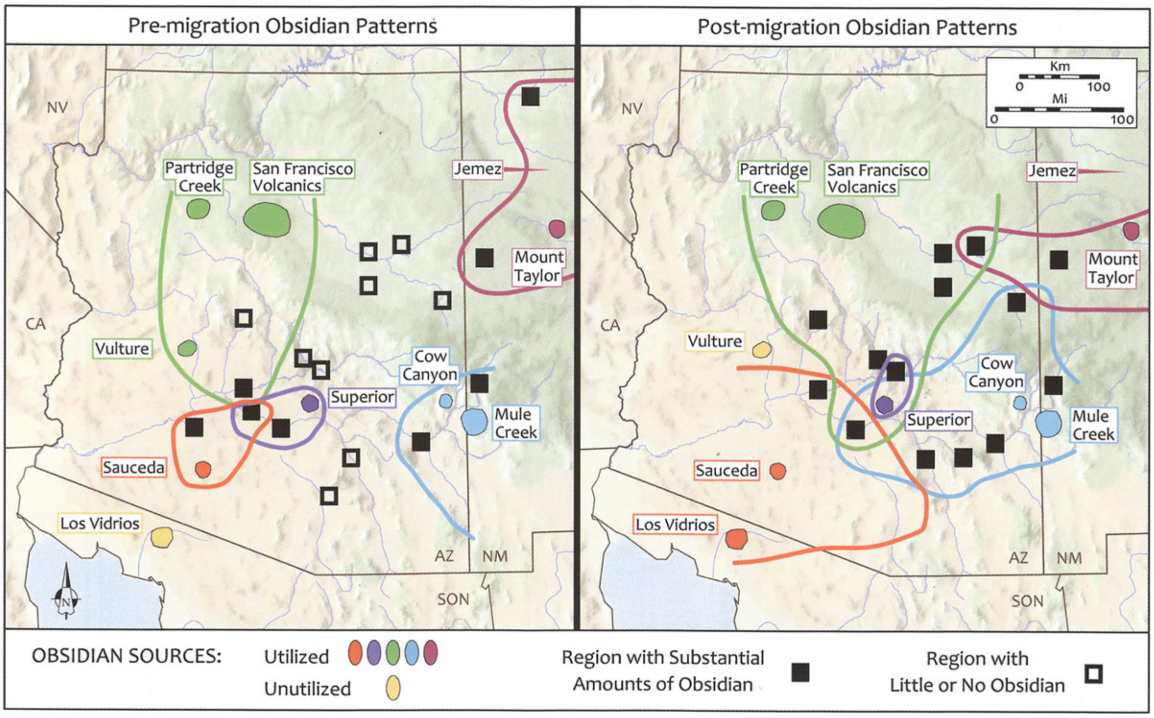

FIGURE 6 Left: Prior to the widespread migration and disruption of the late A.D.1200s, obsidian assemblages tend to follow distance decay models (nearest sources dominate suggesting territoriality). Right: Use of obsidian as a raw material increased significantly after A.D. 1300, when most sites deviate from distance decay expectations suggesting access to a variety of sources. As populations moved to the south and southeast, more southern sources like the Mogollon-Datil sources, mostly Mule Creek (Antelope Creek West), became dominant (adapted from Mills et al. 2013b; see also Taliafero et al., 2010; illustration by Catherine Gilman) [Color figure can be viewed at wileyonlinelibrary.com]

the aphyric glass ranges from an opaque black to a nearly transparent brown. Banding did not occur in this small sample.

Shackley's survey in 1993 indicated that marekanites were directly associated with glassy, perlitic rhyolite in Ewe Canyon to the south derived from a dome complex called Feathery Hill on the Telephone Canyon USGS 7.5′ quadrangle, Catron County, New Mexico (Shackley, 1995). This stream system erodes west toward the San Francisco River. These coalesced domes exhibit nodule densities in the regolith up to 200 per m^2. Unmodified marekanites on the domes have maximum diameters near 50 mm, although the vast majority (95%) is 30 mm and smaller. Bipolar cores and flakes were found on and near Feathery Hill, but in low densities ($<$ 1 per 100 m^2). As noted above, marekanites are eroding into the Ewe Canyon system and possibly the upper San Francisco River, although no nodules were noted in the San Francisco River alluvium as far as Alma, New Mexico.

