Subsource Characterization: Obsidian Utilization of Subsources of the Coso Volcanic Field, Coso Junction, California, USA

Jonathon E. Ericson[1],* **and Michael D. Glascock**[2]

[1]*Department of Environmental Health, Science, and Policy, University of California–Irvine, Irvine, California 92697-7070*
[2]*Research Reactor Center, University of Missouri, Columbia, Missouri 65211*

Six chemical subsource groups were identified in the analysis of 84 obsidian samples collected from subsource locations at Coso volcanic field, California. In prehistoric times, Coso provided obsidian for artifacts found from San Francisco Bay to San Diego to Death Valley to the eastern Mojave Desert. Subsource groups were defined by instrumental neutron activation analysis (INAA) of 29 elements followed by cluster analysis, principal component analysis, and bivariate plotting. The new data are compared to previously published INAA and X-ray fluorescence data. Characterization of 55 obsidian artifacts from archaeological sites located approximately 100 miles from Coso suggests preferential usage of specific subsources as a function of the directionality of travel. The results are consistent with a bimodal (resident and itinerant) model of procurement. This research illustrates the importance of accurate sourcing of obsidian artifacts when attempting to define subsource usage. © 2004 Wiley Periodicals, Inc.

INTRODUCTION

The linkage between quarry production (Ericson and Purdy, 1984) and regional exchange of lithic products (Earle and Ericson, 1977; Ericson and Earle, 1982; Scarre and Healy, 1993; Baugh and Ericson, 1993; Ericson and Baugh, 1994) requires accurate characterization of lithic artifacts. Lithic sources with multiple loci of raw material often present difficulty in determining these loci once the material has been transported to distant sites. Subsource characterization, compared to source characterization (Harbottle, 1982), can be used to trace artifacts back to a specific quarry location (Spence et al., 1984; Braswell and Glascock, 1998; Ambroz et al., 2001).

One of the objectives of this research is to define a method capable of accurately discriminating subsources based on key elements. This study of obsidian characterization in the Coso volcanic field, located east of the Sierra Nevadas in Inyo County, California, demonstrates the application of statistical methodology in determining lithic subsources. The methodology can provide the means to integrate tra-

---

*Corresponding author.

Geoarchaeology: An International Journal, Vol. 19, No. 8, 779–805 (2004)

ditional studies of regional exchange with quarry-production analysis (Ericson, 1984; Glascock et al., 1998). Another regional application of this method is to determine the geographic extent of obsidian use from this particular source area.

PREVIOUS STUDIES OF COSO OBSIDIAN

The first report of a prehistoric obsidian quarry located near Coso Hot Springs in Inyo County, California, was made by Farmer (1937). A later investigation by Harrington (1951) described it as a "colossal quarry." However, it was the geochemical work of Jack and Carmichael (1969) that introduced the importance of Coso obsidian to a larger audience of archaeologists by establishing the extent of its regional distribution (Ericson et al., 1976).

The Coso volcanic field was the focus of early geological investigations (Ross and Yates, 1943; Chesterman, 1956) and more recent geological and geochemical studies of its geothermal potential were conducted by the USGS (Austin and Pringle, 1970; Lamphere et al., 1975; Bacon & Duffield, 1976; Bacon et al., 1981, 1982; Duffield and Bacon, 1981). The results of a geochemical investigation (Bacon et al., 1981) demonstrated that seven eruptive episodes occurred within the Coso volcanic field during the Pleistocene. Although this study was able to identify eruption groups, the data were insufficient for subsource characterization of quarries within the volcanic field. The current research employs instrumental neutron activation analysis (INAA) and multivariate analyses to further investigate the problem of subsource characterization.

An understanding of the obsidian-procurement patterns at Coso is critically important when considering the contexts of more than 12,000 years of human occupation in the southwestern Great Basin. Beginning in the Lake Mojave Period (12,000–6000 yr B.P), Coso obsidian was used extensively by Native Americans for tool-making. (Warren and Crabtree, 1986). Hildebrandt and Gilreath (1988) suggest that exploitation of lag deposits was the primary focus of the Lake Mojave and Pinto Periods, with more formalized exploitation of outcrops occurring during the Gypsum Period. By 8000 yr B.P., Coso obsidian appears in coastal sites more than 200 miles south at the Batiquitos Lagoon in San Diego County (Koerper et al., 1991), west along the Santa Barbara coast (Glassow, 1985), north at SLO-2, in Diablo Canyon in San Luis Obispo County, California (Greenwood, 1972), and in the western and southern Mojave Desert (Jenkins, 1985; Cleland, 1986). Obsidian production actually peaked in Gypsum times, with secondary peaks in production occurring during the earlier Pinto Period and later Saratoga Springs times (ca. 800 yr B.P.) (Hildebrandt and Gilreath, 1988). Exploitation of obsidian at Coso appears to be greatly reduced during the later Saratoga Springs and Protohistoric Periods (Gilreath and Hildebrandt, 1997). The peak tool production at Coso during the Gypsum Period is consistent with tool production at two major obsidian sources at Casa Diablo and Bodie Hills to the north of Coso (Singer and Ericson, 1977; Ericson, 1981), both of which underwent a virtual termination of production by the late Saratoga Springs Period (cf. Jackson, 1984:117–118). Throughout prehistory, Coso obsidian was utilized extensively by people on both sides of the Sierra Nevada range (Moratto, 1984). It occurs in the vast area from San Francisco Bay in the north (Jack, 1976) to San Diego in the south (Hughes and True, 1985), as well as west to the Pacific Coast (Singer and Ericson, 1977; Ericson, 1977, 1981; Koerper et al., 1986) and Mojave Desert.

The reconstruction of Coso lithic production by Hildebrandt and Gilreath (1988) seems to be very consistent with the "so-called hiatus" or termination in Coso obsidian exchange (Elston, 1982; Bettinger and Baumhoff, 1983; Whitley et al., 1988; Cleland, 1989). This termination of obsidian exchange has perplexed researchers for many decades. In the Sierras north of the Kern River, there appears to be a cessation of obsidian trade during Saratoga Springs times (Moratto, 1984, 1987). During this time non-Coso obsidian increases at Fort Irwin to the southeast. In San Diego County, Coso obsidian is replaced in the late Sarasota Springs Period by material from the Obsidian Butte source (Hughes and True, 1985). In Orange County, the same pattern is observed, but Coso obsidian is used later in sites located north of Coyote Canyon (Ericson, 1981; Koerper et al., 1986; Ericson et al., 1989). At the distant Chumash outpost site of Castaic (CA-LAn-324), Ericson and Singer (1971) observed the cessation of Coso obsidian use and its replacement with Grimes Canyon Fused Shale located in Ventura County at approximately 800 yr B.P. Prior to that time, there was also an extensive trade in Pacific Coast marine shells extending inland to the American Southwest, with some Hohokam pottery and three-quarter grooved axes reaching the Pacific Coast. Southwest people were also collecting turquoise from California (Sigleo, 1975). During the late Prehistoric/Protohistoric Periods, there were regional political exchange spheres in Southern California and Arizona, as reconstructed from the ethnographic record (Ericson and Meighan, 1984).

At the time of European contact, the Koso or Panamint Shoshoni occupied the area surrounding the Coso volcanic field within the Kuwiji district (Steward, 1938). Steward (1938) describes four main villages, one at Mua'ta, located near Coso Hot Springs. The Koso were hunters and gatherers whose social organization was highly fluid. They were only loosely organized beyond the bilateral family, which could decide on a seasonal basis where to reside and with whom to cooperate (Nelson, 1891; Colville, 1892; Dutcher, 1893; Kroeber, 1925; Driver, 1937; Steward, 1938, 1941; Theodoratus, 1977; Irwin, 1980; Coombs and Greenwood, 1982; and Thomas et al., 1986).

It is unknown if the Koso maintained exclusive control over the Coso volcanic field in prehistoric times. Coso Hot Springs was important for the northern Paiute and Shoshoni groups who presumably visited this area for spiritual and medicinal purposes (Steward, 1938). Farmer (1937) suggests that the Tubatulabal and the Owens Valley Paiute (eastern Mono) procured obsidian directly from the Coso source. Voeglin (1938) reports that the Tubatulabal obtained stone to make arrowheads at Coso and red face paint near Coso Hot Springs (Cleland 1989). The Kawaiisu territory (Kroeber, 1925; Zigmoid, 1981) adjoined the Kuwiji district to the south, so it is possible that the Kawaiisu also utilized the obsidian sources at Coso (Cleland, 1989). Elston and Zeier (1984) suggest that major procurement activities occurred during the winter. The nearby Kawaiisu maintained largely peaceful relations with neighboring groups, including the Yokuts, Chemehenvi, Tubatulabal, Serrano, and Koso (Cleland, 1989). Limited raiding among the Kawaiisu, Koso, Owens Valley Paiute, and Yokuts was conducted with revenge as a motive (Voeglin, 1938; Smith, 1978). In addition to the Koso, ethnohistoric data suggests that the Tubatulabal, Owens Valley Paiute (Farmer, 1937; Steward, 1938; Voeglin, 1938), and possibly the Kawaiisu (Cleland, 1989), procured obsidian directly from the Coso sources. It is not clear how long these patterns of direct access can be extended into prehistory, and whether these patterns continued or changed around 800 yr B.P. (Ericson and Meighan, 1984).

