

INTERPRETING INTRASOURCE VARIATION IN THE COMPOSITION OF OBSIDIAN: THE GEOARCHAEOLOGY OF SAN MARTIN JILOTEPEQUE, GUATEMALA

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Compositional analyses have long been used to assign obsidian artifacts to particular source areas. In most cases, the chemical "fingerprint" of a particular source area has been determined through the assay of only a few geological specimens from one or two outcrops. As a result, the full range of intrasource compositional variation has rarely been noted, and its spatial patterning frequently has not been studied. This report describes the results of geoarchaeological survey at the important Guatemalan source area of San Martín Jilotepeque. Neutron activation analysis demonstrates the presence of seven distinct chemical "fingerprints" corresponding to spatially discrete subsources within the region. Ancient procurement and production are associated with only three of these subsources. Statistical procedures that can be used to assign artifacts to particular quarries or quarry systems are presented. Several minor Guatemalan source areas also are examined, and one (Media Cuesta) also can be characterized as consisting of two distinct subsources.

Los análisis de composición han sido utilizados desde hace mucho tiempo para relacionar los artefactos de obsidiana con yacimientos particulares. En la mayoría de los casos, la huella química de una fuente determinada ha sido establecida por análisis solamente de pocas muestras geológicas de uno o dos afloramientos. Como resultado, el rango completo de variabilidad en la composición dentro de la misma fuente ha sido raramente identificado y los patrones espaciales no han sido estudiados. El presente estudio describe los resultados del reconocimiento geoarqueológico en la importante fuente guatemalteca de San Martín Jilotepeque. El análisis por activación neutrónica demuestra la presencia de siete huellas químicas distintas, las cuales corresponden a yacimientos secundarios separados espacialmente en la región. La obtención y la producción antigua están asociadas con solamente tres de estos yacimientos secundarios. Presentamos los procedimientos estadísticos que pueden usarse para relacionar artefactos a canteras específicas o a sistemas particulares de canteras. Se examinan también algunas fuentes guatemaltecas menores, una de las cuales (Media Cuesta) se caracteriza por contener dos yacimientos secundarios distintos.

Since 1990, *Ri Rusamäj Jilotepeke* (the Jilotepeque Project) has investigated ancient settlement and lithic production patterns in San Martín Jilotepeque (SMJ), department of Chimaltenango, Guatemala (Figure 1). SMJ is the location of an important obsidian source area exploited by the highland Maya and other Mesoamerican peoples from the Paleoindian period to the present day. Three phases of research have been conducted, including a geological survey, a settlement survey, and test-pitting operations in prehistoric quarries, secondary workshops, and habitation sites.

Results of the first phase of *Ri Rusamäj Jilotepeke* (RRJ)—a foot survey of portions of the

municipios of San Martín Jilotepeque, Comalapa, and Chimaltenango—are the substantive focus of this report. The purpose of the survey was to locate and sample both exploited and unutilized obsidian outcrops in preparation for a settlement survey that would study the spatial patterning of habitation sites around quarry-workshops. Although the approximate positions of some outcrops in the SMJ source area have been known for some time (e.g., Cobean et al. 1971; Heizer et al. 1965; Sidrys et al. 1976; Stross et al. 1983; Williams 1960), coordinate locations of visible extrusions were rarely reported and outcrops were not paced (cf. Clark 1981; Sheets 1983). None of the previous investigations, best characterized as

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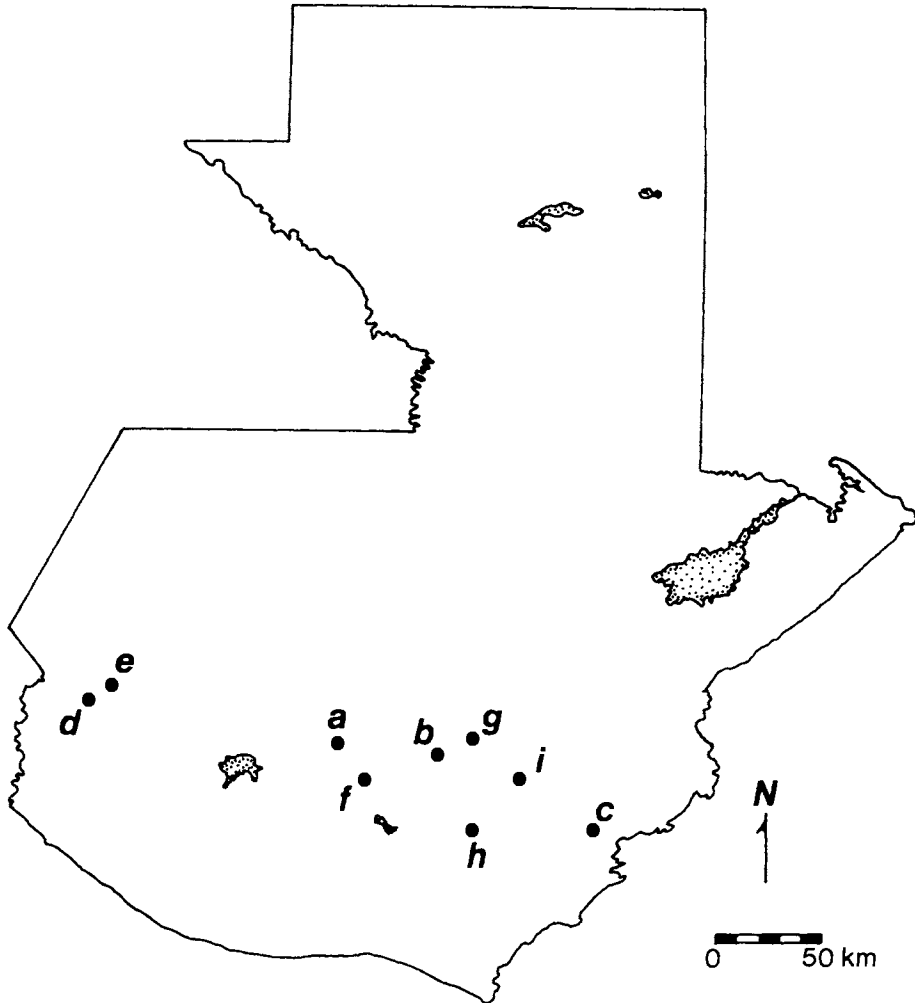


Figure 1. Obsidian source areas of Guatemala: (a) San Martín Jilotepeque; (b) El Chayal; (c) Ixtepeque; (d) Palo Gordo (Tajumulco); (e) San Lorenzo (Tajumulco); (f) San Bartolomé Milpas Altas; (g) Sansare; (h) Media Cuesta; (i) Jalapa.

unsystematic day trips, attempted to locate all the obsidian outcrops in the source area (Braswell 1996:85–89).

Source samples recovered during the geological survey were subjected to neutron activation analysis (NAA) at the Missouri University Research Reactor facility (MURR). The aim of this research was the development of a microsourcing technique that allows obsidian artifacts to be assigned to specific quarries or quarry systems within the source area. A detailed description of the first stage of statistical analysis has already been presented (Glascock et al. 1998).¹ These methods are not particularly new to

compositional studies (e.g., Ericson and Glascock 1992; Glascock 1994; Hughes 1986, 1994; Shackley 1990, 1992) but were applied in ways that may be novel to many Mesoamericanists. Preliminary results indicated that at least six distinct chemical “fingerprints” (compositional groups SMJ1–SMJ6) characterize the SMJ source, but exploratory statistics did not discriminate between the two major quarry systems at the source. In other words, the initial results were geologically meaningful but had little archaeological relevance.

This report is not intended as a description of quarry extraction or production in SMJ (found in

Braswell 1996). Rather, it has two narrow goals. First, it presents results of the geological survey conducted in SMJ. Second, it complements Glascock et al. (1998) by describing a second stage of statistical analysis and the development of methods that can be used to assign obsidian artifacts from SMJ to their original quarries or quarry systems.

Why is the additional precision of chemical microsourcing important? Bayman (1995) and Peterson et al. (1994) have used compositional data at the source-area level to examine complex kin and economic relationships among the Hohokam. Microsourcing allows these and other exciting models to be extended to sites that received the vast majority of their obsidian from

only one source. In Mesoamerica, such sites include Kaminaljuyú, Copán, Palenque, Cantona, Tollan-phase Tula, El Pital, and Xochicalco. Thus microsourcing is a technique with great potential not only for scholars with an interest in exchange systems within obsidian-procurement zones, but also for researchers concerned with broader questions of social structure and economy.