Gwynn and Ewe Canyons were resurveyed in 2013 and more samples were collected. The location and general character of the Feathery Hill locality eroding into Ewe Canyon was confirmed, but another locality to the northwest, above Negrito Creek in Gwynn Canyon, was located and produced artifact quality marekanites. Initial survey of Gwynn Canyon above this locality indicated that no obsidian was present in Gwynn Canyon. Below the above-noted locality, however, abundant marekanites are entering Negrito Creek in Gwynn Canyon and possibly eroding into upper San Francisco River (see on-line map https://swxrflab.net/gwyncyn.htm). This locality is a dome complex consisting of perlitic lava near the military crest of the domes with a thin lahar below. While no marekanites were found *in situ* in the perlite, there were marekanites in the perlitic sand eroding directly from the perlitic lava. The marekanites, in sizes ranging from ≈30 mm to ≈50 mm, were found in a small wash eroding into Negrito Creek. The Feathery Hill obsidian erodes south through Ewe Canyon, while the obsidian in Gwynn Canyon is eroding west through Negrito Creek potentially into the San Francisco River system (see Figure 2). The elemental composition between these localities is similar (see Supplemental Table 2). A perlite sample analyzed from the dome complex on the north side of Gwynn Canyon is well within the range of variability indicating that the marekanites recovered are from the same magma source, although none were located *in situ* (Supplemental Table 2).

The 2013 collection also expanded the character (color, opacity, and sphericity) of these marekanites at the source. All of the marekanites from both localities are subrounded. A few of the samples from Feathery Hill are entirely mahogany to black/mahogany, not seen in the earlier collections or noticed in the archaeological record. The character varies from nearly opaque black to nearly transparent with black banding. There are no detectable elemental differences between colors. Published references for the geology of this source include Findlow and Bolognese (1982:56), the regional geology map by Weber and Willard (1959), and K-Ar age by Marvin et al. 1987 and Ratté et al. (1984).

The Gwynn/Ewe Canyon and Mule Mountains group at Mule Creek are similar in trace element composition. The Rb, Sr, Zr three-dimensional plot is the best method to discriminate these sources using

XRF, in this case energy-dispersive XRF (EDXRF; Figures 3 and 4). This can be an important issue in western New Mexico late prehistory, as noted above, since these sources are located in very different environments that may have had cultural significance in prehistory. Mule Creek, as discussed above, has been a high-quality agricultural area for at least the last 1000 years at about 1600 meters in elevation, but Gwynn/Ewe Canyon is located at over 2300 meters in elevation, an area probably only used for gathering and hunting in prehistory. No large archaeological sites are located in the area at this elevation. It is possible that during the Classic Mogollon period (≈A.D. 1000–1300), Gwynn Canyon obsidian could have been controlled by the Cibola branch of the Mogollon, while the Mule Creek sources could have been controlled by the Mimbres branch (see Taliafero et al., 2010). After the Classic Mogollon period territorial control becomes less well defined (Mills et al., 2013a; Taliafero et al., 2010; see Figure 6). This may or may not influence the spatial distribution of these obsidian sources in the region and confident source assignment can become crucial. Again, the secondary distribution of Mule Creek is quite extensive to the west through the San Francisco and Gila River systems, and the presence of Mule Creek glass in archaeological contexts to the west may not necessarily indicate that it was procured in the highlands, but could have been procured from Gila River alluvium (see Shackley, 1992, 1998, 2005).