Previously, archaeologists have relied on ternary plotting of X-ray fluorescence (XRF) data of Sr, Rb, and Zr concentrations, as well as Fe and Mn for sourcing (Jack, 1976). Alternatively, short half-life NAA data, using stepwise discriminant analysis, has been used (Ericson, 1981; Ericson, 1989). Hughes (1988) used XRF analysis to report geochemical fingerprints of four subsources in the Coso volcanic field, but 17 of 109 obsidian artifacts could not be assigned to subsources using this technique (Hughes, 1988). Most recently, Draucher et al. (2002) used lazer ablation inductively coupled plasma/mass spectrometry (ICP/MS) to identify 25 trace elements in an attempt to distinguish individual quarries within sources, but were unsuccessful. It is suggested here that these techniques are inadequate, given the need for greater accuracy when assigning artifacts to specific subsources and quarries within the Coso field.

METHODS

Sample Preparation

Source specimens from the Coso volcanic field were collected by archaeologists from the China Lake Naval Weapons Center at 15 sampling locations (Figure 1) that are consistent with the sites sampled by Hughes (1988). Between 15 and 20 fist-sized specimens were collected as “grab samples” at each location, and shipped to the University of Missouri Research Reactor (MURR). At MURR, the samples were assigned a six-letter alphanumeric code using a prefix of CV followed by 01, 02, ..., 15 to represent the individual sampling sites, and 01, 02, etc., to identify replicates within each site (for example, the third replicate from site 6 was assigned an identification code of CV0603). Specimens from site 11 were found to be an inferior grade of obsidian with no archaeological value and were not processed further. A total of 84 specimens (six from each of the remaining 14 sites) were prepared for INAA.

Fragments of each specimen were collected for each of the two analytical measurements conducted at MURR. For Prompt Gamma Neutron Activation Analysis (PGNAA), approximately 1 g of fragments was weighed into a Teflon bag and hermetically sealed. For short irradiation measurements, approximately 100 mg of each sample was weighed into 2/5 dram high-density polyvials. For long irradiation measurements, 300 mg of sample was weighed into high-purity quartz vials, which were flame-sealed using an oxygen torch. Standards were similarly prepared for SRM-278 (Obsidian Rock) and SRM-1633a (Fly Ash).

Irradiation and Analysis

The first measurement conducted on each sample was by PGNAA, in which the gamma rays emitted instantaneously after neutron capture are measured. In this

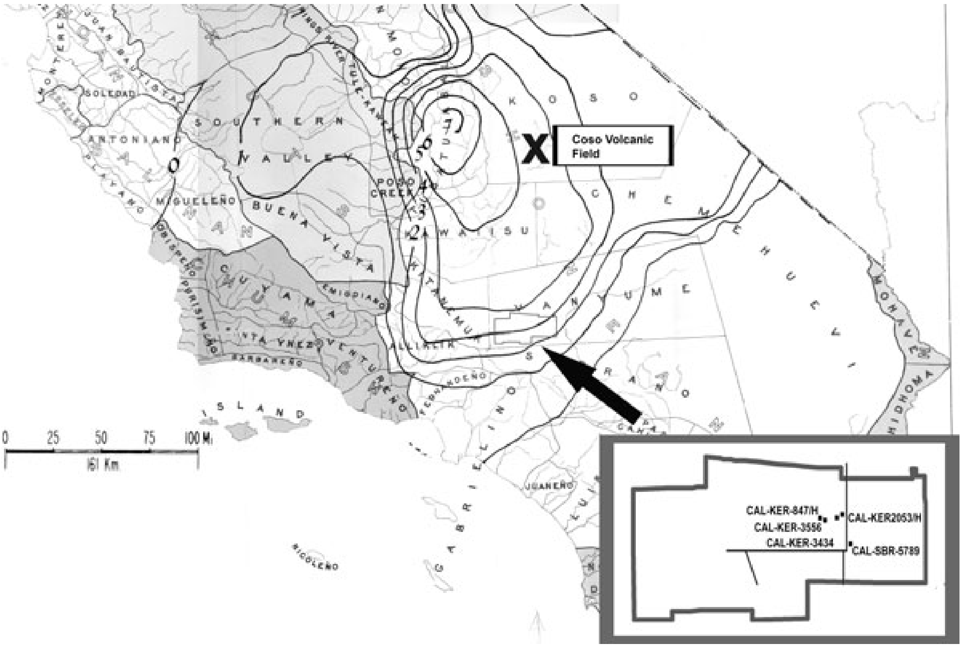

Figure 1. The Coso volcanic field with the locations of 15 subsource sample points and major obsidian flows/domes, Coso, California, after Figure 2 by Hughes (1988). R.E. Hughes. 1988. The Coso volcanic field re-examined: Implications for obsidian sourcing and hydration dating research. Geoarchaeology 3, 253–265. © 1988 John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.

measurement, samples were sequentially irradiated by a neutron beam using a thermal neutron flux of 5×10^8 n/cm^2/s for 1 hour each. The resultant prompt gamma rays were measured by an intrinsic Ge detector coupled to a computer-based analyzer system. Standard materials were irradiated on a daily basis. Concentrations for the elements boron and gadolinium were determined from this measurement.

The standards and unknowns in polyvials were sequentially irradiated at MURR via the pneumatic-tube irradiation system. Samples and standards were irradiated for five seconds each with a thermal neutron flux of 8×10^{13} n/cm^2/s. They were allowed to decay for 25 minutes before being counted by a high-resolution germanium detector for 720 seconds. On a daily basis, three SRM-278 and three SRM-1633a standards were irradiated for every batch of 30–35 unknown specimens. Elements determined by this procedure were Cl, Dy, K, Mn, and Na.

The long irradiation samples and standards were bundled together by wrapping the quartz vials in aluminum foil. For long irradiation, 28 obsidian samples, four SRM-278, and four SRM-1633a standards were bundled together. The bundle was placed in an aluminum can and later inserted into an in-pool irradiation position for 70 hours, where it was irradiated in a neutron flux of 5×10^{13} n/cm^2/s. After completion of the irradiation, the samples were allowed to decay for 8 days before unwrapping and cleaning the vials in aqua regia. The cleaned vials were then loaded on an automatic sample changer, and counted for 2000 seconds each to measure seven medium half-life elements: Ba, La, Lu, Nd, Sm, U, and Yb. The samples were then allowed to decay for an additional 6 weeks and counted again for 10,000 seconds to measure the long-lived elements. Fifteen elements were measured by this long count: Ce, Co, Cs, Eu, Fe, Hf, Rb, Sb, Sc, Sr, Ta, Tb, Th, Zn, and Zr.

The NAA procedures described above produce concentration values for the 29 elements present in most of the obsidian samples. In this study, the concentrations of Sr in all samples were below the detection limit of 20 ppm, and the concentrations for Ba in several samples were below the detection limit of 25 ppm. Rather than input arbitrary substitutes for the missing values, both elements were eliminated from further consideration.

The elemental concentration data were transformed into log base-10 values, in order to counteract the weighting effect that would be inherent when comparing pairs or groups of elements with large differences in magnitude. For example, when comparing the major elements Na and Fe, with certain trace elements, such as the rare-earth elements (REEs), the differences often span three or four orders of magnitude. In addition, because the original distributions of trace-element data are often highly skewed, a log-transformation has the advantage of producing a more normal distribution for geochemical data. Finally, the numerical data were converted into GAUSS data sets for statistical analysis, using a series of GAUSS language routines by H. Neff (personal communication, 1990).

To determine if the subsource characterization of source specimens in this study held any archaeological significance, two sets of artifacts totaling 55 samples from archaeological sites located on Edwards Air Force base were also analyzed. Because the PGNAA procedure was unavailable when the artifacts were being analyzed, only the short and long irradiation procedures described above were employed.

Following the irradiation and collection of element concentrations for all source and artifact samples, the data were tabulated using the LOTUS 1-2-3™ spreadsheet program and exported into dBASE format, where descriptive information about the analyzed specimens was entered. The resulting dBASE file was finally appended to the larger obsidian database at MURR. For additional details concerning the procedures for sample preparation, standardization, and irradiation, the reader is referred to Glascock et al. (1988), Graham et al. (1982), and Vogt et al. (1982). Information about the obsidian data bank at MURR is reported in Cobean et al. (1991), Glascock (1994), and Glascock et al. (1998).

RESULTS AND STATISTICAL ANALYSIS

The primary objective of this study was to accurately define a set of compositional profiles for the obsidian subsources within the Coso volcanic field. A secondary aim was to utilize these profiles to assign sources to a collection of artifacts. For successful characterization in a multi-component source area such as Coso, the subsource groups should be: (1) chemically homogeneous, (2) distinguishable from one another on the basis of elemental composition, and (3) correlate to specific geographic locations.