Survey

During the first phase of RRJ, lasting from April to August 1990, an area of approximately 280 km² was surveyed for obsidian outcrops (Figure 2). The operational method used during this phase of the project was to carefully search each and every

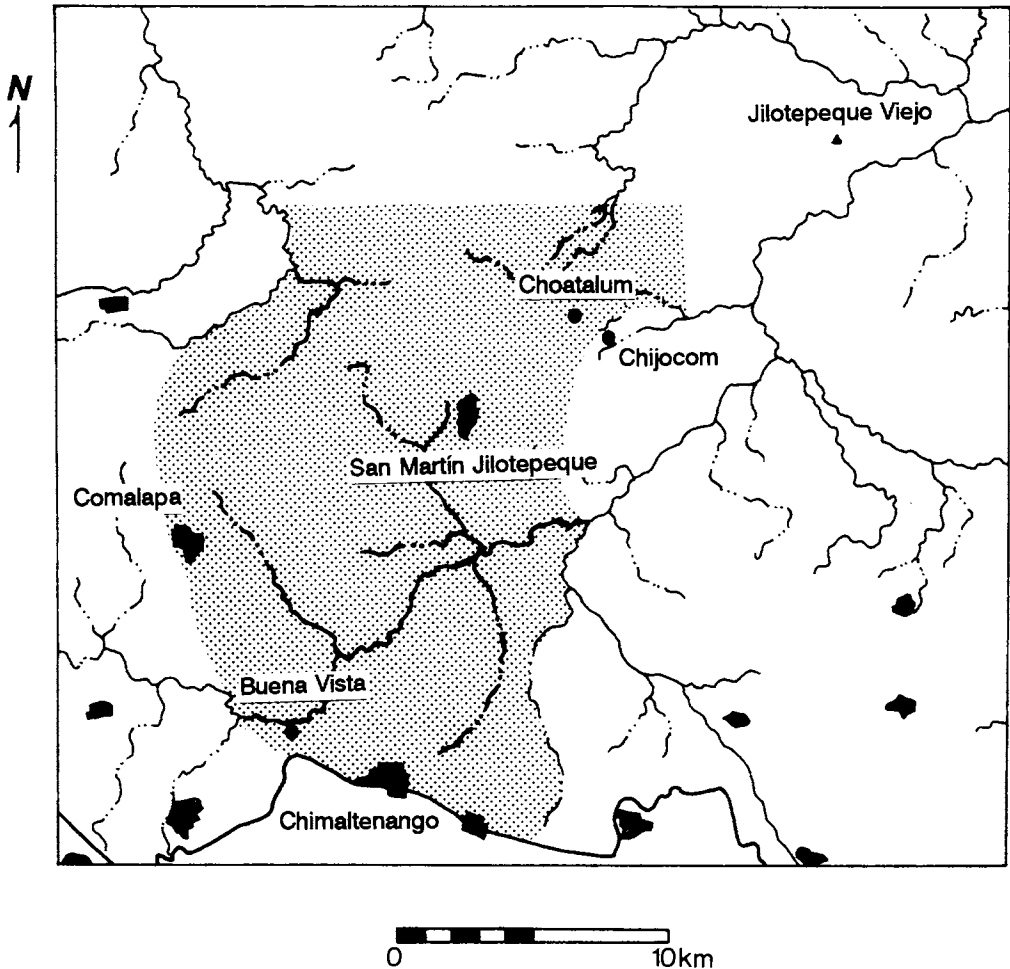


Figure 2. Area of geological survey (light shading). The Pan-American Highway (CA-1), major rivers, and towns (black shading) also are shown.

path, road cut, and stream bed shown on the relevant 1:50,000 scale topographic maps (Instituto Geográfico Militar de Guatemala 1976, 1978, 1983, 1984a, 1984b). Only one team surveyed the region, arriving by foot, motorcycle, or bus to the area to be covered that day. Nearby inhabitants and farmers working their fields were asked if they knew where obsidian could be found. We used both nodules and artifacts to illustrate the object of our search. Nearly everyone questioned knew what *chay* (obsidian) was, recognized that blade fragments and nodules were the same material, and could tell us where natural deposits, often quite distant, were located.

The geological survey was not conducted on a field-by-field basis nor were any transects walked. By the rigorous standards of modern archaeological survey, coverage of the 280-km² region was unsystematic. Nevertheless, it can be asserted with reasonable confidence that all surface outcrops were located, because the geological history of the region precludes the possibility that obsidian can be found throughout all of the area of survey.

Most of the region south of the Río Pixcaya and near Chimaltenango and the Pan-American highway (Figure 2) consists of Quaternary tephra interbedded with pumiceous diamectons (massive, unsorted valley-filling deposits up to 50 m in diameter) and fluvio-lacustrine sediments. The source of this material is the massive beds of Quaternary tephra, gray to white pumice, and darker cinders that spread north from the Acatenango, Fuego, and Agua volcanoes. These deposits, which are much more recent than the SMJ obsidian, are of unknown thickness but can be seen in several *quebradas* to a depth of more than 200 m. Thus, if any obsidian is actually present, it was deeply buried long ago by unrelated volcanic activity and alluviation. This zone of Quaternary tephra and diamectons covers some 60 km² (see Instituto Geográfico Nacional de Guatemala 1977). Reconnaissance of this and other unpromising geological formations focused on riverbeds, paths, and roadcuts—contexts where deeply buried obsidian would most likely be exposed. It quickly became apparent that none is present.

Rather than attempting full coverage of the entire 280 km², it seemed better to concentrate

efforts on geological formations where obsidian deposits are possible. These include the Padre Miguel Group (Tpm in Instituto Geográfico Nacional de Guatemala 1981), consisting of Tertiary water-laid tuffs, sillar, welded ignimbrite, thin andesite and basalt flows, and early Quaternary intrusive extrusions of andesite and olivine-pyroxene andesite. The outcrops located in 1990 were limited to a small zone where these formations are found (Figure 3). The settlement survey (Phase III of RRJ), consisting of systematic field-by-field reconnaissance, included not only all areas where obsidian was found in 1990, but also much of the local distribution of these geological formations. Only one additional outcrop (Figure 3, unanalyzed location), very small in size, was found during this later intensive phase of investigation. The fact that intensive survey of the outcrop zone failed to locate significant new deposits demonstrates the efficacy of the research design of the geological survey.

Geological specimens were collected from 25 locations, and the boundaries of extensive outcrops were paced (Figure 3). The resolution of topographic maps allowed the position of all outcrops to be determined to a precision of 100 m. Almost all of the previously reported outcrops (Clark 1981; Sheets 1983; Stross et al. 1983) were found and sampled. The only exceptions are those reported by Sidrys et al. (1976), which are inaccurately located, and one called Buena Vista (Sheets 1983:Table 1, Coordinate 312228). Buena Vista is in the *municipio* of Chimaltenango, 3 km northwest of the *cabecera* (Sheets 1983; Stross et al. 1983). Project members were unable to locate either primary or secondary geological deposits of obsidian in the vicinity or, for that matter, anywhere within the *municipio* of Chimaltenango.