3.3 | The Nutt Mountain source, Sierra County, New Mexico

In the late 1990s, Tim Church discovered a marekanite source southeast of the Nutt Mountain rhyolite dome in Sierra County, New Mexico. Shackley investigated the source in the late 1990s and more extensively in 2008 and 2013. What became immediately apparent in the XRF analysis of the samples was that most elemental concentrations overlapped those of the Gwynn/Ewe Canyon source in the Mogollon Mountains and the Mule Mountains source at Mule Creek. However, these three sources can be discriminated using Rb, Sr, Zr, and Ba (Figures 3 & 4), as well as the isotopic data and ^{40}Ar/^{39}Ar ages presented here (Figure 5, Table 1; Supplemental Tables 3 & 4). There is no clear geological relationship between these three sources as evident here based on isotopic and geochronological data, other than all being derived from the upper crust of the Mogollon-Datil volcanic province (Tables 1 & 2; Supplemental Tables 2, 3, & 4). While Nutt Mountain can be considered a "minor" source that does not seem to occur in archaeological contexts beyond the southern New Mexico area, its geochemical similarity to the Mule Mountains locality at Mule Creek was initially a cause for concern. Using Rb, Zr, and Ba elemental concentrations, Gwynn/Ewe Canyon and Nutt Mountain can be discriminated (Figures 3 & 4). Mule Mountains and Nutt Mountain can be discriminated with Sr and Rb and to a certain extent Y and Ba.

The marekanites are distributed throughout a large ash flow tuff east of the Nutt Mountain rhyolite, but there is no obsidian directly associated with the Nutt Mountain dome. A chalcedony outcrop, extensively "quarried" in prehistory exists on the east slope of Nutt Mountain and in the bajada eroding from it. There are bipolar banded rhyolite cores and flakes throughout the surface of the tuff in addition to marekanites and obsidian bipolar cores and flakes. The obsidian within and above the tuff covers thousands of square hectares, but the density is irregular, ranging from 1 per ≈500 m^2 to 50 per 5 m^2. Marekanites up to 40 mm in largest dimension were recovered; most are 30 mm or smaller including pea-sized nodules. Many of the samples are near transparent, but many have some banding or smoky clouding, not significantly different from most Tertiary marekanite sources in the Southwest including the other Mogollon-Datil obsidians (Shackley, 2005). The reduced size of these nodules is, at least, in part due to the great age, the oldest in this study and probably the oldest yet dated in North America at 31.74 ± 0.13 Ma and consequent devitrification over time. The small nodule size is also a likely reason that it was not used extensively for a toolstone in prehistory compared to the other Mogollon-Datil sources, especially Antelope Creek West.

The Gwynn/Ewe Canyons and Mule Mountains sources, along with the Nutt Mountain source farther south in Sierra County, New Mexico, are sometimes recovered in archaeological contexts in the Southwest, particularly the two former sources. These sources are also less common in archaeological contexts compared to Antelope Creek West locality obsidian at Mule Creek, with nodules one-half the size of Antelope Creek. While the presence of obsidian artifacts in archaeological contexts may be partly a function of the social and territorial issues at Mule Creek proper, it is likely mainly due to the sheer quantity and larger nodule sizes at the Antelope Creek locality, as well as secondary depositional effects to the west of the primary source (Mills et al. 2013b; Shackley, 2005). However, as discussed, these other sources exhibit elemental compositions, particularly those based on XRF technology, that are similar and require care in discrimination.

3.4 | Other Mogollon-Datil obsidian sources

Cow Canyon, a Tertiary period obsidian source located west of the Blue River and north of Clifton, Arizona, is mapped as part of the Mogollon-Datil volcanic province, as is the McDaniel Tank source recently discovered by Jeff Ferguson in the San Mateo Mountains, south of Magdalena, New Mexico (Jeff Ferguson, oral communication, 2013; Shackley, 1988, 1995, 2005; https://swxrflab.net/mcdaniel_tank_rhyolite.htm). The elemental concentrations of these two sources, however, are quite distinctive with relatively high Sr, and pose no problem in discrimination from the other Mogollon-Datil obsidian sources, and will not be discussed here (see https://swxrflab.net/swobsrcs.htm).

