REPORTS

SOURCES OF IMPORTED OBSIDIAN AT POSTCLASSIC SITES IN THE YAUTEPEC VALLEY, MORELOS: A CHARACTERIZATION STUDY USING XRF AND INAA

Michael E. Smith, Adrian L. Burke, Timothy S. Hare, and Michael D. Glascock

This paper presents the results of obsidian characterization analyses for Middle and Late Postclassic sites in the Yautepec Valley of Morelos, central Mexico. A large sample (N = 390) of obsidian blades from excavated domestic contexts at the site of Yautepec and from surface collected contemporary sites were assigned to a quarry source using X-ray fluorescence (XRF), and a subsample was also analyzed with instrumental neutron activation analysis (INAA). The use of XRF allowed the authors to expand the number of artifacts initially analyzed by INAA. These larger samples of sourced material prove essential to answering research questions regarding regional economies, particularly with regard to issues such as production and exchange. This study demonstrates the complementarity of XRF and INAA and the specific advantages inherent in each of these techniques.

Presentamos un análisis de la caracterización química de las obsidianas procedentes de sitios del Posclásico Medio y Tardío en el valle de Yautepec, México central. Una muestra importante (N=390) de lascas de obsidiana recuperadas en contextos domésticos en el sitio de Yautepec y de otras colecciones de superficie de sitios contemporáneos pudieron ser asignadas a canteras usando la fluorescencia de rayos X (XRF), y en una submuestra la activación neutrónica (INAA). El uso de la técnica de XRF permitió aumentar el número de artefactos inicialmente analizado por INAA. Estas muestras más grandes que incluían materiales de procedencia de origen permitió responder a preguntas sobre la economía regional, en particular las cuestiones en torno a la producción y el intercambio. Los datos que presentamos aquí demuestran las ventajas de la complementariedad en el uso de las técnicas de análisis de XRF y INAA, aprovechando las ventajas específicas de cada una de ellas.

Obsidian was and is abundant in highland central Mexico. A score of geological source areas are known today, many of which consist of numerous discreet procurement zones (Cobean 2002). Obsidian from these geological sources has distinctive chemical signatures in the presence and abundance of trace elements, and the artifacts from different sources can be distinguished by several chemical characterization methods. Unlike regions where obsidian was a rare and valuable exotic import, in central Mexico obsidian implements were abundant utilitarian objects present in large quantities at most archaeological sites. Several decades of chemical characterization research have documented the use of numerous obsidian sources at a variety of sites in central Mexico (Cobean 2002; Glascock et al. 1998).

Nevertheless, our understanding of systems of obsidian exchange remains rudimentary, for several reasons. First, most studies have tested only a small number of artifacts due in part to the costliness of the dominant analytical technique, instrumental neutron activation analysis (INAA). Second, most studies have employed poor sampling procedures that do not permit the chemical results to be generalized from the nonrandom samples to wider populations of interest (Smith and

Michael E. Smith ▪ School of Human Evolution and Social Change, Box 2402, Arizona State University, Tempe, AZ 85287 (mesmith9@asu.edu)
Adrian L. Burke ▪ Département d'Anthropologie, Université de Montréal, C.P. 6128, Succursale Centre-ville, Montréal, Québec, CANADA H3C 3J7 (adrian.burke@umontreal.ca)
Timothy S. Hare ▪ Institute for Regional Analysis and Public Policy, Morehead State University, 100 Lloyd Cassity Building, Morehead, KY 40351 (t.hare@morehead-st.edu)
Michael D. Glascock ▪ 230 Research Reactor Center, University of Missouri, Columbia, MO 65211 (glascockm@missouri.edu)

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Schreiber 2005). Third, many analyses have been conducted without explicit research goals, limiting the extent of the conclusions that can be drawn from the analytical results.

As a result of these limitations, a number of basic research questions about central Mexican obsidian exchange systems remain unanswered. For example, to what extent did minor sources like Fuentezuelas or Zacualtipan supply obsidian to central Mexican peoples? Did obsidian from Tarascan sources cross the hostile Aztec/Tarascan frontier to be traded in central Mexican exchange systems? To what extent was obsidian production and exchange controlled or administered by city-states or by the Aztec empire? Was it distributed primarily through commercial markets or through tribute, taxes, and elite gift channels? Why did individual settlements and households have obsidian tools from a large number of different geological sources?

In this paper we address some of these research questions with a large sample of obsidian characterization data from Middle and Late Postclassic sites in the Yautepec Valley of Morelos. In comparison with prior studies, our research is notable for the large sample (390 artifacts sourced); for the use of random sampling in the selection of one component of that sample; and for the inclusion of both excavated household contexts and surface collected regional contexts within an integrated study. We were able to analyze such a large sample of artifacts because we used the less-expensive technique of X-ray fluorescence (XRF), coupled with targeted analyses of key artifacts by INAA. The combination of INAA and XRF allowed the processing of a large sample at a high level of accuracy, precision, and reliability. Our study therefore also has methodological implications for continuing obsidian characterization research in Mesoamerica.

Instrumental neutron activation analysis (INAA) is generally recognized as the most accurate method for assigning archaeological obsidian artifacts to their geological source. INAA has a long history of use in the analysis of Mesoamerican obsidian (Asaro et al. 1978; Cobean et al. 1991; Glascock et al. 1998; Pires-Ferreira 1975). With a large database of geological source samples and many years of experience, laboratories like MURR have established an impressive record of success in obsidian sourcing analysis (Glascock et al. 1998; Glascock et al. 1994). One drawback to INAA, however, is its higher cost and limited availability relative to other methods of chemical characterization such as X-Ray Fluorescence (XRF). This cost has been partly reduced by the use of an abbreviated INAA technique and short irradiations that allow larger samples to be analyzed via INAA (Dreiss et al. 1993; Glascock et al. 1994; Stark et al. 1992).

XRF has been used in the past to successfully source obsidian artifacts in Mexico and Guatemala (e.g., Pollard and Vogel 1994), and in some cases it has been combined with INAA (Ford et al. 1997; McKillop et al. 1988; Stross et al. 1983); see also Asaro et al. (1994). XRF has not been applied as extensively to archaeological research in Mesoamerica as it has in the U.S. Southwest and the Great Basin however (e.g., Hughes 1984; Jackson 1986; Shackley 1995). As an analytical technique, XRF can attain similar accuracy, precision, and reliability to INAA, but it generally does not match the detection limits of INAA.

The present study therefore continues within this tradition of chemical sourcing and expands the role of XRF as a precise, accurate, and reliable method of identifying the geological sources of central Mexican obsidian artifacts. We argue that the optimal long-term solution to sourcing obsidian is not to employ solely high-precision (and high-cost) INAA, as advocated by Glascock et al. (1998), but rather to use INAA in conjunction with more widely available methods like XRF that consequently permit the analysis of even larger samples of artifacts. Our research is a case study of this approach. We describe our methods and results and then discuss some of the implications of our data for the nature of exchange systems in Postclassic central Mexico. Figure 1 shows the location of Yautepec in relation to the central Mexican obsidian sources.

Source Data and Artifact Sampling

Obsidian Sources and Source Samples

We employed two types of source samples to assign geological origins to the artifacts: quarry samples and artifacts analyzed by INAA (Table 2). Thirty quarry samples were gathered by Smith and Susan Norris in 1993. With the aid of Thomas H. Charlton, obsidian pieces were gathered from the sources

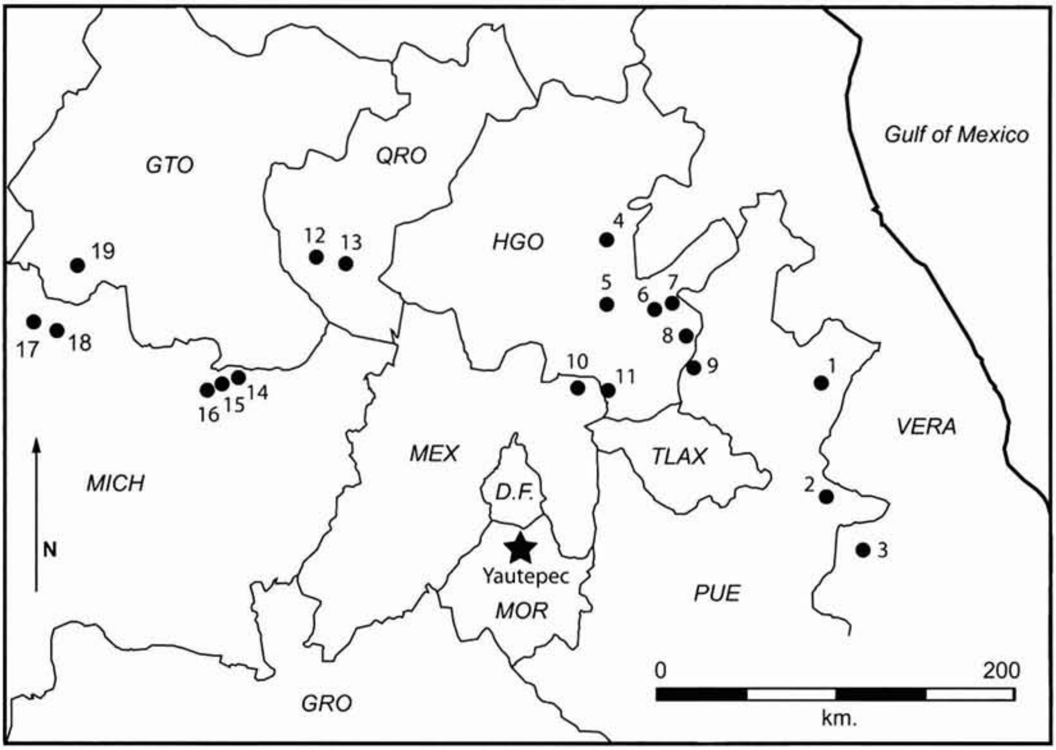

Figure 1. Map of the location of Yautepec in relation to central Mexican obsidian sources (map by Michael D. Glascock). Sources are listed in Table 1. For the locations of sources identified in this study, see Figure 5 below.

of Pachuca (Sierra de las Navajas; 9 pieces), Otumba (10 pieces), and Pizzarin (5 pieces). We obtained five pieces of Zinapecuaro obsidian from Kenneth G. Hirth and one piece of Ucareo obsidian from Dan Healan. These are the samples listed under "quarry" in Table 2.