Although the Río Pixcaya passes just north of Buena Vista, no obsidian nodules were found in this stretch of the river, 9.5 km southwest and 340 m above the confluence with the Quemaya. Riverine action, therefore, cannot account for the presence of the obsidian collected by Sheets (1983). Furthermore, soils in Buena Vista are derived from the deep Quaternary tephra that spreads north from Acatenango, and not from the Padre Miguel Group. Stross et al. (1983) state that obsidian was collected at the site of Buena Vista, but do not specify whether it is an archaeological

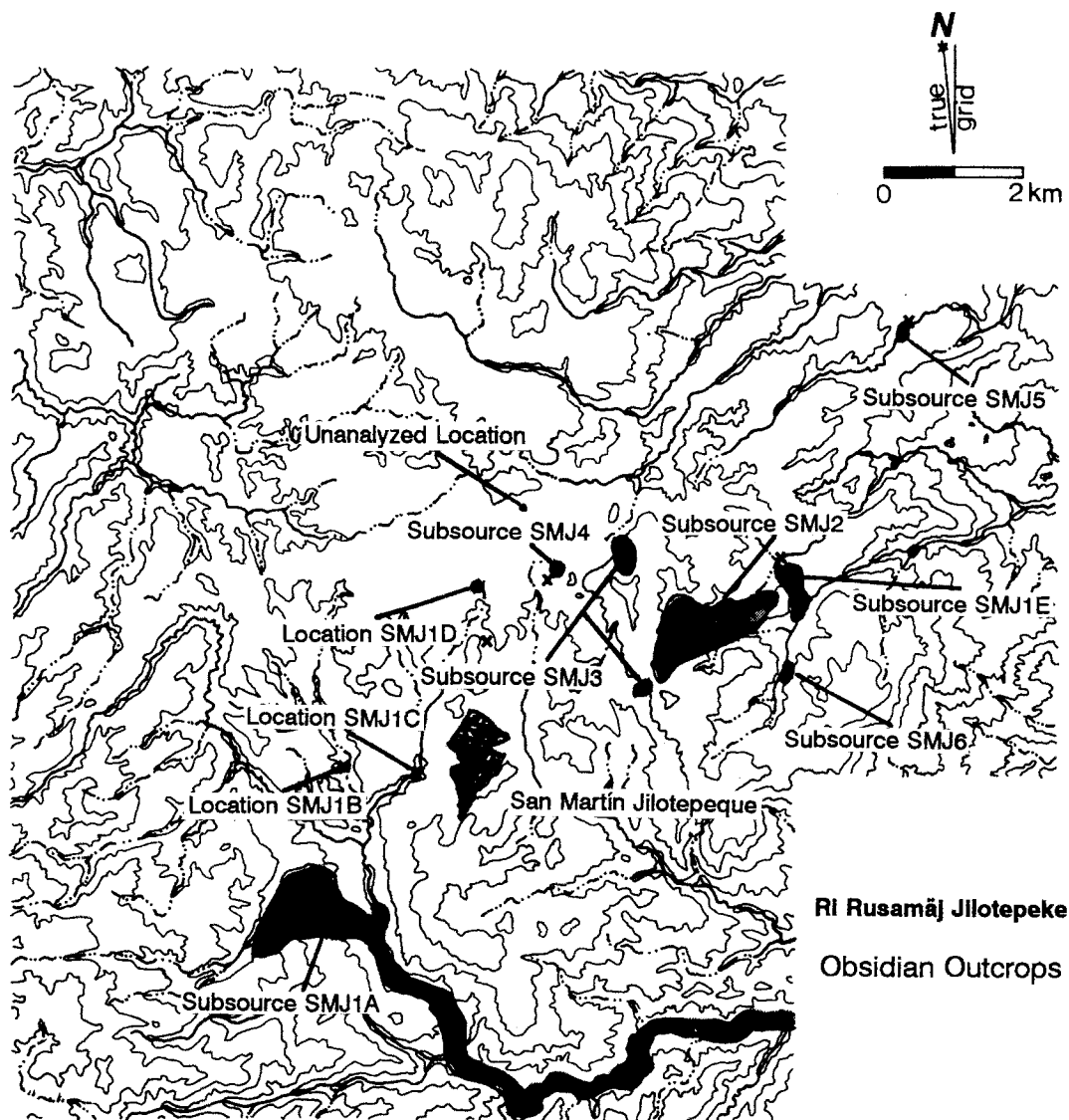


Figure 3. Primary and secondary deposits of obsidian in San Martín Jilotepeque: dark regions are flows and secondary deposits; contour interval = 100 m; contour range = 1200–2300 m above sea level.

site or an outcrop (Fred H. Stross, personal communication 1995). One possibility is that these nodules were either ancient or modern manuports, perhaps used in road ballast.

In 1993, Braswell visited Chijocom (Figure 2) for reasons unrelated to RRJ. Obsidian nodules were seen in several locations in the *aldea*, but time did not allow specimens to be collected. In addition, James Brady (personal communication 1994) has found obsidian cobbles in a dry riverbed near the artificial caves below Jilotepeque Viejo.

Thus, although the survey area was adequately covered, more outcrops are located in the eastern and northeastern extremes of the *municipio*, beyond the borders of the geological survey.

Sixty-nine source specimens from 25 primary and secondary depositional contexts in the SMJ source area were assayed using NAA. In addition, analyses of 40 samples from three minor source areas in the highlands of Guatemala were conducted and are presented. Ten specimens from the newly discovered Sansare source also were ana-

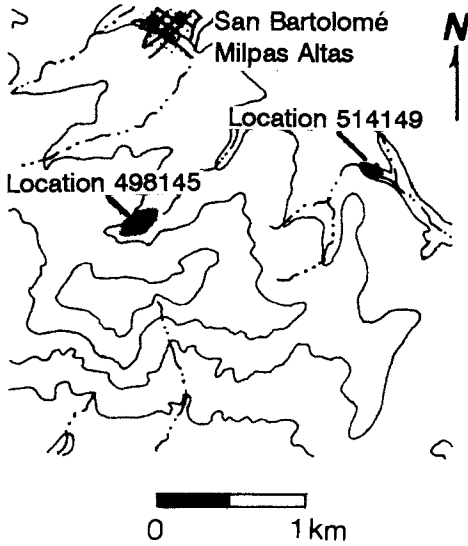


Figure 4. Obsidian outcrops in San Bartolomé Milpas Altas: dark areas are flows; arrow indicates UTM-grid north ($0^{\circ}36'$ east of true north); contour interval = 100 m; contour range = 1900–2300 m above sea level.

lyzed; these results have already been published (Braswell and Glascock 1992). Thus a total of 119 geological specimens from five Guatemalan

source areas were assayed by NAA. Figures 4 and 5 display obsidian outcrops at the San Bartolomé Milpas Altas and Media Cuesta (Laguna de Ayarza) source areas. A map of the outcrop at Sansare can be found elsewhere (Braswell and Glascock 1992:Figure 1).

Chemical Analysis

Compositional Heterogeneity in Obsidian

Obsidian, a form of rhyolite, is created when molten lava cools rapidly under conditions that do not allow crystallization. Obsidian commonly forms as a stratum or envelope encasing rhyolitic lava flows and domes, but can appear as pyroclastic deposits, in rhyolitic agglutinates, and even in extensive ash-flow sheets (Hughes and Smith 1993). The trace-element composition of obsidian from a given source area is not always homogeneous, but the correlations of certain elements are quite distinctive, even in geologically complex source areas (Asaro et al. 1994; Ericson and Glascock 1992; Glascock et al. 1997; Hughes 1994). Some source areas, such as SMJ and Media Cuesta, contain multiple outcrops that are chemically distinct.

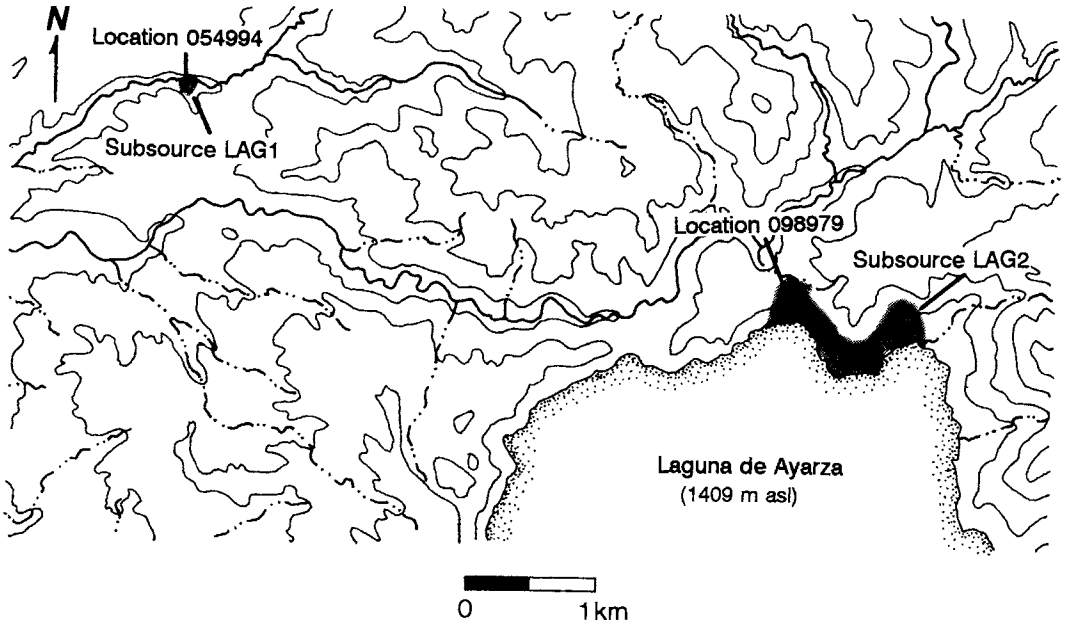


Figure 5. Obsidian outcrops in Media Cuesta: dark areas are flows and secondary deposits; arrow indicates UTM-grid north ($0^{\circ}43'$ east of true north); contour interval = 100 m; contour range = 1300–1800 m above sea level.