Pattern-recognition techniques, such as hierarchial cluster analysis and bivariate scatterplots, provide a powerful means for identifying differences between sources. A data-transformation method, such as principal components analysis (PCA), can also be used to enhance the ability to find patterns within the data. In PCA, one performs a transformation of the sample data, based on eigenvector methods, to find the direction and magnitude of maximum variance in hyperspace (Davis, 1986). Computation of the eigenvectors is derived from either the variance-covariance or correlation matrix of the original variables. The first principal component (PC) is oriented in the direction of maximum variance of the data. The second PC lies in the direction of maximum remaining variance, with the additional constraint that it must be orthogonal to the first PC. The third PC is orthogonal to the first two PCs, again representing the direction of maximum remaining variance. The procedure continues until the number of PCs is equal to the number of original dimensions. The PCA technique creates a new set of axes for describing and displaying the entire distribution on bivariate scatterplots by reducing the dimensionality of the data set, while sacrificing only a minimal amount of the original information.

One strength of PCA, previously described by Baxter (1992) and H. Neff (1994), is that it can be applied as a simultaneous R- and Q-mode technique, with both the variables (elements) and the objects (samples), respectively, displayed on the same set of PC references axes. When examining the first two PCs, the RQ-mode plot of object coordinates is the best possible two-dimensional representation of the shapes of various groups in the data set. At the same time, displaying variable coordinates on the same plot makes it possible to observe the contributions of individual elements to group separation and to the distinctive shapes of the various groups. The interrelationships between pairs of elements can be observed directly through the examination of specific bivariate elemental plots.

Bivariate scatter plots also produce archaeologically interesting groupings or classifications of source specimens that appear as systematic patterns or clusters of data points. The use of 95% confidence ellipses around the compositional groups provides a visual measure of the relative success of establishing groups, and of the success of assigning artifacts to source groups based on the selected elements.

Analysis of the Source Specimens

The dendrogram produced by cluster analysis, and the RQ-mode PCA plots derived from the correlation matrix of the 84-specimen source assemblage, suggests the existence of at least four compositional groups. As shown in Table I, nearly 80% of the total variance in the obsidian-source specimen data set is explained by the first two principal components, and nearly 94% is explained by the first five principal components.

Figure 2 shows an RQ-mode PCA bivariate plot of the source samples and elements plotted against the first two principal components, with 95% confidence ellipses included to illustrate that the four main groups encompass 82 of the 84 source specimens. Samples CV0201 and CV0205 are compositionally different from the main groups. The source group ellipses are labeled according to the geographic names in

Table I. RQ-mode principal components analysis of the correlation matrix derived from 84 source specimens from the Coso volcanic field.

a) Eigenvalues and Percentage of Variance Explained by Each Component

Eigenvalue	% Variance	Cum. % Var.
14.4214	53.4125	53.4125
7.3443	27.2013	80.6137
1.9463	7.2084	87.8222
1.1557	4.2803	92.1024
0.5073	1.8788	93.9812
0.3430	1.2704	95.2516
0.2847	1.0546	96.3062
0.2553	0.9457	97.2519
0.1868	0.6918	97.9437
0.1150	0.4260	98.3697
0.0994	0.3680	98.7377
0.0768	0.2843	99.0220
0.0740	0.2742	99.2962
0.0571	0.2115	99.5077
0.0379	0.1405	99.6482
0.0266	0.0985	99.7467
0.0231	0.0855	99.8322
0.0165	0.0611	99.8933
0.0107	0.0397	99.9330
0.0070	0.0261	99.9591
0.0053	0.0195	99.9786
0.0032	0.0119	99.9906
0.0012	0.0044	99.9950
0.0006	0.0021	99.9970
0.0004	0.0014	99.9984
0.0003	0.0011	99.9996
0.0001	0.0004	100.0000

(continued)

the Coso volcanic field, as originally defined by Hughes (1988), based on XRF measurements for the elements Rb and Zr. The first principal component is positively loaded on the incompatible elements (Rb and Cs) and the heavy-REEs (Tb, Dy, Yb, and Lu) and negatively loaded on the light-REEs (La, Nd, Ce, and Eu). The second component is positively loaded on Mn and negatively loaded on Hf, Sc, and Zr. A few outlier specimens were not associated with any of the four main Coso groups, suggesting that their variability might be due to incorporation of wall-rocks or other fractionational processes. The geochemical rationale for selecting specific elements to distinguish different obsidian sources on bivariate plots has not been elucidated in the geoarchaeology literature until now. The thermogravimetric compositional zonation of silicic magma chambers provides some insight. Hildreth (1979, 1981)

Table I. RQ-mode principal components analysis of the correlation matrix derived from 84 source specimens from the Coso volcanic field. (*continued*)

b) Eigenvectors for the First Five Components (Largest to Smallest)

Element	PC01	PC02	PC03	PC04	PC05
La	–0.1838	–0.2363	–0.1417	0.2034	–0.0523
Lu	0.2491	–0.0265	–0.0745	0.0608	0.0647
Nd	–0.1869	–0.2214	0.0935	–0.1103	–0.1115
Sm	0.1190	–0.3240	0.0151	–0.0707	0.0328
U	0.2121	–0.0822	–0.1859	0.1629	0.1323
Yb	0.2590	–0.0399	–0.0513	0.0396	–0.0142
Ce	–0.1655	–0.2678	–0.1247	0.1729	–0.0452
Co	–0.2183	–0.1666	–0.1100	0.2006	–0.0953
Cs	0.2393	0.0635	–0.1793	0.2406	–0.0148
Eu	–0.2448	–0.0238	–0.1339	0.2485	–0.0854
Fe	–0.1467	–0.2955	–0.0480	0.0890	–0.0959
Hf	0.1195	–0.3129	0.0908	–0.1430	–0.0919
Rb	0.2595	–0.0206	–0.0784	0.0743	0.0068
Sb	0.1981	0.1903	–0.1041	0.1841	–0.1446
Sc	0.0555	–0.3576	–0.0056	–0.0434	0.0051
Ta	0.2588	0.0042	–0.0914	0.0952	0.0264
Tb	0.2435	–0.1263	–0.0028	–0.0464	–0.0111
Th	0.2461	–0.0538	–0.1576	0.1937	–0.0117
Zn	0.1965	–0.1986	0.1550	–0.2168	0.0404
Zr	–0.0132	–0.3303	–0.0800	0.1284	–0.3760
Cl	0.1603	–0.1230	0.3611	–0.1383	0.2963
Dy	0.2362	–0.1199	0.0295	0.1568	–0.0252
K	–0.0871	–0.1434	0.2592	0.5599	0.6255
Mn	–0.0244	0.2193	0.4487	0.3372	–0.3185
Na	0.0963	–0.0674	0.5940	0.1480	–0.3124
Gd	0.1924	–0.1917	0.0398	–0.0684	–0.1062
B	0.2089	0.1427	–0.0706	0.2012	–0.2656

determined the enrichment, and thus concomitant, depletion factors for several trace and minor elements. The enrichment factor for a specific element is defined as its concentration in the earliest ejected phase divided by its concentration in the last ejected phase. Enrichment is a function of two factors: (1) the time since the last eruption, during which interval thermogravimetric diffusion can take place, and (2) the extent to which the magma reservoir has been tapped. Bacon et al. (1981) observed that the concentration correlations between pairs of elements in the Coso geochemical study also fell into two groups. Their Group 1 elements are concentrated towards the roof of the magma chamber. Their Group 2 elements are concentrated much lower in the magma chamber due to gravitation settling of crystallites. The Coso subsources show the effects of compositional zonation within the magma chamber following the model of Hildreth (1979, 1981). Previous researchers in archae-

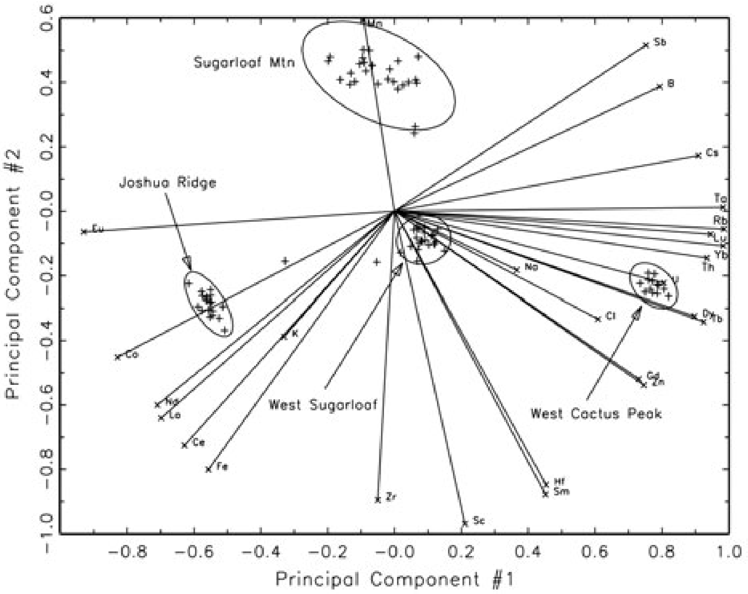

Figure 2. RQ-mode bivariate plot of the source samples and element vectors from PCA of the correlation matrix plotted against the first two principal components. Confidence ellipses at the 95% level shown to indicate the four main groups identified by geographical names consistent with Hughes (1988).

ological chemistry have inadvertently selected Group 1 elements (Mn, Rb) to compare with Group 2 elements (Fe, Zr), respectively, for XRF (e.g., Jack and Carmichael, 1969; Hughes, 1988) and Group 1 elements (Sc, Rb) to compare with Group 2 elements (Eu, Fe), respectively, for INAA (e.g., Glascock et al., 1988). The selection of the Group 1 and Group 2 elemental pairs, as analyzed herein, indicates that chemical characterization of obsidian flows relies, in part, on the enrichment and differentiation processes occurring among different eruptive phases of the magma. Elemental changes can also be due to melting of roof rocks in the magma and other factors.