Table 1. Key to Obsidian Sources Shown in Figure 1.

Code	Source	Utilized
1	Zaragoza	x
2	Guadalupe Victoria	
3	Pico de Orizaba	
4	Zacualtipan	x
5	Sierra de Pachuca	x
6	Tulancingo (Pizzarin)	x
7	Tepalzingo	
8	Santa Elena	
9	Paredon	x
10	Otumba	x
11	Malpais	
12	El Paraiso	x
13	Fuentezuelas	x
14	Ucareo	x
15	Cruz Negra	
16	Zinapecuaro	x
17	Cerro Zinaparo	
18	Cerro Varal	
19	Penjamo	

Note: "Utilized" refers to sources identified in this study.

In 1996 30 artifacts from unit 503 at Yautepec were submitted to MURR for INAA sourcing. The goals were to explore the range of sources represented in the gray obsidian at Yautepec, and to obtain firmly sourced artifacts that could serve as source samples for XRF at Albany. Ten artifacts were chosen by Hare (in 1994) from deposits of each of three phases—Pochtla, Atlan, Molotla (Hare and Smith 1996)—as represented in the dense stratified midden of unit 503. From the levels dating to each phase, one green obsidian artifact was selected, and nine gray artifacts. An effort was made to maximize the variability in the visual characteristics of the gray obsidian in this sample. These 30 artifacts were analyzed at MURR, revealing seven central Mexican sources (NAA-1 in Table 2); the INAA methods employed are discussed below.

Through XRF, these 60 source samples (batches 1 and 3; Table 3) were used to assign preliminary geological sources to 360 artifacts selected from

Table 2. Source Samples Used.

Code	Source	Abbreviation	Quarry	INAA-1	INAA-2	Total
1	Pachuca	Pach	9	3	2	14
2	Otumba	Otum	10	13	7	30
3	Paredon	Pared		5	5	10
4	Ucareo	Ucar	1	3	9	13
5	El Paraiso	El Par		4	1	5
6	Fuentezuelas	Fuen		1	3	4
7	Zaragoza	Zara		1	4	5
8	Pizzarin	Pizz	5			5
9	Zinapecuaro	Zina	5			5
10	Zacualtipan	Zacua			1	1
0	Unassigned	Unkn			2	2
	Totals		30	30	34	94

Note: The identification numbers of sources differ from those shown in Figure 1 and Table 1.

Table 3. Categories of Pieces Analyzed.

Batch	Category	N	XRF	INAA
3	Quarry source samples	30	30	0
8	Random sample, 1993 excavations	142	142	13
1	Test batch, 1993 excavations	30	30	30
9	Sample from valley survey	218	218	21
	Total samples	420	420	64

the 1993 excavations (batch 8) and the 1994 survey of the Yautepec Valley (batch 9; Table 3). On the basis of these preliminary results, an additional 34 artifacts were submitted to MURR in 2001 (13 from batch 8 and 21 from batch 9). These were selected to test the compositional groups and to investigate artifacts that were not clearly assigned to a group. The results of this second INAA batch included one source not previously recognized (Zacualtipan) and two unassigned pieces (Table 2). The statistical sourcing procedure was then rerun using all 94 source samples, producing the final results reported here.

Of the 10 obsidian sources listed in Table 2, nine are represented in the artifacts analyzed here. Information on these and other central Mexican obsidian sources can be found in Charlton and Spence (1982), Cobean (1991, 1998, 2002), Gaxiola G. et al. (1987), Healan (1997), and Pastrana (1991, 1998).

The Sample of Artifacts from Yautepec Excavations (Batch 8)

Excavations at Yautepec in 1993 focused on residential contexts. A major emphasis was the excavation of well-dated intact midden deposits in order to make comparisons among Postclassic domestic contexts. Fieldwork and analyses are described in a variety of sources (Olson 2001; Smith 2006a; Smith et al. 1999). The obsidian sample was selected from midden contexts in the "domestic context sample," a group of well-phased undisturbed middens.[1] Four ceramic phases are represented at Yautepec: Pochtla (A.D. 1100–1300), Atlan (A.D. 1300–1440), Molotla (A.D. 1440–1520+) and Santiago (A.D. 1520–1600+). The Pochtla phase corresponds to the Middle Postclassic (Early Aztec) phase in the Basin of Mexico, the Atlan and Molotla phases cover the interval included in the Late Postclassic (Late Aztec) phase, and the Santiago phase is a postconquest phase whose material culture combines Postclassic materials with Spanish colonial materials such as glazed ceramics, cow bones, and iron nails. This chronology, strongly supported by carbon dates, quantitative seriation, stratigraphy, and cross-dating, is described in Hare and Smith (1996).

Each "domestic context" in the domestic context sample consists of three to eight excavated levels from a single structure (or other discrete occupation context) dating to a single ceramic phase. The obsidian sample was selected in 1996 by Smith, Leah Pickard, and Annette McLeod from the total obsidian collections making up each domestic context. Only prismatic blades were selected for sourcing. The prismatic blades from each excavated level were first classified into green and gray categories. Within each color, artifacts were lined up in size order, from largest to smallest. The largest and smallest artifacts were eliminated from consideration. We employed a systematic sampling program to select the sample from the remaining blades. The target sample size for each domestic sample was two green and six gray artifacts, so we used whatever sampling fraction was necessary to yield the target sample size. This procedure tended to include artifacts from several of the constituent excavated levels in each domestic context.

Several complexities of the sampling require discussion. At the time the sample was drawn, some of the domestic contexts consisted of specific middens, so that some phases at individual structures were represented by more than one midden (e.g., excavation unit 505 in the Pochtla phase was represented by two middens). The obsidian sample was selected from these individual middens. After 1996 the separate middens from a single structure and phase were lumped to form the domestic contexts used in subsequent project analyses. This produced a situation in which some domestic contexts (e.g., unit 505 in the Pochtla phase) have 16 artifacts in the sample, whereas most contexts have eight. The second complexity concerns unit 503. Instead of drawing a new sample, we simply employed the group of artifacts initially selected in 1994 for INAA analysis. Because that sample was not selected through systematic sampling, unit 503 is not completely comparable to the other contexts in the overall collection of sourced artifacts. Nevertheless, we feel that this difference probably has a minimal effect on the representativeness of the sample from unit 503. Third, there were insufficient prismatic blades from the Pochtla phase in unit 501, and the sample from this context consists of three gray and two green blades. Finally, several of the artifacts initially sampled as "gray" obsidian later turned out to be green in color. The chemical analyses (INAA and XRF) were done without knowledge of the color or other attributes of the artifacts, and these misclassifications were discovered by Smith when 11 "gray" artifacts were assigned to the Pachuca source. Upon close examination, nine of these were actually green in tint, and two were clearly gray. This change resulted in lower numbers of gray samples in some contexts.

The Sample of Artifacts from the Yautepec Valley (Batch 9)

The full-coverage 1994 and 1996 Yautepec Valley surveys encompassed the entire Yautepec valley including the contiguous late Postclassic regional polity of Yautepec (Hare 2001; Smith 2006b). Together, they covered approximately 150 km^2 and located over 400 sites, including all ethnohistorically known Postclassic city-state centers that composed the Yautepec regional polity. The full-coverage surveys employed methods based on those applied by previous surveys in Mesoamerica (e.g., Hirth 1980; Parsons et al. 1982; Sanders et al. 1979), although we used a more intensive and systematic program of surface artifact collection (Smith 2006b). Sites were identified by the density of surface artifacts and/or visible features, including mounds, and we made a variety of types of artifact collections. Grab-bag and 2-x-2-m intensive collections were made at all sites. Intensive 5-x-5-m collections were made at a sample of the sites to address specific research questions. Test excavations were conducted at a sample of sites to aid in the application of the Yautepec chronology at the regional scale. Both ceramic and lithic remains were included in all collection types.

The obsidian sample was extracted from a variety of collection types distributed across 31 Postclassic sites (Figure 2). Fifty-five obsidian blade fragments were selected from seven excavation units distributed across three sites. These excavation units were in well-phased and undisturbed midden contexts. Additional samples were taken from a variety of surface collections to increase the sample size. The dates of these surface contexts are less secure than those of the excavations, but all sampled surface collections were dated to either the Pochtla, Atlan, and Molotla, or to a general Postclassic category that encompassed the Pochtla, Atlan, and Molotla phases. Of these, 49 obsidian pieces were sampled from grab-bag collections, 51 from 2-x-2-m collections, and 63 from 5-x-5-m collections. The total for batch 9 is 218 artifacts.