4 | THE ANALYTICAL PROBLEM AND RESEARCH TRAJECTORY

As mentioned above, significant elemental similarity between these Mogollon-Datil obsidian sources, particularly since non-destructive analyses are necessary, requires careful "stepped analyses" and

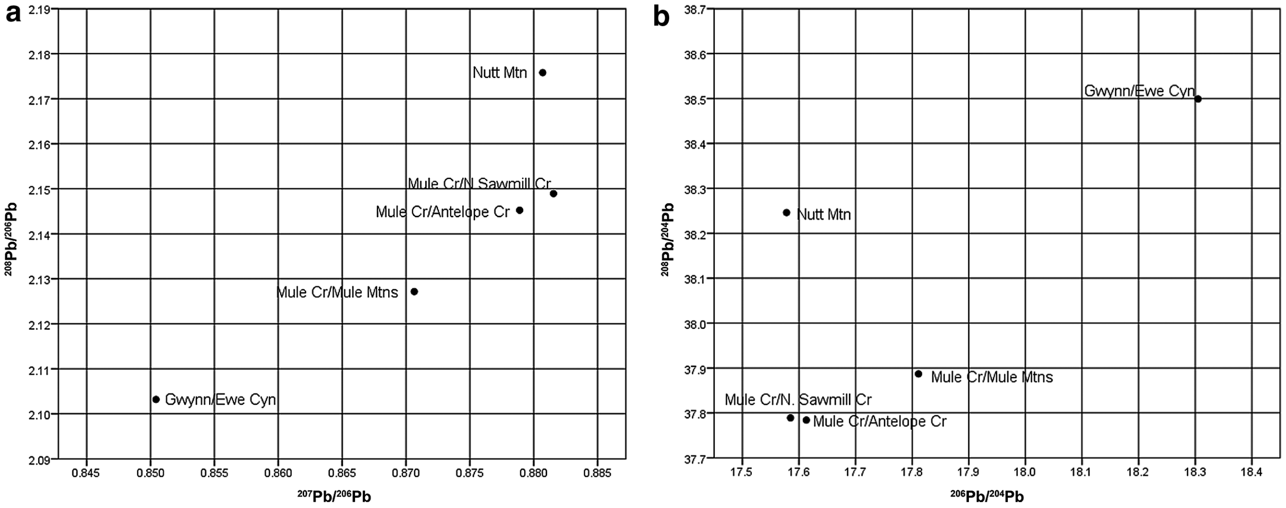

FIGURE 7 Plots of two of the Pb isotope ratios. Note the isotopic similarity between the Antelope Creek and North Sawmill Creek obsidian sources at Mule Creek, while the elemental concentrations, particularly on Rb and Nb are quite different, possibly a reflection of fractionation before eruption at North Sawmill Creek (see Figure 4). See Supplemental Table 1 for additional isotope plots. Uncertainties are smaller than plotted symbols