Four fundamental factors account for intra-source compositional variability within primary geological contexts. The first, magma mixing, occurs when two or more magmas (with different chemical fingerprints) come together during or just before an eruption event (Asaro et al. 1994; Bowman et al. 1973; Mahood 1980, 1981, 1988). Obsidian flows resulting from magma mixing are heterogeneous in composition. Therefore, to define or characterize internal variation adequately, it is often necessary to analyze many specimens from different locations within these flows. Fortunately, magma mixing is easy to detect in the field. Primary outcrops resulting from magma mixing are usually very heterogeneous in appearance. Other volcanic products may be jumbled into the same strata as the obsidian, and transitional forms may be observed.

A second cause of intrasource variability is magma aging. Magma chambers (from which eruptions or extrusions originate) may have life spans of millions of years. During this period, for reasons and in ways that are not well understood, the chemical nature of magma changes, often producing rhyolitic materials with different elemental concentrations. As a result, a single eruption or multiple events closely spaced in time yield outcrops that are chemically homogeneous, but temporally distinct events may create outcrops that differ in composition (Godfrey-Smith et al. 1993; Mahood 1980, 1981, 1988). Thus, while magma mixing forms outcrops that exhibit high intraflow heterogeneity, magma aging causes high interflow compositional variation.

Trace-element concentrations also can vary within a single magma chamber. When a large pyroclastic eruption results in an extensive ash-flow sheet, chemically heterogeneous obsidian can be found near the edges of the sheet and around buried topographic features such as hills. In this case, compositional heterogeneity reflects the joining of materials from different depths within the magma chamber. In certain circumstances, a lump of obsidian from an ash-flow sheet can be internally heterogeneous (Hughes and Smith 1993:85–89).

Finally, chemical heterogeneity in obsidian can be caused by wall-rock reactions (e.g., Bouska 1993; Shackley 1990). Shackley (1990:204) notes that this frequently occurs in the

many bimodal volcanic fields of the southern Sierra Madre. A common result of wall-rock reactions is the formation of sanidine or plagioclase, which in turn increases the proportions of Ba and Sr in obsidian.

Secondary depositional factors also can cause chemically distinct obsidian to become mixed within a single outcrop or deposit. This frequently occurs when obsidian-bearing strata are subject to erosion or alluvial processes. Volcanic activity also may create intra-outcrop mixing, particularly when newly formed obsidian spines break through older deposits or when eruptions eject new glass onto previously existing outcrops.

When the characteristic compositions of obsidian deposits in the same source area are sufficiently different yet internally homogeneous, the area can be divided into chemically distinct subsources. This implies that it should be possible, in some cases, to assign obsidian artifacts to particular quarries or quarry systems.

Trace Element Assay by Neutron Activation Analysis

Obsidian specimens from SMJ and four minor source areas were assayed using neutron activation analysis (NAA). In NAA, specimens are bombarded with thermal neutrons. A small fraction of the neutrons are captured by the atomic nuclei of the sample. As a result, some become unstable and emit gamma rays with characteristic energies. The rate of emission is dependent on the half-lives of the radioactive nuclei and the determination of intensity allows quantitative analysis. A combination of two or three irradiation, decay, and measurement phases allows assay of B, Ba, Ce, Cl, Co, Cs, Dy, Eu, Fe, Gd, Hf, K, La, Lu, Mn, Na, Nd, Rb, Sb, Sc, Sm, Sr, Ta, Tb, Th, U, Yb, Zn, and Zr elemental concentrations. The precision of certain measurements can be enhanced (at the detriment of others) by changing the periods of irradiation, decay, and measurement. This has facilitated the development of a cheaper abbreviated technique useful for most artifact-sourcing purposes but insufficient for characterizing geological material (Glascock et al. 1997; Stross et al. 1983).

Sample preparation for NAA at MURR is discussed by Glascock et al. (1988). A strategy of two

irradiations and three measurements was used for the NAA of all 119 Guatemalan source samples. Each specimen was first irradiated in a neutron flux of 8×10^{13} n/cm²s for five seconds. A 25-minute decay was followed by a 12-minute count for short-lived elements (Ba, Cl, Dy, K, Mn, and Na: the subjects of abbreviated NAA). A 70-hour irradiation in a neutron flux of 5×10^{13} n/cm²s was used for medium-lived (Ba, La, Lu, Nd, Sm, U, and Yb) and long-lived (Ce, Co, Cs, Eu, Fe, Hf, Rb, Sb, Sc, Sr, Ta, Tb, Th, Zn, and Zr) elements.² The concentrations of medium-lived elements were measured by a 2,000-second count after 7–8 days of decay. A 4–5 week decay and 10,000-second count were used for long-lived elements. Measurements were standardized using National Institute of Standards and Technology SRM-278 Obsidian Rock and SRM-1633a Fly Ash reference

materials (Graham et al. 1982).

Table 1 summarizes NAA results for SMJ and four minor Guatemalan sources. The full compositional dataset for these specimens has been presented by Braswell (1996:Tables 4.1–4.2).

Statistical Analysis

Compositional variation within the SMJ source area is much greater than that of the four minor Guatemalan sources (Table 1). Is this variation patterned in any meaningful way? If so, can it be interpreted spatially as well as chemically? Several statistical strategies and methods of visual presentation were used to examine and analyze the dataset. The first stage of statistical analysis has already been presented (Braswell 1996; Glascock et al. 1998) and is described here in summary form.

Table 1. Summary Statistics for Concentrations of Elements in Guatemalan Samples (N=119; in ppm unless noted).

Element	SMJ		JAL		LAG		SBMA		SNS	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Ba	1023	± 26	772	± 18	899	± 14	1080	± 16	703	± 12
Ce	44.7	± 4.2	51.4	± .6	47.7	± .8	40.8	± .9	48.6	± 1.6
Cl	527	± 121	501	± 84	841	± 108	759	± 97	420	± 51
Co	.443	± .217	.417	± .004	.142	± .035	.545	± .023	2.145	± .073
Cs	3.39	± .66	8.01	± .06	2.90	± .05	3.29	± .05	6.53	± .14
Dy	2.00	± .35	2.61	± .33	3.16	± .56	1.82	± .42	2.72	± .29
Eu	.537	± .063	.624	± .007	.639	± .028	.488	± .007	.650	± .012
Fe	6880	± 920	8060	± 90	9020	± 420	8000	± 150	12430	± 270
Hf	3.34	± .52	3.21	± .04	4.20	± .38	4.03	± .07	3.49	± .05
K (%)	3.28	± .22	3.56	± .26	3.33	± .24	3.53	± .26	3.40	± .14
La	24.5	± 2.6	27.2	± .4	24.2	± .4	22.2	± .2	25.6	± .7
Lu	.234	± .022	.260	± .012	.372	± .015	.264	± .007	.285	± .003
Mn	548	± 58	515	± 10	964	± 64	519	± 4	613	± 18
Na (%)	2.91	± .15	2.70	± .05	3.56	± .11	3.04	± .03	2.95	± .09
Nd	15.9	± 1.7	19.0	± .7	19.4	± 1.0	14.4	± .8	19.0	± 1.0
Rb	110	± 6	150	± 1	106	± 3	121	± 2	139	± 3
Sb	.351	± .076	.503	± .043	.285	± .036	.320	± .022	.570	± .032
Sc	1.89	± .18	2.86	± .03	1.68	± .04	2.07	± .04	3.30	± .06
Sm	2.95	± .20	3.76	± .07	3.90	± .17	2.82	± .06	3.70	± .06
Sr	189	± 33	179	± 11	139	± 48	137	± 7	263	± 12
Ta	.794	± .060	.941	± .013	.804	± .023	.614	± .011	.957	± .021
Tb	.350	± .027	.460	± .027	.539	± .038	.345	± .008	.461	± .019
Th	8.24	± .86	10.70	± .08	7.07	± .10	8.91	± .16	10.59	± .20
U	2.90	± .31	3.97	± .19	2.71	± .20	3.09	± .17	4.41	± .19
Yb	1.46	± .15	1.65	± .04	2.43	± .12	1.62	± .03	1.75	± .04
Zn	31.6	± 3.9	37.2	± 1.6	46.5	± 3.8	34.3	± 1.1	40.9	± 2.9
Zr	124	± 20	123	± 11	148	± 17	139	± 5	137	± 5

SMJ = San Martín Jilotepeque source area, 25 sampled locations and all chemical groups (N=69); JAL = Jalapa source, one sampled location (N=5); LAG = Media Cuesta (or Laguna de Ayarza) source area, two sampled locations (N=25); SBMA = San Bartolomé Milpas Altas source area, two sampled locations (N=10); SNS = Sansare source, one sampled location (N=10) (from Braswell and Glascock 1992:Table 1).