The obsidian sample was selected in 1996 by Hare from the total obsidian collections that

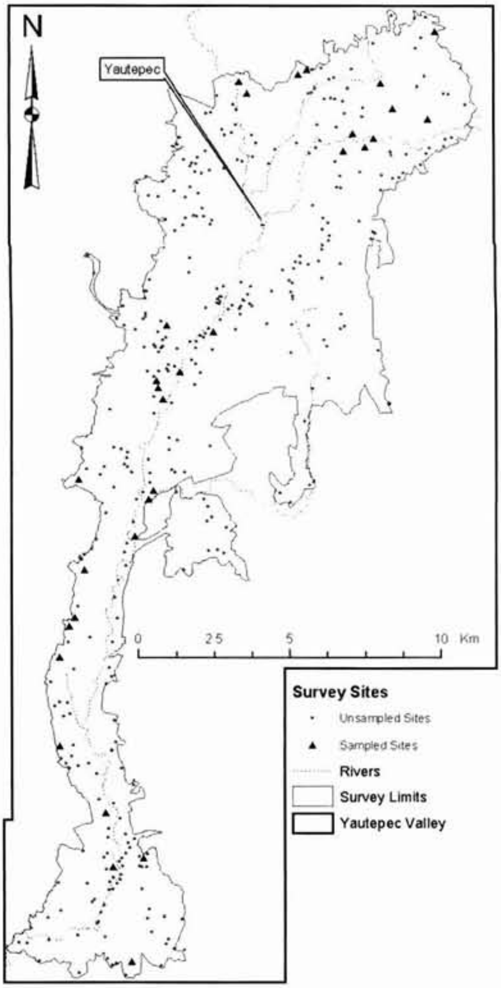

Figure 2. Location of Postclassic sites in the Yautepec Valley, outside of the Yautepec site, that furnished obsidian artifacts for this study (map by Timothy S. Hare).

included prismatic blades and that were datable to the Pochtla, Atlan, and Molotla phases, or to the general Postclassic period. Only gray prismatic blades were selected, given the expectation that most green obsidian would be from the Pachuca source. For each collection, all gray obsidian blades were lined up and the largest and smallest artifacts were removed from the sample. Given the small frequency of acceptable gray obsidian blades, all were selected for the sample from most collections. A random sample of five was taken from collections with more than five acceptable artifacts.

Characterization Methods

Instrumental Neutron Activation Analysis (INAA)

Obsidian samples are prepared for neutron activation analysis by using a trim saw to remove approximately 100 mg from each artifact. Samples are weighed to the nearest .01 mg and encapsulated in polyethylene vials used for short irradiations at MURR. Standards made from SRM-278 Obsidian Rock and SRM-1663 Flyash are similarly prepared. As described in Glascock et al. (1994), short irradiations are carried out by using the pneumatic-tube irradiation system at MURR. Samples and standards are irradiated, two at a time, for five seconds by a thermal neutron flux of 8 x 1013 neutrons cm^2 s^{-1}. Following irradiation, the samples are allowed to decay for 25 minutes so that the dominant short-lived radioisotope 28Al (half-life = 2.24 min) can decrease to acceptable levels for handling and measurement. The individual sample vials are mounted in a rotating sample holder at a distance of 10 cm from the face of a high-purity germanium (HPGe) detector where the emitted gamma-rays are measured during a 12 minute counting period. The short-count gamma-ray spectra are stored and subsequently analyzed in batches to determine the concentrations of elements in the archaeological specimens relative to the concentrations in the standards. The elements measurable by this procedure are aluminum (Al), barium (Ba), chlorine (Cl), dysprosium (Dy), potassium (K), manganese (Mn), and sodium (Na). The element concentration data are listed in Table 4.

Source assignments for individual artifacts were made using procedures described in Glascock et al. (1998) where the individual artifacts are compared to a database of known sources in eastern and central Mexico (see Cobean 2002). A series of bivariate plots for the most useful elements (i.e., Ba, Dy, Mn, and Na) are examined by projecting artifacts against 95 percent confidence ellipses for obsidian sources to determine the appropriate source for each of the analyzed samples (Figures 3, 4). With the exception of two artifacts #54 (OB9-96) and #63 (OB 9-197), the determination of sources for the remaining artifacts was quite clear. For the latter pair, the assigned sources are considered not certain but likely with a high probability.[2]

Table 4. Elemental Concentrations of Artifacts, INAA.

Yautepec No.	MURR No.	Ba ppm	Cl ppm	Dy ppm	K %	Mn ppm	Na %	Source Name
OB1-1	MESB01	773	406	3.47	3.14	395	3.05	Otumba
OB1-2	MESB02	828	401	3.71	3.09	387	2.99	Otumba
OB1-3	MESB03	819	442	3.21	3.41	389	2.99	Otumba
OB1-4	MESB04	*	1282	17.52	3.41	1164	3.93	Sierra de Pachuca
OB1-5	MESB05	705	409	4.09	3.18	390	3.05	Otumba
OB1-6	MESB06	*	1061	8.52	3.91	363	2.93	Paredon
OB1-7	MESB07	63	906	8.30	3.90	362	2.91	Paredon
OB1-8	MESB08	818	442	3.09	3.12	390	2.99	Otumba
OB1-9	MESB09	133	331	4.50	3.94	166	2.72	Ucareo
OB1-10	MESB10	*	1194	33.43	3.68	234	3.56	El Paraiso
OB1-11	MESB11	*	1196	33.32	3.64	234	3.61	El Paraiso
OB1-12	MESB12	*	1267	16.13	3.83	1145	3.85	Sierra de Pachuca
OB1-13	MESB13	823	471	2.66	3.32	393	3.06	Otumba
OB1-14	MESB14	817	416	2.88	3.21	396	3.08	Otumba
OB1-15	MESB15	652	407	3.81	3.21	389	3.02	Otumba
OB1-16	MESB16	*	920	9.05	3.87	361	2.89	Paredon
OB1-17	MESB17	444	574	5.53	3.99	250	2.95	Zaragoza
OB1-18	MESB18	*	1233	33.13	3.43	237	3.62	El Paraiso
OB1-19	MESB19	37	899	17.99	3.63	232	3.33	Fuentezuelas
OB1-20	MESB20	*	1205	32.80	3.35	235	3.58	El Paraiso
OB1-21	MESB21	656	349	3.22	3.14	393	3.03	Otumba
OB1-22	MESB22	96	1123	8.81	3.73	364	2.93	Paredon
OB1-23	MESB23	131	326	4.72	4.00	166	2.64	Ucareo
OB1-24	MESB24	*	1478	17.85	3.61	1144	3.79	Sierra de Pachuca
OB1-25	MESB25	800	361	2.94	3.10	387	3.03	Otumba
OB1-26	MESB26	*	956	8.43	3.99	363	2.83	Paredon
OB1-27	MESB27	765	340	3.56	3.06	390	3.02	Otumba
OB1-28	MESB28	140	355	4.64	3.93	167	2.77	Ucareo
OB1-29	MESB29	686	525	3.73	3.26	385	2.96	Otumba
OB1-30	MESB30	754	377	3.38	3.28	386	2.97	Otumba
OB8-14	MESB31	98	277	3.83	3.84	155	2.66	Ucareo
OB8-16	MESB32	701	349	2.88	3.31	380	2.94	Otumba
OB8-31	MESB33	*	851	7.82	3.91	351	2.86	Paredon
OB8-36	MESB34	709	384	3.26	3.33	384	2.98	Otumba
OB8-55	MESB35	*	701	14.91	3.46	202	2.92	Fuentezuelas
OB8-69	MESB36	84	837	7.74	4.26	356	2.89	Paredon
OB8-85	MESB37	398	533	4.62	3.90	253	2.90	Zaragoza
OB8-89	MESB38	*	1302	14.83	3.63	1107	3.71	Sierra de Pachuca
OB8-98	MESB39	137	322	3.50	4.08	156	2.73	Ucareo
OB8-112	MESB40	728	416	3.19	3.29	379	2.97	Otumba
OB8-128	MESB41	*	743	16.48	3.80	220	3.20	Fuentezuelas
OB8-136	MESB42	149	1028	8.13	4.35	368	2.99	Paredon
OB8-142	MESB43	*	1193	30.53	3.70	230	3.56	El Paraiso
OB9-14	MESB44	431	490	4.74	4.34	249	2.95	Zaragoza
OB9-34	MESB45	726	357	3.60	3.55	390	2.97	Otumba
OB9-43	MESB46	127	393	4.19	4.08	176	2.85	Ucareo
OB9-57	MESB47	451	505	4.96	4.03	250	2.95	Zaragoza
OB9-58	MESB48	125	348	3.82	4.12	175	2.82	Ucareo
OB9-60	MESB49	168	348	3.85	4.11	171	2.80	Ucareo
OB9-77	MESB50	790	349	3.40	3.58	404	3.12	Otumba
OB9-80	MESB51	*	946	7.86	4.16	367	2.98	Paredon
OB9-83	MESB52	334	400	7.94	4.94	160	2.57	Zacualtipan
OB9-90	MESB53	781	380	3.18	3.58	398	3.08	Otumba
OB9-96	MESB54	284	570	6.74	4.16	334	3.56	Paredon?
OB9-98	MESB55	*	851	17.31	3.91	234	3.38	Fuentezuelas
OB9-129	MESB56	171	328	3.97	4.08	172	2.79	Ucareo
OB9-132	MESB57	428	604	4.86	4.07	254	3.00	Zaragoza
OB9-145	MESB58	866	433	2.80	3.40	401	3.13	Otumba
OB9-156	MESB59	*	1004	7.57	4.09	360	2.92	Paredon
OB9-165	MESB60	156	338	3.78	4.10	165	2.83	Ucareo
OB9-178	MESB61	*	1118	14.97	3.60	1057	3.54	Sierra de Pachuca
OB9-195	MESB62	200	387	3.67	4.53	169	2.86	Ucareo
OB9-197	MESB63	133	188	2.48	3.72	362	2.96	Otumba?
OB9-216	MESB64	113	353	3.86	4.05	177	2.87	Ucareo

* Below detection limits.