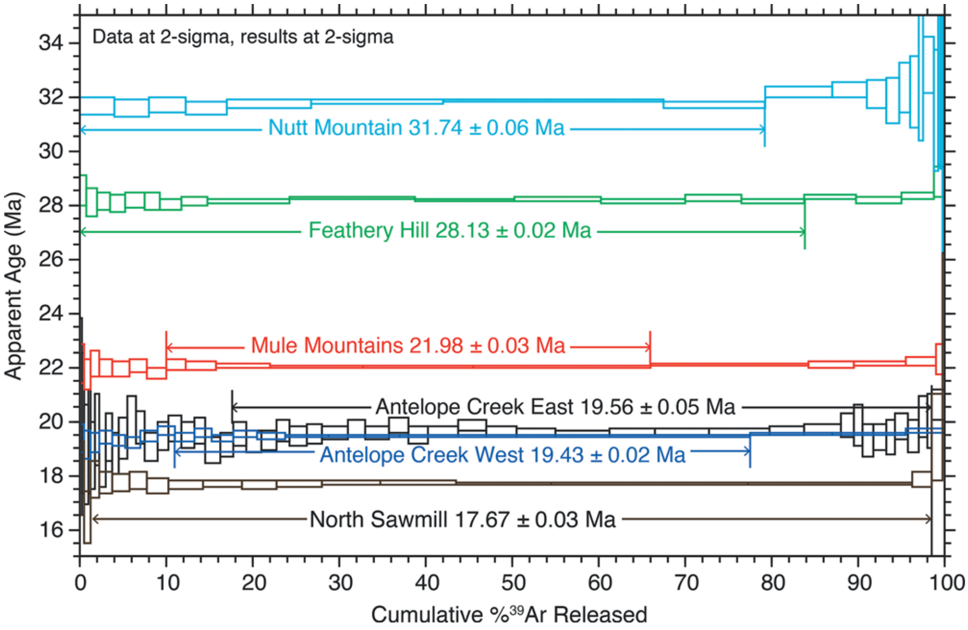

FIGURE 8 ^{40}Ar/^{39}Ar age spectra from step-heating analyses of all samples presented here. Raw data in Supplemental Table 3. Feathery Hill = Gwynn/Ewe Canyon source [Color figure can be viewed at wileyonlinelibrary.com]

knowledge of the geological setting of the region and sources. In order to determine whether the elemental overlap represents truly similar crustal origin, but differing isotopic signatures, a Sr, Pb, Nd isotope study was initiated (see Isotope Analysis Methods in Supplemental Document 1; Figures 7 & 8; and Supplemental Table 3). While the results probably indicate crustal derivation typical for Tertiary rhyolites in western North America (Kemp & Hawkesworth, 2004), the sources are isotopically distinct, and although Antelope Creek and North Sawmill Creek localities at Mule Creek are isotopically similar, they can be easily discriminated elementally with the high Rb and Nb of North Sawmill Creek obsidian as discussed above (Shackley, 2005; Table 2; Supplemental Table 2). While Rb, Sr, Y, Zr, Nb, and Ba are useful discriminating elements, especially Rb, Sr, Zr, and Ba, they are best employed in a stepwise fashion, a stepped analytical trajectory:

1. Rb and Nb discriminates North Sawmill Creek from all the other Mogollon-Datil obsidian (Figure 3).
2. Antelope Creek is easily discriminated with its high Rb and low Zr in any plot with these elemental concentrations (Figures 3 & 4).
3. Gwynn/Ewe Canyons, Mule Mountains, and Nutt Mountain are particularly troublesome, but can be discriminated with Rb, Sr, Zr, and Ba (see Figures 3 & 4). Parenthetically, this means that many portable XRF (PXRF) instruments that cannot acquire Ba Kα lines would be less useful for discriminating the Mogollon-Datil obsidian

sources, although recently a number of PXRF manufactures include higher-Z elements in their instruments (see Speakman & Shackley, 2013).

4.1 | Field methodology and sampling

Shackley has discussed a strategy for sampling archaeological obsidian sources in the field and laboratory elsewhere (Shackley, 1998, 2005, 2008, 2011). For all sources examined since the early 1990s, attempts have been made in the field to determine the horizontal extent of the exposures in the field, collect samples from various points, and record with Geographic Positioning System (GPS) these intra-source localities to determine the locations of potential intra-source variability. Attempts are made to collect 200 to 1000 samples from each source, from which a simple random sample (with replacement) is removed for XRF analysis in the laboratory. Usually, the largest and smallest geological sample is also selected outside the random sampling, due to the sample size (small vs. large) issues inherent in XRF (see Shackley, 2011). All the sources reported here were sampled in this manner. For the Antelope Creek source at the Mule Creek obsidian complex, the initial collection was made during the Keck Foundation sponsored archaeological obsidian field school in 2013. Here, transect survey and collection were accomplished using a number of participants and collection points recorded by GPS. Collecting samples from and determining the extent of secondary deposits downstream is also part of the field sampling strategy as discussed in detail elsewhere (Shackley, 1998, 2005).