In an effort to search for patterns within each of the source groupings, the RQ-mode PCA procedure was repeated on specimens comprising the individual source groups. The only Coso source group found to have a fine structure was Sugarloaf Mountain, which, as shown in the RQ-mode plot (Figure 3) on the first two principal components, indicates that specimens from source-collection site 6 cluster separately from the samples from sites 5, 8, and 15. Concentrations for two of the incompatible elements (Cs and Rb) and three of the light-REEs (La, Ce, and Eu) are most responsible for the observed difference between Sugarloaf Mountain and the satellite source at site 6. These elements are best measured by NAA, which explains why Hughes (1988) was unable to detect this subsource by X-ray fluorescence.

One of the advantages of RQ-mode PCA is a clearer delineation of the elements that contribute most strongly to the variation between sources. Inspection of the

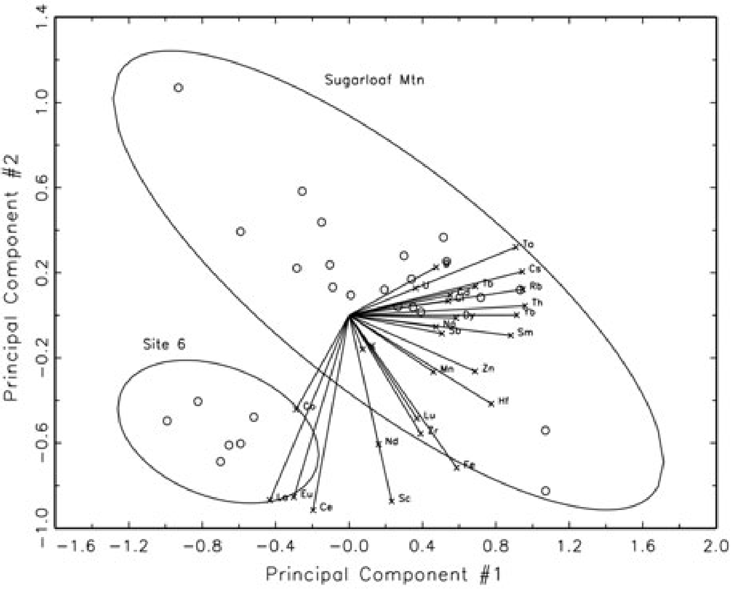

Figure 3. RQ-mode bivariate plot of the source sample and element vectors for source samples from Sugarloaf Mountain and site 6, the subsource of Sugarloaf Mountain. Confidence ellipses at the 95% level are shown.

element vectors in Figures 2 and 3 suggest that Cs, Sc, Fe, Rb, and Eu are among these elements. Bivariate plots of the source specimens for Cs vs. Sc and Fe vs. Rb are shown in Figures 4 and 5, respectively. Both plots clearly show the presence of five non-overlapping chemical groups based on these elements. The locations of the two outlier specimens, CV0201 and CV0205, are also shown on the plots.

Table II lists the groupings for source specimens from each collection site. These groups differ slightly from those reported in previous analytical studies by Hughes (1988) and Bacon et al. (1981). In particular, location 7 has been sourced by our analysis and by Hughes (1988) to the West Sugarloaf group, whereas Bacon et al. (1981) assigned this dome to an earlier eruption coeval with West Cactus Peak formation (Cleland, 1989) (Table II).

The West Sugarloaf group is comprised of specimens from locations 1, 2, 3, 4, and 7, with the exception of specimens CV0401, CV0701, CV0703, and CV0706, which were assigned to other groups, and the ungrouped samples CV0201 and CV0205 (Table II). Locations 1, 2, 3, and 4 appear to be at the base of the West Sugarloaf obsidian, with location 7 appearing to be a parasitic dome (Figure 1). In contrast, Hughes assigned locations 1, 2, and 7 to the West Sugarloaf group. The Sugarloaf group is comprised of specimens from locations 5, 8, and 15, with the exception of specimen CV1506 and the addition of specimens CV0401, CV0703, and CV0706. Locations 5, 8, and 15 form a line of domes to the east of the Sugarloaf Mountain (Figure 1). The

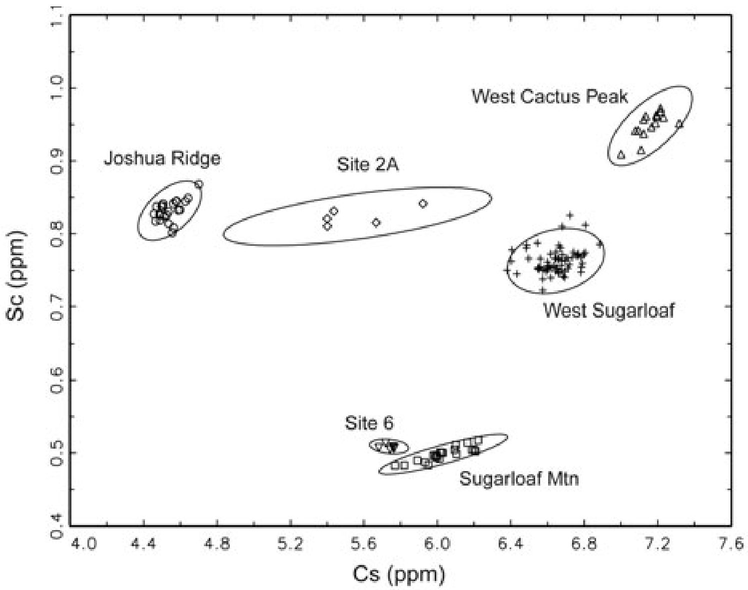

Figure 4. Bivariate plot of source samples for Cs vs. Sc showing presence of five nonoverlapping groups based on these elements. Outliers CV0201 and CV0205 are shown on plots, along with confidence ellipses at the 95% level.

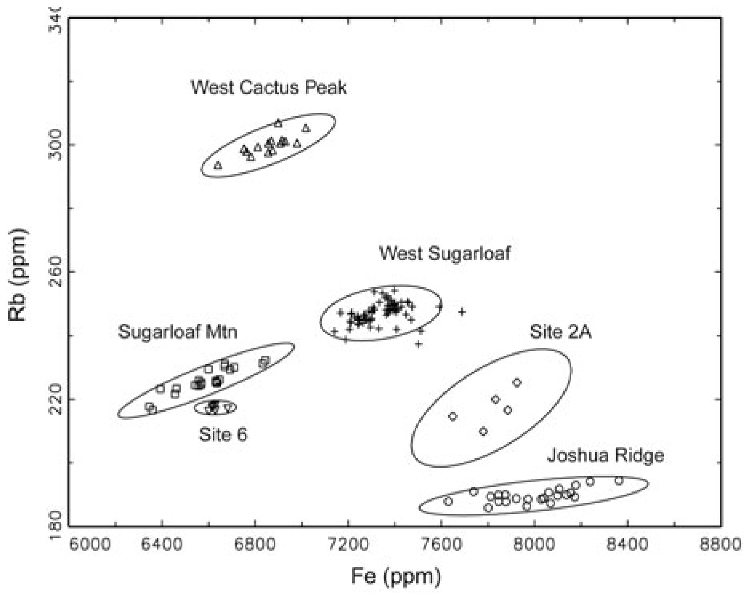

Figure 5. Bivariate plot of source samples for Fe vs. Rb showing presence of five nonoverlapping groups based on these elements. Outliers CV0201 and CV0205 are shown on plots, along with confidence ellipses at the 95% level.

Table II. Source sample grouping by different analysts.

	These Data	Hughes (1986)	Bacon et al. (1981)
West Sugarloaf	1, 2, 3, 4, 7	1, 2, 7	Group 5
Sugarloaf Mountain	5, 8, 15	3, 4, 5, 6, 8, 15	Group 7
Sugarloaf Site 6	6	Not observed	Not observed
Joshua Ridge	12, 13, 14	12, 13, 14	Group 6
West Cactus Peak	9, 10	9, 10	Group 3

satellite group named Sugarloaf site 6 was not identified by Hughes and is comprised only of specimens from location 6. Location 6 appears to be associated with the western part of the Sugarloaf Dome, overlying the basal West Sugarloaf obsidian (Figure 1). Our results differ from those of Hughes (1988), who included locations 3, 4, 5, 6, 8, and 15 in the Sugarloaf Mountain group, a grouping which is more difficult to interpret geologically and geographically. The Joshua Ridge group is comprised of locations 12, 13, and 14, with the addition of specimen CV1506. The West Cactus Peak group is comprised of locations 9 and 10, with the addition of sample CV0701. The sites assigned to the Joshua Ridge and West Cactus Peak groups are in complete agreement with Hughes (Table II).