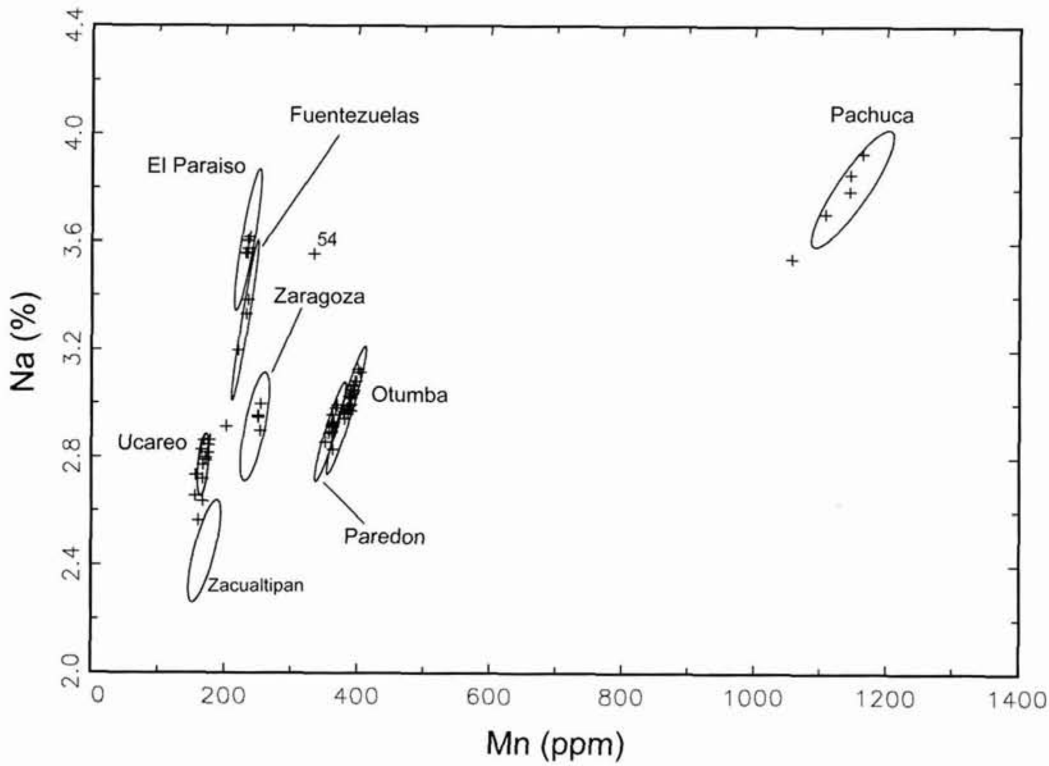

Figure 3. INAA results, bivariate plot of Na v. Mn (graphic by Michael D. Glascock).

X-ray Fluorescence (XRF)

X-ray fluorescence can be used as a nondestructive analytical technique to analyze many different kinds of materials. For a more thorough description of the physics behind x-ray fluorescence analysis, the reader is directed to Bertin (1970) and Potts (1987). XRF analysis of archaeological lithics by similar methods to the ones used in this study are manifold (Erlandson et al. 1992; Hermes and Ritchie 1997; Kuhn and Lanford 1987; Williams-Thorpe et al. 1999). The XRF instrument used in this study is housed at the Accelerator Laboratory of the University at Albany (SUNY). The principles involved in XRF and the use of this particular instrument are presented in detail at the end of this article.[3]

The regression formulas used to convert the semi-quantitative peak area values into ppm values for each of the six elements calibrated are given in Table 5. We used three standards (USGS RGM-1 obsidian, NIST 98b plastic clay, NIST 278 obsidian), and the reproducibility was very good. Only six elements were calibrated because they were most consistently and reliably detected with the Albany XRF instrument, and also because they were present in all of the standards in varying concentrations. These also match the elemental concentrations most commonly published for archaeological obsidian analyzed using XRF in Mesoamerica (Ford et al. 1997; Jackson and Love 1991; Moholy-Nagy 2003a:28; Moholy-Nagy and Nelson 1990). These calibration regression formulas can be improved with the addition of other standards and the analysis of more samples; therefore, they should not be seen as permanent. For a detailed treatment of the issues involved in calibrating instruments using standards as well as other issues in the quantification of standards and silicate rocks see Abbey (1983), Ahmedali (1989), and Flanagan (1976).

Assigning Artifacts to Sources

The assignment of artifacts to geological sources was done in several steps. We began by using the initial two source sample groups—Quarry and

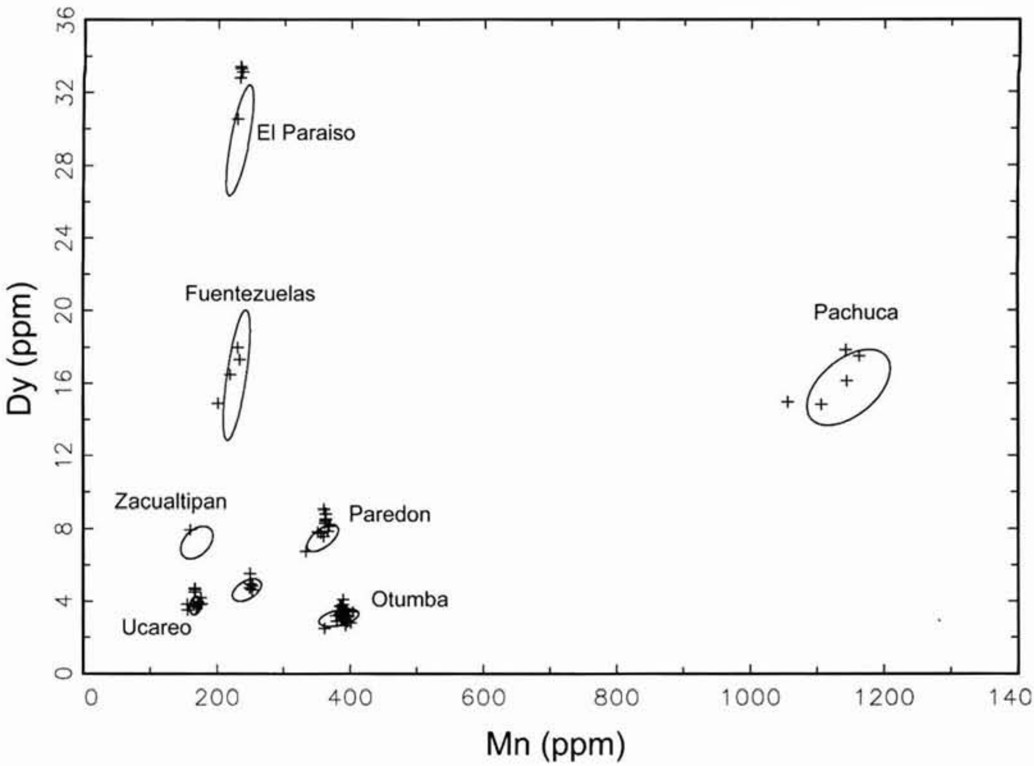

Figure 4. INAA results, bivariate plot of Dy v. Mn (graphic by Michael D. Glascock).

NAA-1 (Table 2)—to assign the artifacts to tentative sources on the basis of their XRF results using discriminant function analysis. The first set of results looked problematic in that two pairs of sources—Otumba and Paredon, and Ucareo and Zinapecuaro—proved quite difficult to distinguish using our data. We selected a sample of 34 artifacts to test the initial results with additional INAA analyses (batch NAA–2). When those results were reported, we discovered that a miscommunication between Glascock and Smith had led to a reversal of the Otumba and Paredon results in the first NAA batch. We reran the discriminant analyses with the corrected data, which improved the results considerably. Finally, we conducted further discriminant analysis runs using all 94 source samples (Table 2); these results are the final source attributions reported here.

Initial Discriminant Analyses

The basic method for assigning sources to artifacts was discriminant analysis. A series of discriminant analyses were run using the "Discriminant Analysis" module of the SPSS software (version 12 for Windows), all employing the same basic parameters. In our applications, the groups are the geological sources of obsidian, and the source samples are the classified cases used to define the discriminant functions.

In the first stage of discriminant analysis, func-

Table 5. Regression Formulae to Convert Peak Areas to ppm, XRF.

Fe ppm	=	(Fe integrated peak area x .81) – 53.8	r^2 = .996
Rb ppm	=	(Rb integrated peak area x .046) – 1.367	r^2 = .997
Sr ppm	=	(Sr integrated peak area x .039) + .686	r^2 = 1.000
Y ppm	=	(Y integrated peak area x .043) + 3.794	r^2 = .933
Zr ppm	=	(Zr integrated peak area x .026) – 2.667	r^2 = .982
Ba ppm	=	(Ba integrated peak area x 1.46) – 23.249	r^2 = .980

tions are constructed and applied to the initial grouped cases. In an ideal example, all cases will be classified into their original groups. In actual applications, however, there are typically a number of "classification errors" in which cases are switched from their original group into another group. The number of such errors provides a means to evaluate the success of a discriminant analysis. In the second stage, the discriminant functions are applied to the unclassified cases; in our applications, these are the unsourced artifacts. For each case, the program calculates the probabilities of membership in each of the groups; in an ideal application most of these probabilities will be high, indicating close correspondence between the cases and the groups. In our application of discriminant analysis, we employed all six elements from the XRF results in the construction of the discriminant functions (i.e., the step-wise method was not employed), and all groups were assigned equal prior probabilities.