5 | DISCUSSION

While it is easy to assume that the elemental discrimination of these Mogollon-Datil sources is a unique problem, as mentioned above, it is unfortunately neither unique, nor is this stepped analytic method necessarily new, but rarely explained in the literature (*c.f.* Hughes & Smith, 1993). These sources, particularly Antelope Creek, are extremely significant for inferences of social identity, migration and social networks, exchange and procurement in Southwest prehistory, and thus successful source provenance assignment has substantial research potential (see Figure 6). We know that while these rhyolites are all derived from the upper crust and older granite plutons from geologically rapid large-scale eruptive events, and thus are similar isotopically and elementally, they can be discriminated using a stepped analytical trajectory. In addition, it is apparent that Antelope Creek West of the Mule Creek obsidian complex is the most common source used in the region with a larger nodule dimension and numerically superior at both the primary source and secondary deposits through Antelope and Cienega Creeks to the San Francisco River, and on through the Gila River well west into Arizona. We can and should use that as the first approximation from which the stepped analytical trajectory can be applied. Importantly, the extent, marekanite size, and purity (with respect to other secondarily deposited sources such as Cow Canyon) of secondarily deposited Antelope Creek West obsidian in the Gila River and tributaries seem to be an important avenue for future research considering its extensive prehistoric use.

5.1 | Isotopic and geochronological contribution

This isotopic and geochronological pilot study was instituted to resolve the issue of discriminating similar elemental compositions of the Mogollon-Datil obsidian sources, some of which are over 100 km distant, and thus certainly not from the same magma sources. Due to fiscal constraints given the cost of high-quality isotopic and geochronological analyses, the number of samples analyzed remains small. While not a specific goal here, some of the previously K-Ar dated obsidians were shown to be inaccurate by tens of millions of years—pointing yet again to the value of re-dating with modern ^{40}Ar/^{39}Ar methodology, and solidifying this method's utility for addressing archaeological problems (see Morgan et al., 2009; Sahle et al., 2014; and Vogel et al., 2006). With regard to isotopic analyses in archaeology, laser applications are making isotope analyses much quicker, less expensive, somewhat less destructive, and readily amenable to rocks with high concentrations of Pb, Nd, and Sr. Therefore, analytical costs are becoming less of an issue, but still well out of range for most archaeological investigations. In regions where the distance to source is great and the potential for misassignment to source is equally great, such as the Pacific Basin, isotopic analyses backing XRF or inductively coupled plasma-mass spectrometry (ICP-MS) could very well be necessary (see Weisler & Woodhead, 1995).

As noted previously, we can discriminate these important sources of archaeological obsidian using a stepped analytical approach with XRF-derived elemental concentrations. The goal here was to verify that this method was not only sound, but had a geological basis. The inclusion of isotope and ^{40}Ar/^{39}Ar analyses is not a method usually applied in the archaeological endeavor, but in this case provides clarity and substantiation of the XRF method, the most frequently used method in archaeological chemistry, at least in North America, for reasons elucidated here (Shackley, 2005, 2011). Although other geochemical methods (e.g., instrumental neutron activation analysis, ICP-MS) can also be useful in discriminating between sources, isotopic and chronological methods may be necessary in some cases (*c.f.* Glascock, 2011). The geochemical data are applicable beyond its utility for tracing artifacts. There are few Pb isotope analyses of obsidians in the region (mostly only Sr and Nd) so the data are useful to petrologists and geochemists doing work on obsidian formation/crustal source in the region. This is the geological focus, and we were concerned that the elemental composition of Mule Mountains and Nutt Mountain is within 5 parts-per-million (ppm) for a number of elements. Were they truly isotopically different? The answer is yes, and the isotopic as well as elemental composition does indicate similar crustal derivation. This will be useful to both the geological and archaeological communities, as it is with the authors from both disciplines. So, although isotopic and geochronological methods are more involved than those typically used for a study of archaeological obsidian, here in addition to confirming source discrimination for geoarchaeology, they also provide valuable data for a more perceptive understanding of this volcanic province.

The late Wolf Elston not too long ago lamented the lack of more recent research in the Mogollon-Datil (Elston, 2001, 2008). It seems that in some regions, geoarchaeological research becomes the driver of geological study, and perhaps that is as it should be.

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SUPPORTING INFORMATION

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