The specimens that were not similar to other replicates from the same site are a curious problem. These samples may have been transported by people over the 12,000-year history of the quarries, or represent sampling error during collection and processing. The ungrouped specimens CV0201 and CV0205 are possible indicators of one or two additional subsources.

Table III lists the means and standard deviations for each of the six geochemically distinct groups identified from the source specimens analyzed in this study. Data from Bacon et al. (1981) and Hughes (1988) are also shown for comparison. The elements in common among the studies are in agreement. The most notable differences are the Mn concentrations, which Bacon et al. (1981) actually reported as MnO. The remaining differences between the three data sets are a consequence of smaller differences between standards, analytical techniques, and sample concentrations.

Analysis of the Artifacts

Two collections of artifacts were analyzed, and the data were evaluated using the same procedures described for source specimens. A brief description of the sites is provided in the Appendix and shown in Figure 6. Hughes (1988) performed X-ray fluorescence (XRF) analysis on 50 Rose Spring series projectile points from the Rose Spring site (CA-INY-372), (Heizer and Hester, 1978) and 59 artifacts from the Stahl Site (CA-INY-182) (Harrington, 1957). Yohe (1998) describes the 5500-year occupation at (CA-INY-372) Rose Spring Village, located 12 miles northwest of Sugarloaf Mountain, as well as the reduction strategies used in point production. The Stahl Site predates the Rose Spring site by a millennium (Meighan, 1981), and is located 10 miles southwest of Sugarloaf Mountain. Interestingly, Joshua Ridge was not identified in either collection (Hughes, 1988). These two sites are considered to be inhabited by “resident” groups. They serve

Table III. Average element concentrations for subsources in ppm for subsources in the Coso volcanic field and comparison with previous analyses.

	Joshua Ridge			Sugarloaf Mtn		
Element	This Study (n = 19)	Bacon et al. (1981) **Group 6	$^{+}$Hughes (1988)	This Study (n = 20)	Bacon et al. (1981) **Group 7	$^{+}$Hughes (1988)
B	31.5 ± 1.5	–	–	43.5 ± 5.8	–	–
Ba	66.9 ± 9.0	48	–	46.0 ± 6.6	13	–
Ce	69.1 ± 0.9	73	–	35.7 ± 0.8	37	–
Cl	659 ± 53	–	–	659 ± 54	–	–
Co*	162 ± 7	200	–	100 ± 4	100	–
Cs	4.54 ± 0.07	4.4	–	6.03 ± 0.13	6.0	–
Dy	6.44 ± 0.30	–	–	6.89 ± 0.33	–	–
Eu*	129 ± 4	140	–	63 ± 2	70	–
Fe%	0.802 ± 0.017	0.85	0.91–0.93	0.659 ± 0.014	0.69	0.76–0.78
Gd	5.81 ± 0.50	–	–	5.63 ± 0.49	–	–
Hf	5.68 ± 0.10	5.3	–	5.12 ± 0.12	5.1	–
K%	3.97 ± 0.16	3.82	–	3.71 ± 0.19	3.64	–
La	34.0 ± 0.4	42	–	14.8 ± 0.2	18	–
Lu*	636 ± 27	640	–	745 ± 46	750	–
Mn	235 ± 9	132	291–294	251 ± 11	155	321–325
Na%	3.12 ± 0.09	3.21	–	3.12 ± 0.11	3.26	–
Nb	n.d.	50	35–36	n.d.	50	41–43
Nd	23.6 ± 1.3	32	–	14.3 ± 0.9	22	–
Rb	190 ± 2	205	187–189	226 ± 4	243	218–226
Sb	0.703 ± 0.030	0.7	–	1.01 ± 0.06	0.9	–
Sc	0.836 ± 0.012	0.86	–	0.498 ± 0.010	0.51	–
Sm	5.72 ± 0.07	6.6	–	4.88 ± 0.08	4.9	–
Sr	< 20	9.0	12	< 20	4.7	7.8
Ta	3.53 ± 0.05	4.2	–	4.51 ± 0.09	5.5	–
Tb	0.950 ± 0.016	1.08	–	0.993 ± 0.027	1.10	–
Th	23.3 ± 0.3	25.7	–	26.0 ± 0.5	28.8	–
U	6.07 ± 0.49	8.0	–	6.63 ± 0.43	12.6	–
Y	n.d.	49	38–40	n.d.	58	42–43
Yb	4.24 ± 0.06	5.0	–	4.87 ± 0.09	5.5	–
Zn	47.9 ± 1.0	46	–	46.0 ± 2.0	44	–
Zr	179 ± 7	138	150–152	155 ± 7	92	108–113

* Reported in ppb.

** INAA data from Bacon et al. (1981), where Na, K, and Mn have been converted from Na_2O, K_2O, and MnO, respectively.

$^{+}$ XRF data from Hughes (1988), where Fe has been converted from Fe_2O_3.

(continued)

as local spatial and temporal control sites, since all subsources are nearly equidistant and their time of occupation overlaps Southern sites in this study.

The artifact data were projected against the source groups using bivariate plots of Cs vs. Sc and Fe vs. Rb to show the differences. The most probable source group for each of the artifacts was determined by inspecting the proximity of artifacts to the source ellipses. Figures 7 and 8 show bivariate plots for the first collection of 19 artifacts (IDs from 1 through 19). Figures 9 and 10 show similar bivariate plots for

Table III. Average element concentrations for subsources in ppm for subsources in the Coso volcanic field and comparison with previous analyses. (*continued*)

	West Sugarloaf			West Cactus Peak		
Element	This Study (n = 11)	Bacon et al. (1981) **Group 5	+Hughes (1988)	This Study (n = 13)	Bacon et al. (1981) **Group 7	+Hughes (1988)
B	42.3 ± 1.6	–	–	45.6 ± 1.3	–	–
Ba	62.5 ± 8.0	32	–	< 25	6.5	–
Ce	54.8 ± 0.8	58	–	37.8 ± 0.5	39	–
Cl	652 ± 43	–	–	886 ± 183	–	–
Co*	128 ± 7	200	–	81 ± 4	100	–
Cs	6.65 ± 0.07	6.6	–	7.18 ± 0.06	7.0	–
Dy	8.14 ± 0.52	–	–	10.3 ± 0.4	–	–
Eu*	81 ± 2	100	–	20 ± 4	20	–
Fe%	0.734 ± 0.008	0.78	0.86–0.89	0.687 ± 0.008	0.74	0.80–0.82
Gd	6.25 ± 0.31	–	–	7.92 ± 0.27	–	–
Hf	5.55 ± 0.07	5.3	–	6.24 ± 0.08	5.9	–
K%	3.86 ± 0.20	3.80	–	3.72 ± 0.18	3.55	–
La	25.4 ± 0.3	31	–	14.1 ± 0.2	17	–
Lu*	814 ± 8	810	–	1000 ± 50	980	–
Mn	233 ± 9	139	301–312	232 ± 6	147	297–299
Na%	3.06 ± 0.11	3.20	–	3.26 ± 0.08	3.32	–
Nb	n.d.	54	43–46	n.d.	75	65–66
Nd	16.2 ± 1.4	28	–	14.5 ± 1.1	24	–
Rb	247 ± 2	270	243–248	300 ± 3	323	299–303
Sb	0.972 ± 0.063	1.0	–	1.03 ± 0.06	1.0	–
Sc	0.763 ± 0.009	0.78	–	0.954 ± 0.011	0.98	–
Sm	5.69 ± 0.04	6.3	–	6.53 ± 0.08	6.9	–
Sr	< 20	6.8	10–12	< 20	2.9	.5
Ta	4.97 ± 0.05	5.9	–	6.17 ± 0.05	7.0	–
Tb	1.10 ± 0.02	1.24	–	1.41 ± 0.03	1.59	–
Th	29.1 ± 0.3	32.2	–	31.8 ± 0.2	34.6	–
U	7.62 ± 0.42	11.5	–	8.36 ± 0.40	12.5	–
Y	n.d.	62	46–48	n.d.	73	57
Yb	5.27 ± 0.08	6.1	–	6.42 ± 0.10	7.4	–
Zn	48.2 ± 0.5	45	–	60.6 ± 1.0	57	–
Zr	175 ± 5	113	133–140	174 ± 4	102	121

* Reported in ppb.
** INAA data from Bacon et al. (1981), where Na, K, and Mn have been converted from Na_2O, K_2O, and MnO, respectively.
+ XRF data from Hughes (1988), where Fe has been converted from Fe_2O_3.

(continued)

the second collection of 36 artifacts (IDs from 20 through 57), with omission of samples with ID 51 and 55.