The first discriminant analysis run included all artifacts and source samples from the Quarry and NAA-1 groups (Table 2). As mentioned above, the initial results did not look promising. Of the source samples, 8.9 percent were switched to another source (i.e., classification errors). Of all artifacts, 69 percent were assigned to a source at a probability of 90 percent or more. All the green artifacts were assigned to the Pachuca source. In order to focus on the gray artifacts, a second run was done with only the gray source samples and artifacts. We expected that without the green artifacts, the chemical relationships among the gray artifacts would be clearer and stronger. This was not the case, however. A greater frequency of the source samples were misclassified (13.0 percent), and far fewer artifacts (56.2 percent) were assigned to a group with a probability of 90 percent or more. Numerous artifacts were almost evenly distant from either Otumba and Paredon, or Ucareo and Zinapecuaro, and 20 artifacts were not close to any of the groups. A variety of additional statistical analyses were conducted to explore the dataset and attempt to improve the results, but without much success (these included hierarchical cluster analyses, multidimensional scalings, and additional discriminant analyses).

At this point a second set of samples, NAA-2, was selected for INAA at MURR. Two categories of artifacts were submitted: (1) a group of 12 unassigned artifacts from the discriminant analysis, and (2) 22 randomly selected sourced artifacts from the 319 sourced gray artifacts. All tests confirmed that the green artifacts indeed come from Pachuca (source 1), so additional testing of this group was not needed. For this sample, we used systematic random sampling, a method recommended as especially suitable for selecting artifacts for technical analyses (Orton 2000:183). The artifacts were sorted by source and by batch and catalog number within sources. Starting numbers were selected from a table of random numbers, and then items were selected at a set interval chosen to produce the number of objects desired. In all, 34 artifacts were submitted for INAA.

Final Discriminant Analyses

As noted above, at the time of the second INAA batch we discovered an error in the reporting of the initial INAA results. At that point we conducted a new discriminant analysis (run 3) using the corrected source groups and using all source samples in the Quarry and NAA-1 groups and all artifacts (green and gray). These results were improved; there were 8.7 percent classification errors among the source samples, and 71.6 percent of the artifacts were assigned to a group at a probability of 90 percent or higher. Many of the artifacts included in NAA-2 were switched to different sources, however, reducing the value of this sample as a methodological test of the XRF results.

For the final discriminant analysis run (run 5), all 94 source samples were used to assign all artifacts to source groups. The results of this run are presented in Table 6. The number of classification errors (source samples switched to another group) remained at the level of 8.7 percent (i.e., eight of the 92 source samples in Table 6 were switched by the discriminant functions to another group). Of the artifacts sourced by XRF alone, a larger proportion of the artifacts (83.7 percent) were classified at probabilities of 80 percent or greater.[4] All artifacts were assigned by discriminant analysis to a group with a probability of at least 50 percent. Until archaeologists have a better understanding of the nature and extent of chemical variability within individual sources (Cobean 2002; Glascock et al. 1998; Tenorio et al. 1998), it is difficult to decide whether artifacts classified to a source with a rela-

Table 6. Discriminant Analysis Classification Table for Source Samples.

Original	Disc. Ans Predicted Group:										
Group	1	2	3	4	5	6	7	8	9	10	Total
1	14										14
2		29							1		30
3			10								10
4			1	8					4		13
5					5						5
6					1	3					4
7							5				5
8								5			5
9				1					4		5
10										1	1
Total	14	29	11	9	6	3	5	5	9	0	92
Ungrouped	47	186	36	30	6	9	2	0	12	0	328
	14.3	56.7	11.0	9.1	1.8	2.7	0.6	0.0	3.7	0.0	
8.7%	errors										

For key to groups (sources), see Table 2.

tively low probability (e.g., under 60 percent) should be attributed to that source or to a catchall category of "unassigned."

For the remainder of this paper we will consider that all artifacts do indeed come from the source they are classified into. Our results for gray obsidian are shown in Table 7, labeled Model 1. If we were to take a more conservative approach, however, and assign all artifacts whose group probability is less than 60 percent to a category of "unassigned," 26 artifacts (6.7 percent) would be changed. Table 7 shows our results for gray obsidian using these alternate assumptions ("Model 2").

Results

We discuss the results of these analyses under three headings: the sources of obsidian utilized, household variation within the city of Yautepec, and regional patterns within the Yautepec Valley. All data are consistent with the broad interpretation that obsidian in the Yautepec area was obtained through commercial exchange channels involving merchants and markets.

The Sources of Obsidian in the Yautepec Region

The frequencies of artifacts from the sources identified in this study are given in Table 7. The right-hand column in Table 7 lists the number of identified sources for gray obsidian only. When the green obsidian from the Pachuca source is added, the total number of sources for the survey sample increases to eight. The number of obsidian sources represented in our total sample—both excavation and survey—is nine. Their locations are shown in Figure 5. These nine sources are well distributed within the overall area of central Mexican obsidian sources, covering all major regions except the easternmost geological sources (Guadalupe Victoria and Pico de Orizaba).

These results fit well with other studies of Mesoamerican obsidian sources. Nearly all Mesoamerican sites ever sampled for obsidian characterization had obsidian from more than one geological source (e.g., Braswell 2003; Glascock 2002). The number of different obsidian types (sources) represented at individual sites varies regionally, however (Table 8).[5] As might be expected, sites in northern Mesoamerica, home of numerous obsidian sources (Figure 1), all have six or more types of obsidian, whereas sites in southern and coastal Mesoamerica, more distant from geological sources, tend to use fewer types. Nevertheless, there is no simple relationship between the number of sources represented at sites and the distance from individual obsidian sources (Moholy-Nagy 2003b). The number of obsidian types at sites in northern Yucatán, however, is more in line with central Mexico than other parts of southern and coastal Mesoamerica. Regardless of

Table 7. Sources of Gray Obsidian, Yautepec Excavations and Survey.

	no.	Pach	Otum	Pared	Ucar	El Par	Fuen	Zara	Zin.	Zacua	Un assn.	no. src*
Model 1: All artifacts assigned to a source												
Counts:												
Excavations	126	2	71	25	5	11	6	6				7
Survey	214		135	22	41		1	11	3	1		7
Percent:												
Excavations		1.6	56.3	19.8	4.0	8.7	4.8	4.8				
Survey			63.1	10.3	19.2		.5	5.1	1.4	.5		
Model 2: Lower probability artifacts classified as "unassigned"												
Counts:												
Excavations	126	2	71	21	3	11	6	4			8	7
Survey	214		135	20	31		1	8		1	19	7
Percent:												
Excavations		1.6	56.3	16.7	2.4	8.7	4.8	3.2			6.3	
Survey			63.1	9.3	14.5		.5	3.7		.5	8.9	

* "no. src" refers to the number of sources identified for gray obsidian. For the excavated sample, this includes Pachuca; for the survey sample Pachuca is not included in this column.

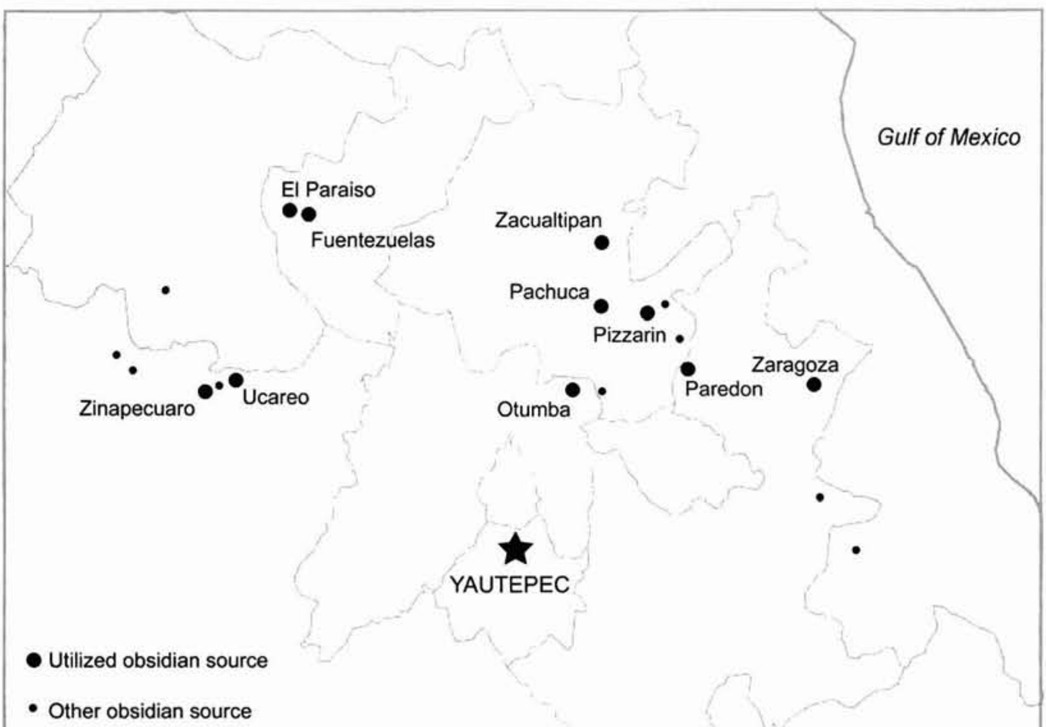

Figure 5. Sources of obsidian identified at Postclassic sites in the Yautepec Valley (graphic by Michael D. Glascock and Michael E. Smith).