Stage 1—Exploratory and Classificatory Analysis

Gluscock et al. (1994) have noted that a small subset of elements (in decreasing order of importance: Co, Cs, Sb, Mn, and Sc) are particularly useful for distinguishing among the Guatemalan obsidian sources. A reasonable first assumption was that intrasource variation at SMJ would also be reflected most clearly by these same elements. Several bivariate plots, showing the concentrations of pairs of these elements, were created. These demonstrate that six distinct compositional groups easily can be seen for the SMJ source area (Figure 6).

Cluster analysis was used next to create groups of specimens based on all reliable compositional data (see Braswell 1996 for documentation of the clustering method). The elements Cl, Dy, K, Nd, Sb, Sr, and U were omitted because of the low analytical precision associated with their measurement (see Table 1). The total number of ele-

ments considered in the cluster analysis, then, was 20 (Ba, Ce, Co, Cs, Eu, Fe, Hf, La, Lu, Mn, Na, Rb, Sc, Sm, Ta, Tb, Th, Yb, Zn, and Zr). Cluster analysis indeed confirms the existence of six chemical groups (referred to as SMJ1-SMJ6) within the SMJ source area (Figure 7).³ Table 2 summarizes the compositional data for each chemical group. Comparison with Table 1 reveals a significant reduction in the standard deviations associated with elemental concentrations.

Having demonstrated that the SMJ source can be divided into at least six chemical groups and that assignments can be made with a high degree of accuracy for five of these groups,⁴ we reevaluated source assignments for all SMJ obsidian artifacts in the MURR database. To date, 10 SMJ-source artifacts have been assayed using the full analytical procedure and approximately 350 using abbreviated NAA. All of these artifacts can be assigned to chemical group SMJ1 with a confidence of $p \geq .95$. Thus, even though the SMJ

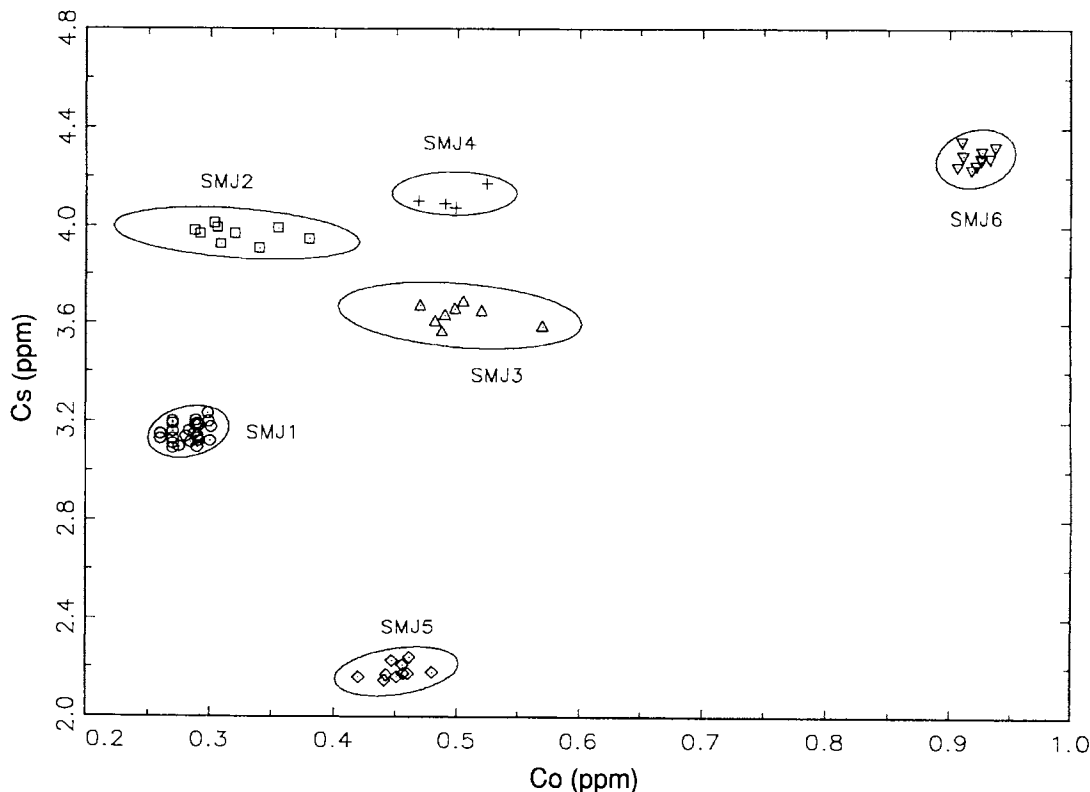


Figure 6. Cobalt versus cesium concentrations for SMJ source samples (N=69). Ellipses represent 95-percent confidence level for inclusion in the six compositional groups; superposition of symbols creates the appearance of less than 69 specimens.

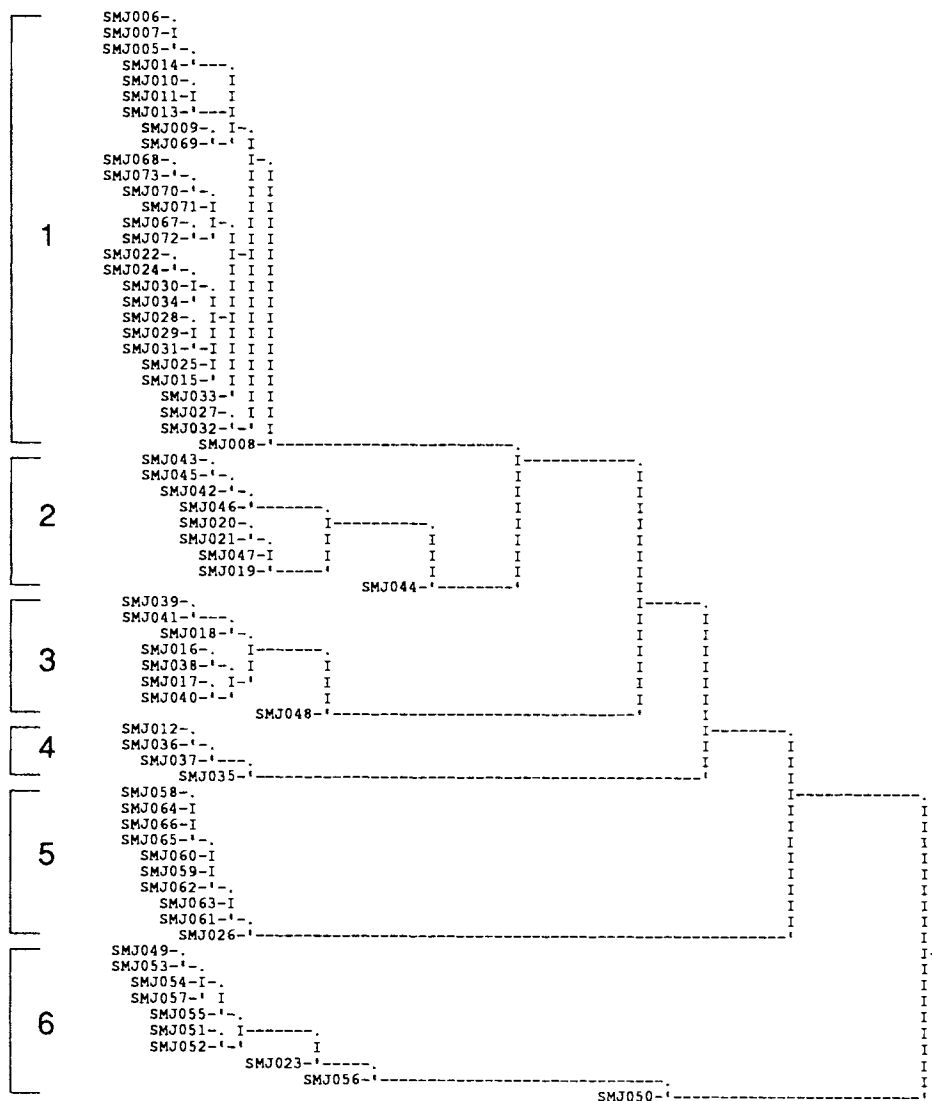


Figure 7. Dendrogram displaying results of cluster analysis for 69 source specimens from SMJ. The clusters numbered 1–6 correspond to compositional groups SMJ1–SMJ6 (after Glascock et al. 1998:Figure 2.5).

source area is large and complex, ancient extraction and production was focused at specific locations where obsidian from the SMJ1 compositional group can be found.