The first collection of 19 obsidian artifacts, shown in Figures 7 and 8, were excavated from three sites: CA-SBr-5789 (ID 3-12; 14-19), CA-Ker-3556 (ID 1-2), and CA-Ker-3434 (ID 13). Among the 16 artifacts from CA-SBr-5789, one artifact (ID 17) was made from the Joshua Ridge obsidian source and 13 were made from the West Sugarloaf obsidian source. One of the unassigned artifacts (ID 5)

Table III. Average element concentrations for subsources in ppm for subsources in the Coso volcanic field and comparison with previous analyses. (*continued*)

	Site 6	Site 2A
Element	This Study (n = 6)	This Study (n = 5)
B	39.7 ± 2.1	34.0 ± 2.5
Ba	46.4 ± 6.3	103 ± 23
Ce	38.1 ± 0.4	62.0 ± 2.0
Cl	597 ± 27	792 ± 91
Co*	104 ± 5	184 ± 29
Cs	5.74 ± 0.03	5.56 ± 0.23
Dy	6.64 ± 0.13	7.27 ± 0.38
Eu*	69 ± 1	125 ± 7
Fe%	0.663 ± 0.003	0.781 ± 0.011
Gd	5.11 ± 0.37	5.60 ± 0.41
Hf	5.04 ± 0.05	5.64 ± 0.05
K%	3.73 ± 0.10	3.97 ± 0.12
La	16.3 ± 0.1	30.2 ± 0.4
Lu*	751 ± 79	755 ± 40
Mn	249 ± 3	250 ± 3
Na%	3.06 ± 0.04	3.23 ± 0.07
Nb	n.d.	n.d.
Nd	14.8 ± 0.4	20.8 ± 6.2
Rb	217 ± 1	217 ± 6
Sb	0.991 ± 0.008	0.83 ± 0.08
Sc	0.509 ± 0.003	0.824 ± 0.012
Sm	4.78 ± 0.05	5.51 ± 0.20
Sr	< 20	< 20
Ta	4.28 ± 0.04	4.22 ± 0.19
Tb	0.967 ± 0.005	0.990 ± 0.042
Th	25.1 ± 0.1	26.1 ± 0.8
U	6.21 ± 0.54	6.34 ± 1.24
Y	n.d.	n.d.
Yb	4.69 ± 0.03	4.61 ± 0.16
Zn	44.9 ± 0.4	43.9 ± 2.4
Zr	155 ± 4	181 ± 24

* Reported in ppb.

is compositionally similar to the ungrouped source specimen (CV0201) from source site 2. One artifact (ID 14) was not assigned to any of the five Coso sources identified from the analysis of the source specimen collection. Of the two artifacts from CA-Ker-3556, one artifact (ID 1) was from West Sugarloaf and the other (ID 2) was from Joshua Ridge. The single artifact (ID 13) from CA-Ker-3434 was from an undefined source or subsource at Coso and, therefore, is not shown on Figures 7 and 8.

The second collection of 36 obsidian artifacts, shown in Figures 9 and 10, were excavated from three archaeological sites: CA-Ker-3361 (IDs 20-53), CA-Ker-2053

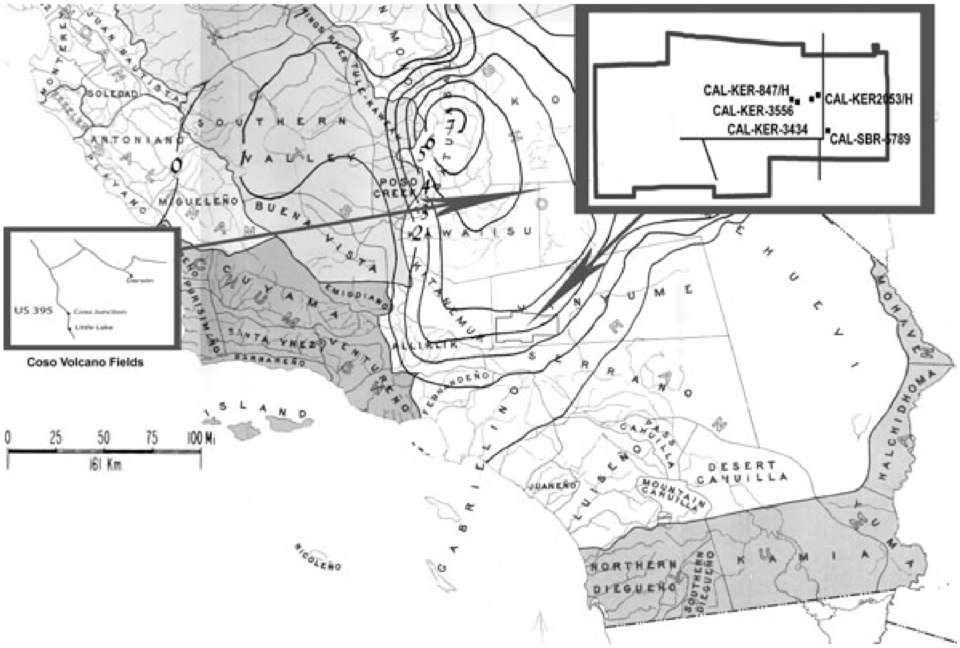

Figure 6. A study area indicating the Coso volcanic field and archaeological sites in this study, ethnographic groups after Kroeber (1925). Contour intervals of Coso obsidian in the chipped stone tool category after Ericson (1981). Copyright permission for Coso obsidian distribution layer resides with J.E. Ericson, published by British Archaeological Reports (1981). Map of ethnographic groups appears in Plate 1, Bulletin 78, Bureau of American Ethnology, Smithsonian Institution Handbook of the Indians of California, by A.L. Kroeber (1925). U.S. Government Printing Office in the public domain.

(IDs 54-55), and CA-EAFB-1317 (IDs 56-57). Data from ID 51 were not available, since the sample was missing. Among the 33 artifacts excavated from CA-3361, one artifact (ID 40) was made from Joshua Ridge obsidian, one artifact (ID 44) was made from West Cactus Peak, one artifact (ID 41) was made from Sugarloaf, and 27 artifacts were made from West Sugarloaf obsidian. Three artifacts (ID 32, 45, and 50), although not assigned to any of the five sources, were compositionally similar to source specimen CV0201 and artifact ID 5. This cluster of five samples strongly suggests the presence of a sixth compositional group that is either located near or part of site 2. We have assigned this new Coso subgroup the name site 2A. Site 2A obsidian may have been extruded late in the formation of the West Sugarloaf dome, as there are several obsidian fissures in the surface of this dome. Of the two artifacts from CA-Ker-2053, one (ID 54) was made from the West Cactus Peak obsidian source and the other (ID 55) was omitted for lack of adequate sample. Of the two artifacts from CA-EAFB-1317, one (ID 56) was made from Joshua Ridge obsidian and the other (ID 57) was made from West Sugarloaf obsidian source. No artifacts were assigned to source site 6, located on Sugarloaf Mountain.

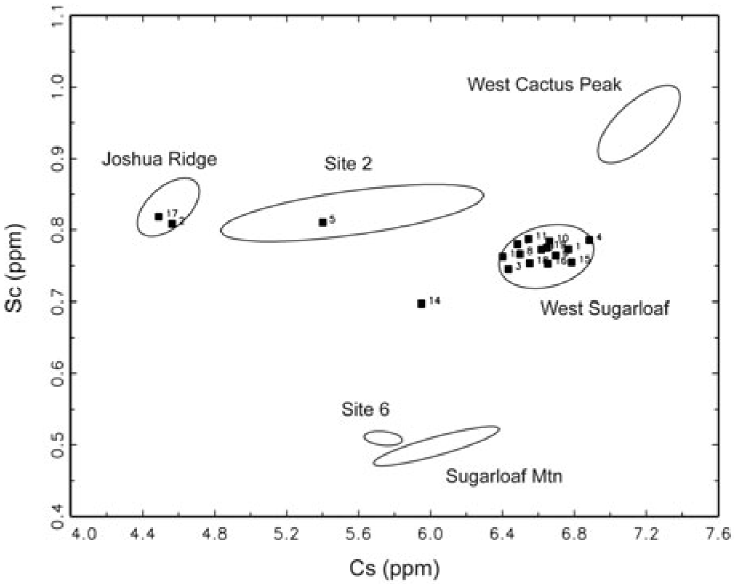

Figure 7. Bivariate plot for Cs vs. Sc of artifacts from CA-SBr-5789 (ID 3-12; 14-19), CA-Ker-3556 (ID 1-2), and CA-Ker-3434 (ID-13), which was not plotted. Confidence ellipses are shown at the 95% level for all subsources. The confidence ellipse for site 2A was calculated from source samples and artifacts.

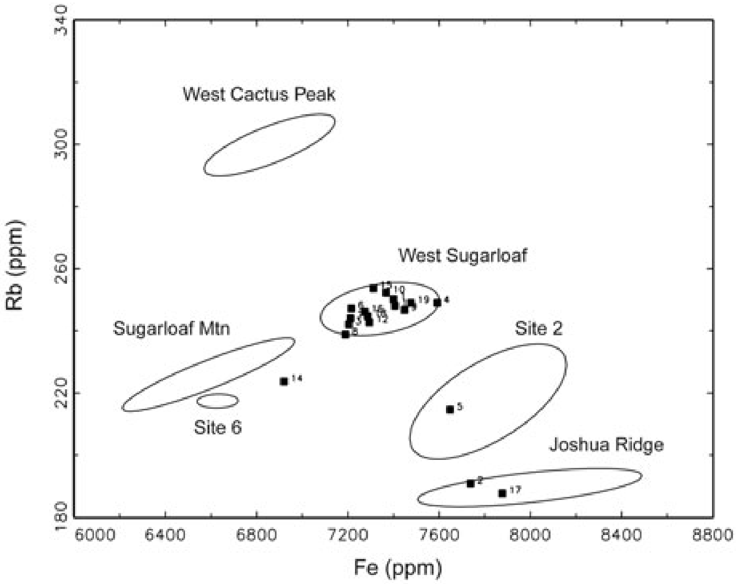

Figure 8. Bivariate plot for Rb vs. Fe of artifacts from CA-SBr-5789 (ID 3-12; 14-19), CA-Ker-3556 (ID 1-2), and CA-Ker-3434 (ID-13), which was not plotted. Confidence ellipses are shown at the 95% level for all subsources. The confidence ellipse for site 2A was calculated from source samples and artifacts.