Table 8. Numbers of Obsidian Sources at Mesoamerican Sites.

Site	Period	Method	No. of sources	Sample	Citation
Northern Mesoamerica:			mean: 7.3		
Tzintzuntzan	Late Postclassic	XRF	10	381	Pollard & Vogel 1994
Yautepec	Late Postclassic	XRF/NAA	7	172	This study
Otumba	Late Postclassic	INAA	6	74	Neff et al. 2000
Xochicalco	Epiclassic	?	6	115	Hirth 1989
Northern Yucatan:			mean: 7.3		
Chichén Itzá	Late Classic	NAA/visual	10	2,745	Braswell & Glascock 2002
Uxmal	Late Classic	NAA/visual	10	509	Braswell & Glascock 2002
Isla Cerritos	Late Classic	NAA/visual	7	54	Braswell & Glascock 2002
Yaxuna	Late Classic	NAA/visual	7	180	Braswell & Glascock 2002
Coba	Late Classic	NAA/visual	6	307	Braswell & Glascock 2002
Ek Balam	Late Classic	NAA/visual	4	198	Braswell & Glascock 2002
Southern Mesoamerica:			mean: 4.6		
Tikal	Classic & Preclassic	XRF/NAA	10	64	Moholy-Nagy & Nelson 1990
Copan	Late Classic	visual	6	9,146	Aoyama 2001
Tikal-Yaxha	Late Classic	XRF/NAA	5	??	Ford et al. 1997
La Blanca	Preclassic	XRF	5	174	Jackson & Love 1991
Cihuatan	Postclassic	XRF/NAA	3	21	Fowler et al. 1987
Quelepa	Classic	INAA	3	49	Braswell et al. 1994
Colha	Classic	INAA	3	199	Dreiss et al. 1993
El Mirador	Preclassic	XRF	2	23	Fowler et al. 1989
Intermediate Coastal Areas:			mean: 4.7		
Rio Verde, Oax.	Classic	INAA	6	16	Joyce et al. 1995
Tuxtla area	Classic	INAA	4	44	Santley et al. 2001
San Lorenzo	Preclassic	INAA	4	65	Cobean et al. 1991

this regional variation, however, nearly all sites had obsidian from three or more sources.

The use of multiple types of obsidian at individual settlements has yet to be satisfactorily explained. A number of adaptationist interpretations (for this concept, see Brumfiel and Earle 1987) of this phenomenon were proposed in the 1980s: "The exploitation of multiple sources of a key commodity is less vulnerable to disruption or overcharging than is reliance on a single source" (Stross et al. 1983:335); or "The diversification of obsidian sources would have been an effective hedge against the fragility of the alliances and exchange networks" (Fowler et al. 1987:159); see also Rice (1984:182). These views assume that each source had an independent distribution system: either people went directly from consuming settlements to quarries, or else different merchants came from each quarry to individual settlements. In the words of Rice: "most sites were apparently exploiting multiple sources at the same time" (Rice 1984:182).

Although this model may have been appropriate for southern Mesoamerica, or perhaps for northern Mesoamerica early in the Formative period, it is clearly inadequate for Middle and Late Postclassic northern Mesoamerica, where there is abundant ethnohistorical and archaeological evidence for commercial exchange of obsidian and other commodities (Smith and Berdan 2003). But it is still difficult to find an adequate explanation for the diversity of types of obsidian found at Yautepec, sites in the Yautepec Valley, and other sites in highland central Mexico (e.g., Neff et al. 2000; Pollard and Vogel 1994). Below we offer some thoughts on this question, but we do not claim to provide an adequate model to explain the situation.

Household Variation in Yautepec

There is considerable variation among individual excavated household assemblages in the use of different obsidian sources, but that variation does not appear to relate to systematic social factors such as wealth, craft production activities, or change through time. The amount of obsidian in domestic

Table 9. Sources of Gray Obsidian from Yautepec House Excavations (%).

unit	No.	Pach*	Otum	Pared	Ucar	El Par	Fuen	Zara	No.src
Pochtla phase:									
501	3		66.7	33.3					2
503	9		55.5	22.2	11.1	11.1			4
505	12	8.3	75.0	8.3		8.3			4
Average:	2.8	65.8	21.3	3.7	6.4	.0	.0	3.33	
Standard dev:	4.8	9.8	12.5	6.4	5.8			1.15	
Atlan phase:									
501	6		66.7	16.7	16.7				3
503	9		33.3	11.1		33.3	11.1	11.1	5
505	6		50.0	16.7		16.7	16.7		4
506	6		50.0	33.3		16.7			3
507	4		50.0	50.0					2
508	4		75.0		25.0				2
509	12		75.0	16.7				8.3	3
512**	6		16.7	16.7		16.7	33.3	16.7	5
Average:	.0	52.1	20.1	5.2	10.4	7.6	4.5	3.38	
Standard dev:		20.3	15.1	9.9	12.4	12.2	6.6	1.19	
Molotla phase:									
501	5		60.0	20.0				20.0	3
503	9		55.6	22.2	22.2				3
504	12		58.3	33.3		8.3			3
506	12	.1	66.7			8.3	8.3	8.3	5
512**	5		20.0	60.0		20.0			3
Average:	1.7	52.1	27.1	4.4	7.3	1.7	5.7	3.40	
Standard dev:	3.7	18.4	22.0	9.9	8.2	3.7	8.8	.89	
Santiago phase:									
509	6	.0	50.0	16.7	.0	.0	16.7	16.7	4

* Gray sample attributed to Pachuca by XRF.
** Unit 512 was an elite residence.

middens—on the other hand—does show relationships with patterns of wealth and time. First, the amount of chipped stone in domestic assemblages (nearly all of which is obsidian) declines steadily through the four time periods represented. The ratio of pieces of obsidian per 1,000 sherds declines from 31.9 in the Pochtla phase to 18.6 in the Santiago phase (Smith 2006a:cuadro E1-4). Second, elite households had more obsidian than commoner households in the Molotla phase, but not in the Atlan phases. These patterns are explored in greater detail in other works (Norris 2002; Olson 2001; Smith 2006a:ch. E1).

In contrast to the overall quantities of obsidian, the relative contributions of different geological sources do not show systematic patterns of variation with wealth or time. The situation can be examined in more detail when the sourcing results of the present study are examined by household context (Table 9). The average number of sources of gray obsidian per household averages between three and four in all time periods. When the green (Pachuca) obsidian is added, the average number of sources increases by one. All houses have obsidian from Pachuca and Otumba, nearly all have material from Paredon, and the remaining minor sources vary in their household occurrences. The elite residence (unit 512) does not stand out in either of the Atlan or Molotla phases.

These patterns—widespread use of multiple sources in similar frequencies, and the lack of pronounced elite/commoner differences—are consistent with the operation of commercial exchange as the primary mechanism responsible for the supply of obsidian to Yautepec (Braswell and Glascock 2002; Hirth 1998; Smith 1999, 2004). In some ways, the gray obsidian data are similar to the household distribution of imported polychrome ceramics at Yautepec. Imported ceramics from several regions are present, including the Basin of Mexico, Northeast Guerrero, Malinalco, the Toluca Valley, the Puebla/Tlaxcala region, and at least three other parts of Morelos: western Morelos, the Tepoztlan area, and southeastern Morelos (Smith 2003a, 2006a). Middens at the elite residence have higher frequencies of imported ceramics, but no single type is found exclusively in elite contexts. Ceramics from these diverse areas, identified from their regionally distinctive painting styles and techniques, are widely distributed among Yautepec houses, both commoner and elite.

In the case of the polychrome ceramics, one might argue that consumer choice played a role in determining the types present at individual houses. Perhaps some people preferred Toluca Valley polychromes and others favored decorated types from Tepoztlan. This type of argument, however, is not easy to evaluate empirically (for discussion, see Olson 2001). For the different types (sources) of gray obsidian, however, it is difficult to argue that consumers made deliberate choices to obtain specific types. The visual differences among obsidian items from different gray sources are quite subtle. Although some archaeologists claim a degree of success in visually sourcing Mesoamerican obsidian (Braswell et al. 2000; Clark et al. 1989), such efforts have been criticized by others (Moholy-Nagy 2003b). Regardless of the level of success of visual sourcing by modern scholars, however, it is hard to imagine that Prehispanic consumers were able to, or even cared to, distinguish gray obsidian from the various source areas; visual differences between gray and green obsidian, on the other hand, are easy to see and were probably obvious to ancient peoples.

Unless the different types of gray obsidian can be shown to have obvious and significant technological differences (e.g., in their workability or suitability for particular tasks), it seems unlikely that consumers had preferences in the kind of obsidian they obtained. Most Yautepec residents probably purchased their obsidian in local marketplaces. If our logic holds, we can only conclude that vendors offered many types of gray obsidian for sale, and it seems likely that customers bought whichever type was available, or whichever was least expensive at the time of purchase. Unfortunately we know almost nothing about potential differences in the costs of obsidian from different sources, changes in costs through time, or other economic factors that may very well have influenced the kinds of obsidian available in markets and the kinds of obsidian that consumers purchased there. Nevertheless, the Yautepec household data fit well with recent material culture models for the operation of markets and commercial exchange systems (Braswell and Glascock 2002; Hirth 1998; Nichols et al. 2002; Smith 1999, 2004).