Stage 2—Distinguishing between SMJ1A and SMJ1E Obsidian

Another conclusion, from the perspective of artifact assignment, is that the ability to divide SMJ into six chemical groups yields no new information. But it is reasonable to ask if there is further structure *within* compositional group SMJ1. That

is, can SMJ1 be divided into meaningful chemical subgroups? The answer is yes, but classificatory assignments can be made at a confidence level of only 84 percent.

In this stage, discriminant function analysis (DFA) was used to examine the compositional data for 25 of the 28 members of chemical group SMJ1. DFA requires that the number of groups and group membership (for at least two specimens per group) are known. For analytical purposes, two compositional subgroups were defined: SMJ1A (containing the 14 specimens

Table 2. Summary Statistics for Elemental Concentrations in SMJ Source Obsidian by Compositional Group (in ppm unless noted)

Element	SMJ1 (N=28)		SMJ2 (N=9)		SMJ3 (N=8)		SMJ4 (N=4)		SMJ5 (N=10)		SMJ6 (N=10)	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Ba	1046	± 12	1012	± 13	1019	± 20	970	± 11	1024	± 8	996	± 12
Ce	45.8	± .9	40.7	± .6	44.5	± .8	35.8	± .5	48.2	± .6	45.4	± 7.6
Cl	550	± 81	467	± 53	471	± 54	461	± 48	733	± 48	384	± 59
Co	.284	± .012	.321	± .031	.503	± .031	.495	± .023	.451	± .16	.922	± .010
Cs	3.15	± .04	3.97	± .03	3.63	± .04	4.11	± .04	2.18	± .03	4.28	± .04
Dy	1.86	± .29	2.23	± .22	2.14	± .31	1.93	± .11	2.26	± .42	1.84	± .39
Eu	.526	± .009	.487	± .007	.575	± .009	.441	± .005	.666	± .008	.488	± .022
Fe	6230	± 150	5950	± 260	7630	± 320	6200	± 100	8410	± 90	7670	± 40
Hf	3.16	± .05	3.05	± .38	3.51	± .06	2.68	± .03	4.49	± .05	3.10	± .03
K(%)	3.24	± .17	3.41	± .22	3.21	± .24	3.16	± .12	3.16	± .24	3.49	± .16
La	25.4	± .5	21.6	± .5	24.1	± .4	19.4	± .3	25.8	± .2	25.4	± 4.7
Lu	.221	± .006	.257	± .005	.261	± .005	.204	± .004	.260	± .007	.213	± .006
Mn	532	± 10	574	± 8	602	± 8	523	± 4	637	± 6	446	± 5
Na(%)	2.85	± .04	2.88	± .04	3.04	± .04	2.88	± .02	3.18	± .02	2.72	± .02
Nd	16.1	± .7	14.4	± .6	16.2	± .5	12.9	± .3	18.3	± .7	15.3	± 2.3
Rb	108	± 2	120	± 1	111	± 2	116	± 1	100	± 1	112	± 1
Sb	.342	± .054	.388	± .063	.367	± .072	.456	± .086	.241	± .022	.394	± .050
Sc	1.76	± .02	1.88	± .03	1.93	± .05	2.05	± .03	1.79	± .02	2.27	± .02
Sm	2.88	± .05	2.96	± .05	3.06	± .04	2.52	± .02	3.26	± .04	2.89	± .25
Sr	191	± 15	134	± 11	185	± 7	175	± 10	247	± 11	185	± 9
Ta	.781	± .011	.837	± .007	.774	± .012	.812	± .006	.695	± .010	.899	± .013
Tb	.331	± .008	.370	± .014	.373	± .014	.317	± .004	.392	± .010	.335	± .019
Th	8.33	± .12	8.52	± .09	8.39	± .13	8.20	± .09	6.51	± .07	9.38	± .84
U	2.86	± .19	3.17	± .07	2.95	± .12	2.94	± .11	2.35	± .11	3.27	± .11
Yb	1.39	± .03	1.63	± .04	1.63	± .03	1.22	± .05	1.63	± .04	1.32	± .03
Zn	31.4	± 1.0	28.2	± 1.0	31.9	± .8	27.0	± .3	39.9	± .70	28.2	± 1.0
Zr	117	± 6	112	± 17	131	± 5	100	± 6	166	± 4	116	± 7

labelled SMJ005-SMJ007, SMJ009, SMJ013-SMJ015, and SMJ067-SMJ073 in Figure 7) and SMJ1E (containing the 11 specimens called SMJ022, SMJ024-SMJ025, and SMJ027-SMJ034 in Figure 7). The choice of two groups, their names and membership, and the exclusion of three (SMJ008, SMJ010, and SMJ011) of the 28 specimens from the SMJ1 compositional group were not arbitrary but based on spatial observations discussed in the next section.⁵ Table 3 displays summary statistics for the SMJ1A and SMJ1E specimens.

What is the probability that the two proposed chemical subgroups in Table 3 share the same centroid? Table 4 displays the *U* statistic (Wilks' Lambda) and *F* value for all 27 elemental concentrations measured. The probabilities that mean concentrations for the elements Co, Fe, and Mn are the same in SMJ1A and SMJ1E are less than .0001 and equal to .0002 for Hf. Similarly, the null hypothesis can be rejected at the .01 confi-

dence level for Eu and at the .03 confidence level for Zn. Differences in group means for Na and Th also appear to be significant (with confidence levels of .05 and .1). Although the significance values for K, Nd, and U also are in this range, they are considered unreliable because of the low level of analytical precision associated with these elements. These results make it quite clear that SMJ1A and SMJ1E are statistically distinct.

Given that SMJ1A and SMJ1E are different, the next step was to devise a procedure that best discriminates between the chemical subgroups. The variables considered in DFA were 21 elemental concentrations. In this case, Sr was included in the analysis because it always appears in the SMJ source-sample database at concentrations significantly higher than the limit of detection. DFA was conducted in a stepwise fashion using Mahalanobis' metric D^2 as the criterion for variable selection. Tolerance was set at a minimum value of .001, the minimum *F*-value for

Table 3. Summary Statistics for Elemental Concentrations in Subgroups SMJ1A and SMJ1E (in ppm unless noted)