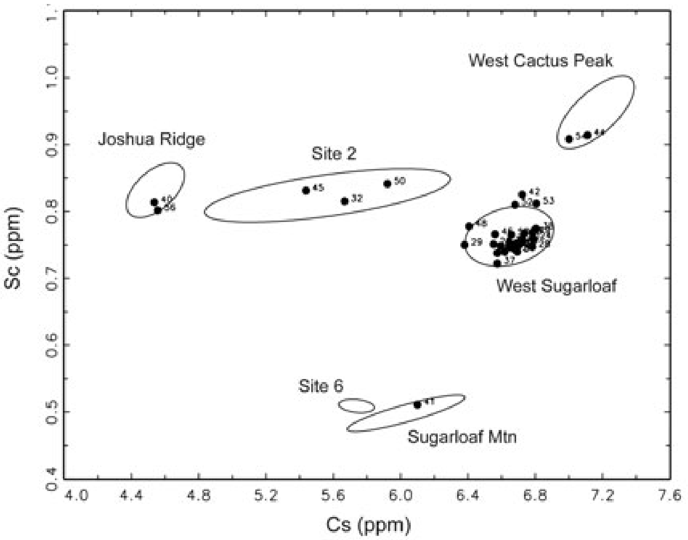

Figure 9. Bivariate plot for Cs and Sc of artifact samples from CA-Ker-3361 (ID 20-57), omitting missing data ID 51 and 55, (ID 20-53), CA-Ker-2053 (ID 54), and CA-EAFB-1317 (ID 56-57). Confidence ellipses are shown at the 95% level for all subsources. The confidence ellipse for site 2A was calculated from source samples and artifacts.

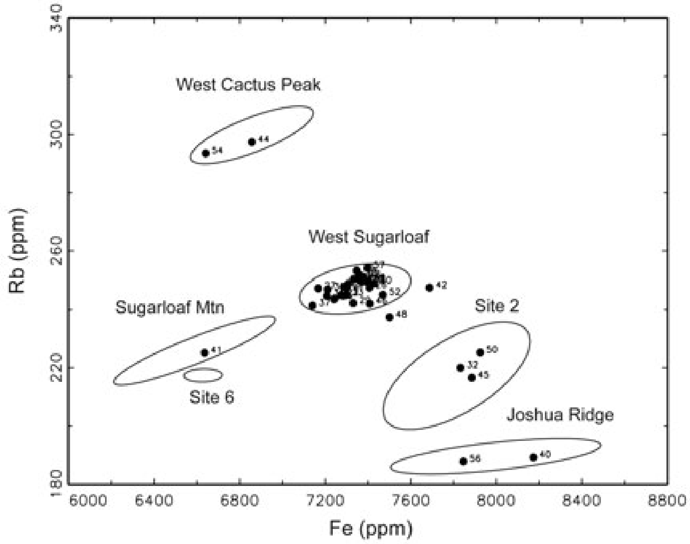

Figure 10. Bivariate plot for Rb vs. Fe of artifact samples (ID 20-57), omitting missing data ID 51 and 55, from CA-Ker-3361 (ID 20-53), CA-Ker-2053 (ID 54), and CA-EAFB-1317 (ID 56-57). Confidence ellipses are shown at the 95% level for all subsources. The confidence ellipse for site 2A was calculated from source samples and artifacts.

Table IV. Subsource use of obsidian sources, Coso Volcanic Field.

Site	Homeland	N	West Sugar-loaf	Site 2	Sugar-loaf	West Cactus Peak	Joshua Ridge	Undefined
CA-Ker-3361	100 miles South	33	82%	9%	3%	3%	3%	0%
CA-SBr-5789	100 miles South	16	81%	6%	0	0	6%	6%
CA-Iny-372	12 miles Northwest	50	72%	0	6%	14%	0	8%
CA-Iny-182	10 miles Southwest	59	76%	0	15%	3%	0	5%

INY-372 Rose Spring (Hughes, 1988).
INY-182 Stahl Site (Hughes, 1988).

Analysis of Obsidian Use from Specific Subsources

The distinct elemental composition and geographical distribution of obsidian artifacts from subsources within the Coso volcanic field provide a unique opportunity to evaluate a direct-access procurement model at distant sites. It is assumed that people coming to Coso did so to exploit West Sugarloaf, the best subsource, and this is supported by geochemical data from distant archaeological sites. However, prevalence of the secondary sources in assemblages from distant sites could depend on the direction traveled from home range to the quarries. Indeed, subsource characterization may be able to define differential usage of subsources, as well as infer directionality of travel.

Cleland (1986) proposes a bimodal obsidian procurement system in which local groups exploited obsidian directly from nearby winter villages, such as Coso Hot Springs, with neighboring southern Sierran groups exploiting the source in conjunction with summer subsistence activities in the High Sierras. As a preliminary test of this, we examined the Coso subsources used by “resident” groups in proximity to Coso volcanic field and itinerant groups located approximately 100 miles to the south. Given their proximity, the “resident” groups had equal access to all subsources in the volcanic field. In this model, we expect that the “resident” groups and southern itinerant groups will exploit different groups of obsidian subsources.

The results of the artifact study from CA-SBr-5789 and CA-Ker-3361 representing southern itinerant groups, and the data from CA-INY-372 and CA-INY-182 (Hughes, 1988) representing resident groups, are presented in Table IV. Data from Ker-3556, Ker-3434, Ker 2053, and EAFB-1317 (a total of six artifacts) were not tabulated on Table IV. They indicate travel from the south, with the procurement of the southern subsources obtained en route to West Sugarloaf, namely Joshua Ridge (2) and West Sugarloaf (3).

Our analysis indicates that West Sugarloaf is the main obsidian subsource within Coso volcanic field. West Sugarloaf is arguably the best obsidian quarry with respect to the quality of obsidian, quantity of debitage, and artifacts supported by characterization data (Ericson, 1981; Hughes, 1988; Yohe, 1998). Groups living at distant sites to the south obtained more than 70% of their obsidian from this source. Since they are geographically overlapped, West Sugarloaf and Sugarloaf contribute obsidian to both local and itinerant groups. The other subsources, West Cactus Peak and Joshua Ridge, appear to be secondary obsidian sources within the Coso volcanic field. In our study, secondary subsources account for 15%

Table V. Elemental groups indicative of compositional zonation within magma chambers (model after Hildreth, 1979, 1981). Group 1 (upwards concentrating) and Group 2 (downwards concentrating) (data after Bacon et al., 1981).

Group 1 (upwards concentrating elements)	Group 2 (downwards concentrating elements)
Be	Ba
Cs	Ca
F	Ce
HREE	Co
Li	Eu
Mn	Fe
Na	K
Nb	La
< Pb	
Rb	Mg
Sb	Nd
Sc	Sr
Sm	Ti
Sn	Zr
Ta	
Th	
U	
Y	
Zn	

or less of the obsidian assemblage. The data support the hypothesized procurement pattern by the southern itinerant groups relative to resident controls among the four sites (Table IV). The resident group procured 3–14% of their obsidian from Sugarloaf, but, interestingly, not from Joshua Ridge (Table IV). In contrast, the southern itinerant group (CA-Ker-3361; CA-SBr-5789) appear to have procured obsidian from Joshua Ridge (3–6%) and source site 2 (6–9%); however, low to no procurement occurred at Sugarloaf or West Cactus Peak (0–3%), which is represented by one artifact. We suggest that the results from the southern artifact assemblage reflect the direction from which these itinerant groups traveled. The preliminary results suggest that prehistoric knappers traveled to, and exploited one or more, secondary sources en route to/from the main quarry source at West Sugarloaf. It is also interesting to note the similarity of the percentages of use among the primary and secondary subsources. Although the above data are from a sample of limited size, they have been used to test preliminarily the model of direct access procurement proposed by Cleland (1986).

CONCLUSIONS

Obsidian from Coso is critically important in light of more than 12,000 years of human occupation of the southwestern Great Basin and coastal California. Coso obsidian appears at 8000 yr B.P. in San Diego County and as far north as Diablo Canyon in San Luis Obispo County. Prior to 800 yr B.P., Coso obsidian was used from San Francisco Bay to San Diego. There is an abrupt cessation of Coso obsidian use and a switch to local, alternative lithic materials by other groups in the region in Saratoga Springs times (ca. 800 yr B.P.). This termination has been the basis for debate among archaeologists for years.

In our study of subsource characterization, we observe that there appears to be a southern procurement pattern relative to resident groups in close proximity to the Coso source. No statistical test is possible due to overlap of subsource use and the small sample size. However, the results of this analysis support, in a preliminary manner, the bimodal (resident and itinerant) model of obsidian procurement proposed by Cleland (1986). Additional analysis is warranted.