There are some minor temporal trends in the use of gray obsidian through time at Yautepec (Table 9 and Figure 6). The frequency of Otumba obsidian—the most abundant type—declined between the Pochtla and Atlan phases, and then remained constant at close to 50 percent of the sourced gray obsidian. The Fuentezuelas and Zaragoza sources were apparently not used in the Pochtla phase, and then became regular minor sources in the succeeding periods. Until more data are available from other Postclassic sites, it is not clear whether the absence of these sources in the Pochtla phase (Middle Postclassic) means that they were first exploited in the Late Postclassic period, or alternatively, that their obsidian only became available in Yautepec during Late Postclassic times, due perhaps to shifts or expansions in central Mexican exchange networks. Overall, there was a marked increased in imported goods of all types at Yautepec in the Atlan phase (Smith 2001, 2003b), and the increase in the number of gray obsidian types fits with this overall pattern.

Regional Patterns in the Yautepec Valley

The pattern of obsidian distribution by source at sites in the Yautepec Valley generally parallels the distribution found in the Yautepec excavations (Table 7), reflecting the integration of the entire valley into a large-scale market system. There are a total of seven gray sources represented at valley sites. Two of these—Zinapecuaro and Zacualtipan—are not found at Yautepec and one source present at Yautepec—El Paraiso—is not present in any survey sample. Despite the small sample sizes at some sites, most material types are widely distributed throughout the valley (Figure 7). Except for the low frequency types of El Paraiso, Fuentezuelas, Zinapecuaro, and Zacualtipan, the similarity of the overall configuration of sources to Yautepec indicates that Yautepec could have functioned as a

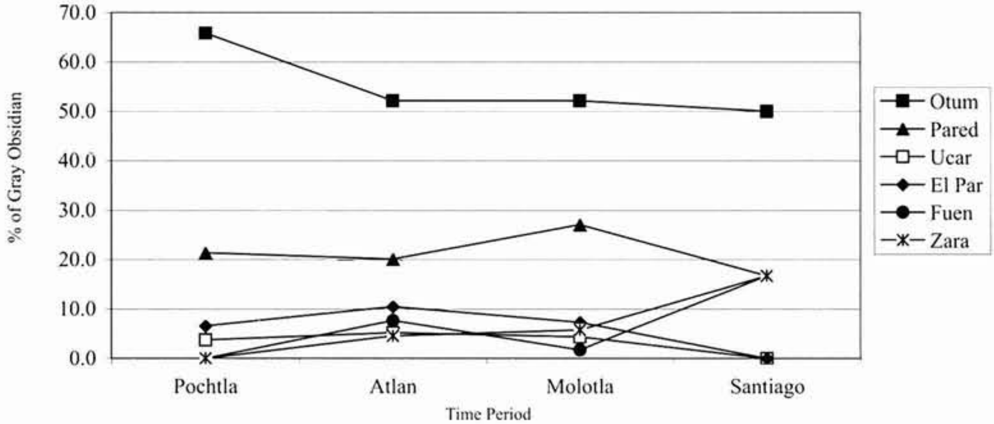

Figure 6. Graphs of frequencies of gray obsidian sources through time, Yautepec excavations (graphic by Michael E. Smith).

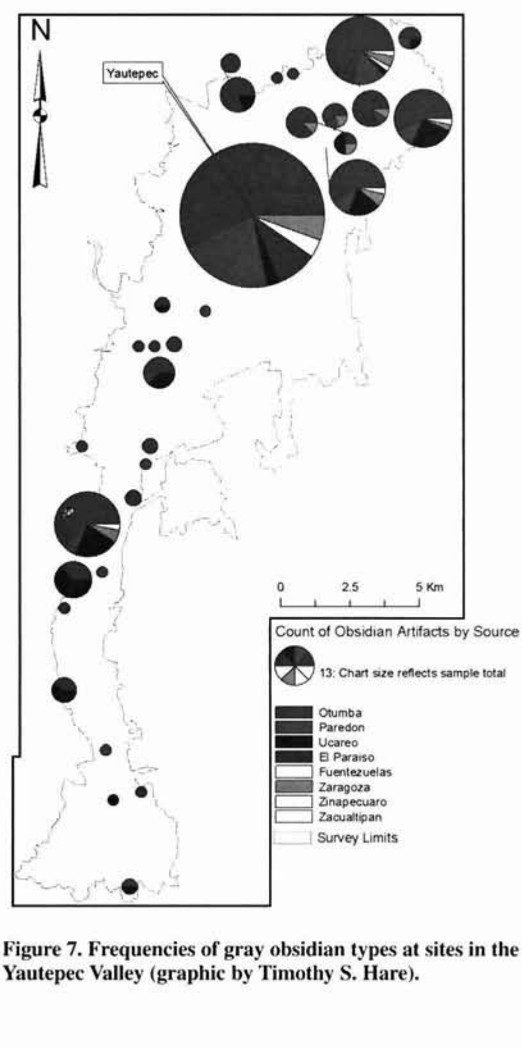

Figure 7. Frequencies of gray obsidian types at sites in the Yautepec Valley (graphic by Timothy S. Hare).

regional market hub supplying the rest of the valley. This interpretation is reinforced by the lack of differences in distributions across estimated polity borders (Hare 2004).

Although the Yautepec and valley data show similar patterns, two distinct differences can be identified. First, individual survey sites generally contain fewer types of material than are present in Yautepec. Second, gray obsidian is more common at survey sites than in Yautepec. Green obsidian at survey sites makes up only 71.7 percent of total lithics, compared to over 90 percent at Yautepec (Tables 8, 10). Table 10 also shows the frequencies of green and gray obsidian for the phased and unphased surface collections from the Yautepec Valley. It is difficult, however, to draw robust conclusions about changes in the relative frequencies of lithic material types found outside the urban center of Yautepec due to small sample sizes, the nature of surface collections, and the mixing of multiple chronological phases in many collections (including those that yielded the samples analyzed in this study). For these reasons we refrain from making social interpretations of the chronological data in Table 10.

Spatial variation in the distributions of obsidian artifacts by material type also shows patterns that defy easy interpretation (Figure 7). Otumba obsidian dominates most gray assemblages throughout the valley. Only sites with samples of one artifact contradict this pattern. Artifacts of Paredon and Ucareo are moderate to low frequency types distributed throughout the valley, but not at every site. Yautepec has the highest proportions of Paredon

Table 10. Chipped Stone Frequencies, Yautepec Valley Sites (%).

Phase	Chipped stone Total	Obsidian Green	Obsidian Gray	Chert
Pochtla	431	63.3	31.8	4.9
Atlan	270	36.7	61.9	1.5
Molotla	375	58.1	39.2	2.7
Unphased	2,835	78.1	19.6	2.3
Total	3,911	71.7	25.7	2.5

and El Paraiso in the valley. No El Paraiso artifacts are found outside Yautepec. Only one site south of the urban center of Yautepec has an artifact made of Zaragoza obsidian; this is Ticoman, the urban center of the Ticoman city-state. At the same time, Zaragoza obsidian is found at all sites northeast of Yautepec. Zinapecuaro obsidian is not found in Yautepec, but only three Zinapecuaro artifacts were found in the valley and no sample site has more than one.

Given these complex patterns and deviations from the Yautepec pattern, the survey data suggest some independence from the Yautepec market or exchange system. To further investigate this issue and to alleviate the problem of low sample sizes at some sites, the obsidian artifacts were aggregated by source region and by estimated political boundaries (Figure 8); see Hare (2004) on political boundaries. Even after aggregation, two regions still have small samples. Tlaltizapan at the southern tip of the valley is the only region where Otumba obsidian does not make up the majority of the gray obsidian sampled, but it is also the region with the smallest sample (five artifacts). Atlihuelican, located in the mid-valley between Yautepec and Ticoman, has only 15 artifacts.

The aggregated data highlight the distinctiveness of Yautepec and Coacalco. Yautepec itself has the largest variety of obsidian types in the valley, in part due to its much larger sample. Together, Yautepec and Coacalco have the highest proportions of Paredon and the lowest proportions of the Tarascan sources. The Yautepec and Coacalco city-states had the largest populations in the valley and hence the largest consumer markets. Therefore, these polities should manifest artifacts of the most diverse sets of obsidian sources, but they lack Tarascan material and have a distinctly higher proportion of Paredon obsidian.

The greater abundance of Tarascan obsidian in the south suggests that a separate exchange system may have linked this area to the Cuauhnahuac area to the west. Despite the small sample sizes from the Tlaltizapan and Atlihuelican areas, it appears that the highest proportions of Tarascan obsidian are in the southern arm of the valley. This matches the distribution of B-4 polychrome ceramic sherds, a type that originates in the Cuauhnahuac area (Smith 2008). The pattern is complicated, however, by the high proportion of Tarascan obsidian at the two Ytzamatitlan sites. These data suggest several interpretations about the exchange systems that supplied obsidian to settlements in the Yautepec Valley. First, multiple merchants and markets probably operated in the region. Second, the merchants had different origins and differential access to obsidian from particular sources. Third, most of the valley polities were probably integrated into a market system centered in Yautepec. Variability in merchants, market sizes, and integration probably determined the distribution of artifacts made from different obsidian sources.

Conclusions

Braswell (2003) has recently synthesized available data on obsidian exchange in Postclassic Mesoamerica. In many ways our results correspond well with the patterns he identifies, but some details of his conclusions may need to be modified to account for our data. Braswell states that:

> Most sites in the Aztec empire exhibit the same basic procurement strategy: 90–98 percent of all obsidian comes from Pachuca. This remarkably consistent pattern suggests the existence of a very large regional market system [Braswell 2003:157].