Element	SMJ1A (N=14)		SMJ1E (N=11)	
	μ	σ	μ	σ
Ba	1049	± 11	1042	± 12
Ce	45.8	$\pm .6$	45.6	$\pm .7$
Cl	545	± 75	573	± 90
Co	.279	$\pm .009$	.294	$\pm .006$
Cs	3.16	$\pm .04$	3.15	$\pm .04$
Dy	1.82	$\pm .37$	1.94	$\pm .17$
Eu	.523	$\pm .006$	.533	$\pm .009$
Fe	6140	± 90	6380	± 90
Hf	3.14	$\pm .03$	3.21	$\pm .05$
K (%)	3.30	$\pm .14$	3.17	$\pm .19$
La	25.4	$\pm .2$	25.3	$\pm .2$
Lu	.223	$\pm .007$	.220	$\pm .003$
Mn	527	± 7	542	± 6
Na (%)	2.83	$\pm .05$	2.87	$\pm .03$
Nd	16.2	$\pm .5$	15.7	$\pm .6$
Rb	108	± 2	108	± 2
Sb	.346	$\pm .052$	.324	$\pm .057$
Sc	1.76	$\pm .02$	1.76	$\pm .02$
Sm	2.89	$\pm .05$	2.89	$\pm .05$
Sr	195	± 18	188	± 9
Ta	.780	$\pm .011$	.783	$\pm .012$
Tb	.331	$\pm .005$	.332	$\pm .010$
Th	8.38	$\pm .11$	8.29	$\pm .13$
U	2.94	$\pm .15$	2.80	$\pm .23$
Yb	1.39	$\pm .03$	1.39	$\pm .02$
Zn	31.0	± 1.1	31.9	$\pm .7$
Zr	117	± 6	118	± 6

entrance or removal of a variable from the discriminant function (DF) was set at 1, and prior probabilities for inclusion in either compositional subgroup were set at .5. SPSS/PC+ (version 5.0.2) was used to conduct a 15-step analysis. Concentrations (C_x) for the elements Ce, Co, Cs, Eu, Fe, La, Rb, Ta, Tb, Th, and Yb are present in the resulting DF. To facilitate computation, the DF is presented here in both unstandardized and standardized forms:

$$\text{(standardized) } D = 3.296C_{Ce} - 1.235C_{Co} - 1.416C_{Cs} + 3.048C_{Eu} - 3.539C_{Fe} + 1.514C_{La} + 2.408C_{Rb} - 1.794C_{Ta} + 1.255C_{Tb} - 1.920C_{Th} - 1.349C_{Yb}$$

$$\text{(unstandardized) } D = 5.132C_{Ce} - 164.1C_{Co} - 35.54C_{Cs} + 393.2C_{Eu} - 0.3914C_{Fe} + 7.344C_{La} + 1.421C_{Rb} - 155.4C_{Ta} + 166.4C_{Tb} - 16.55C_{Th} - 46.11C_{Yb} - 109.5.$$

How effective is this DF at discriminating between the two chemical subgroups? Several

Table 4. Significance of Differences in Mean Elemental Compositions for SMJ1A and SMJ1E Subgroups (with 1 and 23 degrees of freedom)

Element	U		Significance Level
	(Wilks' λ)	F	
Ba	.9093	2.294	.1435
Ce	.9804	.461	.5039
Cl	.9687	.742	.3979
Co	.4679	26.16	.0000
Cs	.9825	.410	.5282
Dy	.9538	1.114	.3022
Eu	.7182	9.024	.0063
Fe	.3427	44.12	.0000
Hf	.5460	19.12	.0002
K (%)	.8689	3.471	.0753
La	.9273	1.802	.1925
Lu	.9365	1.560	.2242
Mn	.3965	35.00	.0000
Na (%)	.8541	3.930	.0595
Nd	.8287	4.755	.0397
Rb	.9579	1.011	.3250
Sb	.9606	.944	.3415
Sc	.9925	.173	.6812
Sm	.9993	.016	.9019
Sr	.9399	1.471	.2375
Ta	.9834	.388	.5397
Tb	.9944	.129	.7227
Th	.8803	3.128	.0902
U	.8751	3.285	.0830
Yb	.9862	.322	.5757
Zn	.8103	5.386	.0295
Zr	.9764	.557	.4632

measures involve the distribution of D scores. Within-group variability of D scores should be much smaller than between-group variation. Table 5 displays the D scores calculated for each of the 25 source specimens considered in the analysis. An eigenvalue of 26.07 is calculated from the 25 D scores, demonstrating that the DF is a powerful tool for discrimination. The degree of association between D scores and groups, called the canonical correlation, is a similar measure. In this example, the canonical correlation is .981, a value very close to the ideal of 1. A final measure is the U statistic. Here U equals .0369, close to the ideal of 0. This is transformed into a χ^2 value of 57.72 with 11 degrees of freedom. The associated significance level is less than .00005, indicating that SMJ1A members and SMJ1E specimens do not share the same mean D score.

These three statistics demonstrate that the DF is extremely effective when used to discriminate

between chemical subgroups SMJ1A and SMJ1E. But how strong a classificatory tool is it? The 25 specimens were next assigned to compositional subgroups according to *D* scores. As can be seen in Table 5, there were no errors of assignment. Table 5 also presents probabilities of belonging to either SMJ1A or SMJ1E, given the *D* scores calculated by the DF. These probabilities, $P(\text{SMJ1A}|D)$ and $P(\text{SMJ1E}|D)$, are calculated using Bayes' rule with the assumption of a prior probability of .5 for belonging to either chemical subgroup. They are all optimal (greater than .99995 for the correct assignment, less than .00005 for the incorrect chemical subgroup).

Models typically fit the data from which they are derived better than other samples drawn from the same population. For this reason, the successful classification rate of 100 percent suggested by using the DF to make assignments for the 25 specimens of known compositional subgroup affiliation is optimistic. A better way to test the classificatory efficacy of the model is to use the posterior jackknife method. In this test, each specimen of known membership was sequentially excluded, a new DF was calculated based on the remaining 24 specimens, and the excluded specimen was then reclassified using the new DF.

Four specimens (Figure 7:SMJ009, SMJ015, SMJ024, and SMJ027) are given incorrect compositional subgroup assignments when the posterior jackknife procedure is used. The overall classificatory efficacy rate predicted for the DF is therefore only 84 percent. It is below the mystical value of 95 percent, but not by a considerable amount. But it is important to remember that specimens could be randomly assigned to SMJ1A or SMJ1E with a success rate of 50 percent.

An attempt also was made to divide the four minor Guatemalan sources into compositional groups. The Media Cuesta (or Laguna de Ayarza) source area, in the department of Santa Rosa, Guatemala, can be characterized as consisting of two distinct chemical groups: LAG1 (Braswell 1996:Table 4.2, specimens LAG001-LAG003 and LAG016-LAG025) and LAG2 (Braswell 1996:Table 4.2, specimens LAG004-LAG015). Although the discriminatory ability of this DF, like that generated for SMJ1A and SMJ1E, is virtually perfect, its classificatory ability also is slightly suspect. Samples from the San Bartolomé

Table 5. *D* Scores and Posterior Probabilities of Inclusion in Subgroups SMJ1A and SMJ1E

Specimen ID	Actual Subgroup	<i>D</i>	$P(\text{SMJ1A}|D)$	$P(\text{SMJ1E}|D)$
SMJ005	SMJ1A	4.46	1.0000	.0000
SMJ006	SMJ1A	4.88	1.0000	.0000
SMJ007	SMJ1A	3.59	1.0000	.0000
SMJ009	SMJ1A	3.42	1.0000	.0000
SMJ013	SMJ1A	5.00	1.0000	.0000
SMJ014	SMJ1A	5.93	1.0000	.0000
SMJ015	SMJ1A	1.26	1.0000	.0000
SMJ022	SMJ1E	-4.47	.0000	1.0000
SMJ024	SMJ1E	-5.41	.0000	1.0000
SMJ025	SMJ1E	-6.61	.0000	1.0000
SMJ027	SMJ1E	-4.63	.0000	1.0000
SMJ028	SMJ1E	-4.89	.0000	1.0000
SMJ029	SMJ1E	-4.56	.0000	1.0000
SMJ030	SMJ1E	-6.22	.0000	1.0000
SMJ031	SMJ1E	-5.70	.0000	1.0000
SMJ032	SMJ1E	-6.18	.0000	1.0000
SMJ033	SMJ1E	-5.67	.0000	1.0000
SMJ034	SMJ1E	-6.43	.0000	1.0000
SMJ067	SMJ1A	3.92	1.0000	.0000
SMJ068	SMJ1A	4.47	1.0000	.0000
SMJ069	SMJ1A	5.47	1.0000	.0000
SMJ070	SMJ1A	4.85	1.0000	.0000
SMJ071	SMJ1A	3.98	1.0000	.0000
SMJ072	SMJ1A	5.18	1.0000	.0000
SMJ073	SMJ1A	4.35	1.0000	.0000

Milpas Altas, Sansare, and Jalapa source areas could not be divided into meaningful compositional groups.

Spatial Interpretation

Subsources within SMJ

Thus far, variability in composition has been considered without reference to geography. The groups and subgroups defined by statistical analysis are compositional in nature and are not necessarily related to the spatial patterning of outcrops and other sampled locations. Thus, the use of the term *subsource* (a chemically and spatially distinct deposit) has so far been avoided when referring to these groups. Fortunately, despite all the possible reasons that chemical data may not be spatially interpretable, obsidian belonging to the major compositional groups in SMJ did come from distinct locations. Figure 3 displays the boundaries of the flows and secondary deposits where obsidian specimens belonging to the SMJ1-SMJ6 compositional groups were found.

Because there are no flows where obsidian from more than one compositional group were encountered, SMJ1-SMJ6 can be said to form separate subsources. One streambed (location 419380) yielded two specimens from different compositional groups (SMJ2 and SMJ3), but the secondary nature of this deposit suggests that gravity and water are responsible for their association.

Subsources SMJ2, SMJ4, SMJ5, and SMJ6 each consist of only one flow or secondary deposit. Subsource SMJ2 is an extensive flow originating from an eroded rhyolitic dome to the southwest. The outcrop at subsurface SMJ4 was deposited by unknown depositional processes. Subsource SMJ5 is the edge of a flow originating from a small dome to the southeast. Subsource SMJ6 is a localized outcrop that appears to have been redeposited. SMJ3 consists of two distinct extrusions on the same ridge as subsurface SMJ2. Another specimen belonging to this group was recovered from road ballast.

Obsidian from chemical group SMJ1 is found in five distinct areas and also in the Ríos Quemaya and Pixcaya. These areas are labeled in Figure 3 as subsources SMJ1A and SMJ1E, and locations SMJ1B-SMJ1D. The 25 specimens chosen for membership in compositional subgroups SMJ1A (Pachay-Las Lomas) and SMJ1E (Choatalum) correspond with subsources SMJ1A and SMJ1E, the locations of the only important quarry workshops in the region (Braswell 1996). Thus, the spatial separation of the outcrops in Pachay-Las Lomas and Choatalum served as the basis for group membership in the DFA. Both SMJ1A and SMJ1E consist of rhyolitic lava domes, associated flows, and secondary deposits.

It is not known whether the three analyzed specimens (Figure 7:SMJ008, SMJ010, and SMJ011) from locations SMJ1B-SMJ1D should be grouped with subsurface SMJ1A, SMJ1E, or in one to three additional subsources. For this reason, their spatial correlates are called locations rather than subsources. SMJ1B and SMJ1C are small pyroclastic deposits. Larger blocks and greater quantities of obsidian are found at location SMJ1D, which may be a flow at the southern edge of a small dome. Use of the DF, which automatically classifies *any* set of compositional data (e.g., derived from obsidian, ceramic sherds,

jadeite, human bones) as belonging to either SMJ1A or SMJ1E, is not appropriate for these three specimens since they may come from other subsources. Examination of Figure 7, in fact, suggests that specimen SMJ008 (from location SMJ1B) is different from all other members of compositional group SMJ1. On the other hand, SMJ010 and SMJ011 seem to be very similar to each other and closely related to some members of chemical subgroup SMJ1A. Compositional analysis of more specimens from these three locations is needed to resolve this issue.

Quarry Systems and Subsources

Clear evidence of prehistoric extraction and production was found only at subsources SMJ1A (in Aldea Pachay-Las Lomas), SMJ1E (in Aldea Choatalum), and to a lesser degree at SMJ6 (also in Aldea Choatalum). It is highly unlikely that debitage or tools made of obsidian from the other subsources and locations will be found in archaeological assemblages. Why were these the only subsources exploited by ancient inhabitants of the region?

Obsidian nodules from locations SMJ1B-SMJ1D and subsurface SMJ4 are quite small and unsuited for prismatic blade and biface production, the two most important lithic industries practiced in Mesoamerica. Furthermore, obsidian from locations SMJ1B-SMJ1C and subsurface SMJ4 is of extremely poor quality and crumbles easily when handled; this material is unfit even for bipolar and casual flake production. Nodules from subsources SMJ2-SMJ3 and SMJ5 often are large, but they fracture unpredictably and contain many inclusions. Although suitable for the casual flake and bipolar industries, replicative experiments demonstrate that obsidian from these three subsources is too poor for reliable prismatic blade or biface production. Oddly enough, nodules from subsurface SMJ6 also are of low quality and fracture unevenly. Nevertheless, evidence of prehistoric exploitation can be found at that subsurface. Debitage analysis suggests that casual percussion flakes were the principal product made of SMJ6 obsidian, but prismatic blade production also was practiced or at least attempted. Because of the low quality of SMJ6 obsidian and the relatively

small amount of worked material found at the outcrop, this subsurface was probably exploited on a very small scale. For these reasons, it seems highly unlikely that obsidian from this subsurface was ever exported in quantity.

In contrast, obsidian from subsources SMJ1A and SMJ1E fractures in a predictable manner and often is found in large nodules. It is therefore not surprising that these two subsources were the focus of prehistoric exploitation. The obsidian cobbles found in the Río Quemaya and Río Pixcaya all belong to compositional subgroup SMJ1A (see Figure 7). The Quemaya, in fact, crosses part of the obsidian flow at Pachay-Las Lomas (subsource SMJ1A). All obsidian found in these rivers is located downstream from this point (see Figure 3). Cobbles recovered from these rivers, then, are secondarily deposited obsidian from subsurface SMJ1A. It seems unlikely that the rivers were centers of raw material extraction. Obsidian cobbles in the Río Quemaya and Río Pixcaya are few and far between and tend to be too small for either biface or prismatic blade production. Most importantly, no concentrations of debitage were found along their banks during the intensive site survey.

The two compositional groups defined for the Media Cuesta source area also correspond to distinct locations and hence define distinct subsources (Figure 5). LAG1 obsidian was found in a small outcrop near San Rafaelito (location 054994). LAG2 material was collected from a small flow and surface outcrop near Media Cuesta (location 098979). Obsidian from subsurface LAG1 and the northwestern portion of subsurface LAG2 appears as deposits of pebble-size fragments that crumble when handled. Obsidian from these locations is not suitable for stone-tool production. Very low densities of larger nodules are found in secondary depositional contexts on the slope above the lake, particularly in the southeastern portion of subsurface LAG2 (Figure 5). This material is of somewhat better quality, suitable for the production of small bifaces, bipolar flakes, and casual flake tools. No evidence of quarry-workshop production was found at either subsurface. Since artifacts of Media Cuesta obsidian are common near Laguna de Ayarza, it seems likely that nodules were col-

lected from the surface of subsurface LAG2 and worked elsewhere.

Conclusions

A combined program of survey, geochemical assay, and statistical analysis demonstrates that quarry-specific source assignments can be made for obsidian artifacts, allowing Mesoamerican archaeologists to ask more sophisticated questions of their compositional datasets. A discriminant function generated for the two principal quarry systems of the San Martín Jilotepeque source area, called SMJ1A (in Aldea Pachay-Las Lomas) and SMJ1E (in Aldea Choatalum), discriminates between these two subsources at a confidence level greater than 99.995 percent. Archaeologists working at sites where SMJ obsidian is found can use this discriminant function to assign their artifacts to either quarry system with an estimated accuracy rate of 84 percent.

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Notes

1. The initial stage of statistical analysis was conducted at MURR using SYSTAT and GAUSS routines written by Hector Neff.
2. Ba may be considered either a short-lived or medium-lived element, but error rates are relatively large if the abbreviated procedure is used.
3. Specimen SMJ050 appears as an extreme outlier in Figure 7. Examination of several bivariate plots (including Figure 6), however, strongly suggests that it is a member of compositional group SMJ6. Furthermore, specimen SMJ050 was recovered from the same geological context as other members of group SMJ6. For these reasons, we classify it as an outlier of SMJ6 and not as the sole member of a seventh compositional group.
4. Because group SMJ4 has only four members, just two principal components (PCs) could be considered in principal

component analysis. This limited the overall accuracy of classification of SMJ obsidian to 89.9 percent. Since no evidence of quarrying was found at the locations where SMJ4 material was collected, the group was removed from analysis. This allowed the addition of a third PC and raised the rate of successful classification for the remaining groups (and all other Guatemalan obsidian sources) to 100 percent (Glascocock et al. 1997). Fortunately, there is no evidence suggesting that SMJ4 obsidian was ever used for stone-tool production.

5. The dendrogram (Figure 7) also can be interpreted as suggesting two subgroups for SMJ1 with similar memberships. One important difference, however, is that cluster analysis assigns specimen SMJ015 to subgroup SMJ1E rather than SMJ1A. In part, this is a result of the particular clustering algorithm used to generate the dendrogram. Although we recognize that specimen SMJ015 is somewhat anomalous, we assign it to subgroup SMJ1A because of its clear spatial context.

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