Data from the city of Yautepec fit this generalization well (Smith 2006a:chapter E1), and our interpretations of the movement of obsidian through markets and commercial exchange networks accord

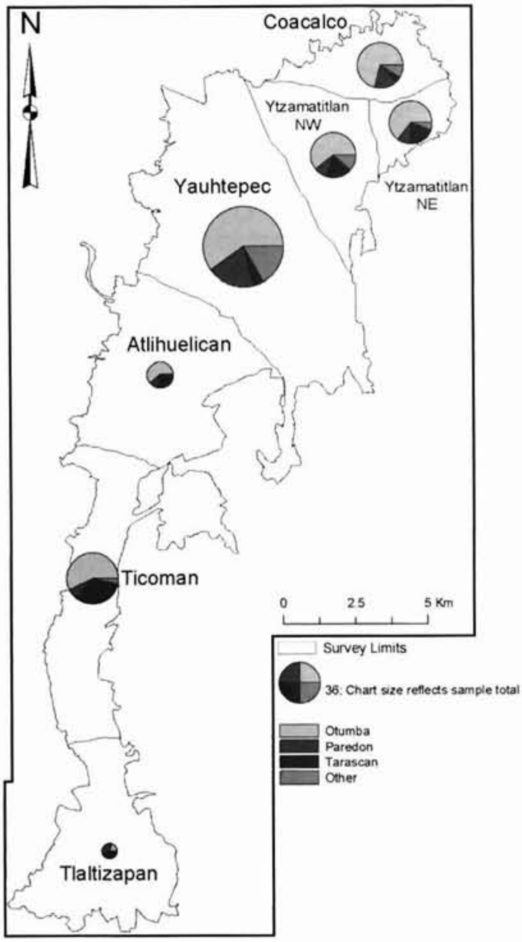

Figure 8. Frequencies of gray obsidian types in the Yautepec Valley. Obsidian types are aggregated into four categories and site data are aggregated by reconstructed Postclassic polities (graphic by Timothy S. Hare).

with Braswell's views.[6] One puzzling aspect of our data, however, is the lower frequency of green obsidian at sites outside of Yautepec in the Yautepec Valley (Table 10). Does this observation suggest some kind of limitation in access to Pachuca obsidian outside of Yautepec proper, or does it suggest instead an augmented access to the various types of gray obsidian outside of Yautepec? Unfortunately, limitations imposed by different types of data prevent comparisons of the total amount of imported obsidian (standardized by ceramics or some other standard) at Yautepec and valley sites.

Our data go against several of Braswell's minor generalizations (Braswell 2003:153). First, he concludes that there is little or no Tarascan obsidian in central Mexico in Late Postclassic times. Although the city of Yautepec only produced 5 pieces of Ucareo obsidian (and none from Zinapecuaro), these Tarascan sources account for 20.6 percent (44 pieces) of the gray obsidian at sites in the Yautepec Valley. The concentration of many of these at sites in the southern valley, far from Yautepec, suggests the possible operation of an alternative exchange system. Tarascan obsidian was dominant at Epiclassic Xochicalco in southwestern Morelos (Hirth 1989, 1995). Perhaps in the Late Postclassic period there were vestiges of an earlier exchange system providing Tarascan obsidian to western Morelos, and some of this material was traded to the southern Yautepec Valley from the south, avoiding the city of Yautepec. In any case, we have strong evidence for considerable Tarascan obsidian in the Yautepec Valley, and a good portion of this is from the Late Postclassic period. Second, Braswell suggests that Paredon obsidian was used primarily in the Tepeapulco region, but we have identified 47 pieces in our sample (Table 7). Third, Braswell suggests that there was little or no eastern obsidian in central Mexico in Late Postclassic times. Although we have no material from two of the eastern sources (Figure 5), we did identify 17 pieces of obsidian from the Zaragoza source. These sources may have had wider distribution areas than Braswell suggested. In sum, our data help refine the patterns identified by Braswell, and contribute to an ongoing effort to improve our understanding of exchange systems in Postclassic Mesoamerica.

The methodological implications of this research for obsidian characterization studies are clear. Analytical techniques like XRF and INAA can be highly complementary, but it is important for the archaeologist to recognize the advantages and limitations of each technique (e.g., cost, accessibility, turnaround times, sample size limits, precision, accuracy, destructive vs. nondestructive) prior to embarking on a characterization program. Day by day these techniques become more accessible to a wider group of researchers. We encourage our colleagues to apply these techniques but only once they have defined explicit research goals that describe the role of the characterization analyses as part of the research problems from the outset. In addition, we insist on the need for clearly defined sampling procedures, both in the field and in the lab, that allow these characterization results to be generalized from a series of samples to wider populations. Finally, by using XRF to expand an already large INAA sample of obsidian, we are able to address issues of production and exchange at a truly regional level as well as looking at these economic systems diachronically.

Our data contribute to a growing refinement in our understanding of patterns of obsidian production and exchange in Postclassic central Mexico. Our use of a combination of XRF and INAA methods permitted the analysis of a large sample of artifacts (390 artifacts), and our results bode well for continuing development of low-cost analytical techniques for the chemical characterization of obsidian and other materials from ancient Mesoamerican sites.

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Notes

1. In 1995 a preliminary batch of artifacts were sourced by XRF by Leah Pickard. This was a haphazard sample of 56 artifacts selected in 1994 by David Schaffer to maximize variability in the visual attributes of the Yautepec obsidian assem-

blage. The results were presented in a conference paper (Smith et al. 1996), but they were not published. Because we now have a much larger sample—based upon systematic random sampling—analyzed with more rigorous methods and based upon a large collection of source samples, this early work is now superceded. Unfortunately, that study was used in Braswell's (2003) compilation of Postclassic obsidian sourcing results. We comment below on how our data relate to Braswell's interpretations of central Mexican obsidian exchange patterns.

2. These two samples are classified as "unknown source" in our analysis.

3. A radioactive isotope source of americium (Am) 241 with a secondary tin (Sn) target was used for the XRF analysis. Samples were placed on an automated sample changer and no vacuum was used. Characteristic x-rays for each element from the sample were detected using a Si/Li detector and counted and sorted out by a multichannel analyzer (MCA). Resolution for this XRF apparatus is estimated as 165 eV for iron (Fe) at 6.40 keV. Elements and their peaks were identified by using two computer programs: Analysis and AXIL. All samples were analyzed for 60 minutes. Each time we ran a series of samples, a control sample of cut geological obsidian was included. The area of the sample exposed when placed in the sample rack is approximately 3 cm^2 (circular opening of 1 cm radius). The effects of surface geometry of the archaeological samples analyzed (the flat ventral side of prismatic blades) were assumed to not affect the XRF analytical procedure based on previous experimental work (Hermes and Ritchie 1997; Kuhn and Lanford 1987; Stevenson et al. 1990; Williams-Thorpe et al. 1999). All samples were cleaned with a clean paper towel and ethyl alcohol. Quantitative analysis of the samples was done in AXIL by integrating the area under the peak over several iterations using a constant fitting model for all standards and samples. The values for the peak area of the calibration standards were plotted against the known concentrations in parts per million (ppm) for the standards. This is done for each element that is being quantified and a regression line is fitted to the data (R^2 values indicating goodness of fit for calibration lines were all above .980). Six elements were calibrated (Fe, Rb, Sr, Y, Zr, Ba) using three standards (USGS RGM-1 obsidian, NIST 98b plastic clay, NIST 278 obsidian). Samples examined in this analysis fulfill the infinite thickness requirement for all other elements. Multiple runs of the same sample standards were done to test the precision and accuracy of the XRF instrument. Iron (Fe) peak area values for 16 repeated runs of the NIST clay and obsidian standards produced coefficient of variation values of 4.10 and 5.13 and indicate a high degree of precision and accuracy for our XRF results. We chose not to use the compton scatter peak to correct for matrix absorption effects in the obsidian for three reasons: (1) all samples are made of similarly homogeneous volcanic glass, (2) all samples were blades and had similar cross sections and geometries, (3) we could not fit the compton scatter peak for all spectra with equal reliability (Davis et al. 1998).

4. Of the 53 artifacts whose probabilities of group membership are below 80 percent, 31 are classified with the Ucareo source (most with a probability between 70 percent and 80 percent), ten are classified with the Zaragoza source, and the others are distributed among the sources (excluding Pachuca and El Paraiso, each of whose artifacts were classified with greater than 80 percent probability).

5. Table 8 is based on a survey of articles with obsidian characterization data published in the major journals between 1990 and 2003, plus several book chapters. For publications with more than one time period, data are considered only for the most abundant and major time period included. For studies with unassigned samples ("unknown" sources), all unassigned artifacts were tallied as a single source. The following sources are used in Table 8: (Aoyama 2001; Braswell et al. 1994; Braswell and Glascock 2002; Cobean et al. 1991; Dreiss et al. 1993; Ford et al. 1997; Fowler et al. 1989; Fowler et al. 1987; Hirth 1989; Jackson and Love 1991; Joyce et al. 1995; Moholy-Nagy and Nelson 1990; Neff et al. 2000; Pollard and Vogel 1994; Santley et al. 2001).

6. In Smith's initial fieldwork season at the Middle-Late Postclassic site of Calixtlahuaca in the Toluca Valley, intensive systematic surface collections recovered abundant obsidian, of which only 22.3 percent is green (Smith 2006a:chapter 6). This amount is strikingly lower than the amount of green obsidian at most sites of this time period.

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