The method demonstrated herein can be used by analysts to identify, with greater accuracy, the specific subsource/quarry for obsidian artifacts. We defined a method capable of accurately discriminating obsidian subsources based on key elements. We applied INAA with RQ-mode principal component analysis to identify the key discriminating elements, and bivariate plots of these elements illustrate specific subsource discrimination. The characterizing elements may be linked to chemical enrichment processes, resulting in an upward and downward concentration of elements within the magma chamber. Sc/Cs and Rb/Fe are the characterizing elements presented as bivariate pairs in this analysis. Whereas Hughes (1988) defined only four compositional groups by XRF, we have advanced earlier studies (Bacon et al., 1981) by clearly identifying two additional compositional groups. Archaeologists should be able to more accurately determine the procurement patterns related to obsidian exchange, thus advancing the study of California's prehistory.

The study of procurement patterns of specific subsources using this method is a refinement of the chemical characterization technique. The analysis of obsidian artifacts from different subsources found at distant sites might reflect detailed procurement behaviors of groups of people and their regional interaction.

We acknowledge Caroline Shepard, and her staff at the Naval Weapons Center China Lake, China Lake, California, for obtaining obsidian samples for analysis. We want to thank Mark Campbell, Computer Science Corporation, Inc., Edwards, California, for providing obsidian artifacts for analysis from KER-3361, KER-2053, and EAFB-1317; also, Rick Norwood and his staff at Edwards Air Force Base. Also, we want to thank Susan L. Bupp, Senior Archaeologist, Tetra Tech Inc., San Bernardino, California, for providing obsidian artifacts for analysis from KER-3556, SBR-5789, and KER-3434, located at the Phillips Laboratory, Edwards Air Force Base, Edwards, California. We offer special thanks to Amy J. Gilreath and William R. Hildebrandt of Far Western Anthropological Research Group, Inc., who provided extensive background information. We also acknowledge Ms. Sara Meadors and J. Michael Elam, who prepared the specimens for analysis, and Susan Brians for discriminant analysis. We want to thank James N. Gundersen, Robert A. Yohe, II, and other anonymous reviewers for their comments and revisions on the earlier manuscript. Of course, the authors are responsible for any errors of fact or interpretation. We gratefully acknowledge funding from the National Science Foundation through Archaeometry Program Grant BNS-9102016, which supported the INAA work at MURR.

REFERENCES

Ambroz, J.A., Glascock, M.D., & Skinner, C.F. (2001). Chemical differentiation of obsidian within the Glass Buttes complex, Oregon. Journal of Archaeological Science, 28, 741–746.

Austin, C.F., & Pringle, J.K. (1970). Geological investigations of the Coso thermal area, China Lake Naval Weapons Center Technical Publication No. 4878. China Lake, CA: Naval Weapons Center.

Bacon, C.R., & Duffield, W.A. (1976). Phenocryst mineralogy of Pleistocene rhyolites and heat constant of the Coso Range geothermal system. California Geological Society Abstracts, Abstracts with Programs, 8, 761–762.

Bacon, C.R., Giovannetti, D.M., Duffield, W.A., Dalrymple, G.B., & Drake, R.E. (1982). Age of the Coso formation, Inyo County, California, USGS Bulletin 1527. Washington, DC: U.S. Geological Survey.

Bacon, C.R., MacDonald, R., Smith, R.L., & Baedecker, P.A. (1981). Pleistocene high-silica rhyolites of the Coso volcanic field, Inyo County, California. Journal of Geophysical Research, 86(B11), 10223–10241.

Baugh, T.G., & Ericson, J.E. (1993). Trade and exchange in a historical perspective. In T.G. Baugh & J.E. Ericson (Eds.), Prehistoric exchange systems in North America (pp. 1–16). New York: Plenum Press.

Baxter, M.J. (1992). Archaeological uses of the biplot—a neglected technique? In G. Lock & J. Moffett (Eds.), Computer applications and quantitative methods in archaeology (pp. 141–148), BAR International Series S577. Oxford: Tempvs Repartvm, Archaeological and Historical Associates.

Bettinger, R.L., & Baumhoff, M.A. (1983). Return ratios and intensity of resource use in Numic and Prenumic adaptive strategies. American Antiquity, 48, 830–834.

Braswell, G.F., & Glascock, M.D. (1998). Interpreting intrasource variation in the composition of obsidian: The geoarchaeology of San Martin Jilitepeque, Guatemala. Latin American Antiquity, 9, 353–369.

Chesterman, C.W. (1956). Pumice, pumicite, and volcanic cinders in California. California Division of Mines and Geology Bulletin, 174, 119.

Cleland, J.H. (1986). Recommended evaluation program: Twelve wells pads and four access roads in Coso Geothermal Area. Los Angeles: Department of Water and Power, City of Los Angeles.

Cleland, J.H. (1989). Sugarloaf Archaeological District cultural resources management plan. China Lake, CA: Naval Weapons Center.

Cobean, R.H., Vogt, J.R., Glascock, M.D., & Stocker, T.R. (1991). High precision trace element characterization of major Mesoamerican obsidian sources and further analyses of artifacts from San Lorenzo Tenochtitlan, Mexico. Latin American Antiquity, 2, 69–91.

Colville, F.V. (1892). The Panamint Indians of California. American Anthropologist, 5, 351–361.

Coombs, G.B., & Greenwood, R.S. (1982). A cultural resources overview and inventory plan of the Naval Weapons Center, China Lake. China Lake, CA: Field Commander's Officer, China Lake Naval Weapons Center.

Davis, J.C. (1986). Statistics and data analysis in geology (2nd edition). New York: Wiley.

Driver, H.E. (1937). Culture Element Distributions VI: Southern Sierra Nevada. University of California at Berkeley Anthropological Records, 1, 53–154.

Draucker, A., Baron, D., Horton, R., & Yohe, R. (2002). Trace element characterization of distinct obsidian flows within the Coso volcanic field, California by laser ablation ICP/MS and archaeological implications. Abstracts with Program, 2002 Annual Meeting Geological Society of America, 34, 87.

Duffield, W.A., & Bacon, C.R. (1981). Geological map of the Coso volcanic field and adjacent areas, Inyo County, California, scale 1:50,000, Miscellaneous Geological Investigations Map I-1200. Washington, DC: U.S. Geological Survey.

Dutcher, B.H. (1893). Pinon-gathering among the Panamint Indians. American Anthropologis 6, 377–380.

Earle, T.K., & Ericson, J.E. (1977). Exchange systems in archaeological perspective. In T.K. Earle & J.E. Ericson, (Eds.), Exchange systems in prehistory (pp. 3–14). New York: Academic Press.

Elston, R.G. (1982). Good times, hard times: Prehistoric culture change in the western Great Basin. In D.B. Madsen & J.F. O'Connell, (Eds.), Man and environment in the Great Basin (pp. 196–206), Papers No. 2. Washington, DC: Society for American Antiquity.

Elston, R.G., & Zeier, C.D. (1984). The Sugarloaf obsidian quarry. China Lake, CA: Commander's Office, China Lake Naval Weapons Center.

Ericson, J.E. (1977). Prehistoric exchange systems in California: The results of obsidian dating and tracing. Ann Arbor, MI: University Microfilms.

Ericson, J.E. (1981). Exchange and production systems in Californian prehistory: The results of hydration dating and chemical characterization of obsidian sources. British Archaeological Reports, International Series, 110, 1–240.

Ericson, J.E. (1984). Toward the analysis of lithic production systems. In J.E. Ericson & B.A. Purdy (Eds.), Prehistoric quarries and lithic production (pp. 1–9). Cambridge, UK: Cambridge University Press.

Ericson, J.E. (1989). Towards flow-specific obsidian hydration rates, Coso volcanic field, Inyo County, California. Contribution of the University of California Archaeological Research Facility, 48, 13–22.

Ericson, J.E., & Baugh, T.G. (1994). Systematics of the study of prehistorical regional exchange in North America. In T.G. Baugh & J.E. Ericson (Eds.), Prehistoric exchange systems in North America (pp. 3–15). New York: Plenum Press.

Ericson, J.E. & Earle, T.N. (1982). Contexts of prehistoric exchange. New York: Academic Press.

Ericson, J.E., Hagan, T.E., & Chosterman, C.W. (1976). Prehistoric obsidian sources in California, II: Geological and geographic aspects. In R.E. Taylor (Ed.), Advances in obsidian glass studies: Archaeological and geochemical perspectives (pp. 218–239). Park Ridge, NJ: Noyes Press.

Ericson, J.E., & Meighan, C.W. (1984). Boundaries, alliance and exchange in California. In S.P. De Atley & F.W. Findlow (Eds.), Exploring the limits: Frontiers and boundaries in prehistory (pp. 143–152), International Series 223. Oxford: British Archaeological Reports.

Ericson, J.E., & Purdy, B.A., Eds. (1984). Prehistoric quarries and lithic production. Cambridge, UK: Cambridge University Press.

Ericson, J.E., & Singer, C.A. (1971). Geoscience at Castaic Creek site, CA-LAn-324, unpublished manuscript on file. Los Angeles: UCLA Archaeological Clearinghouse, UCLA.

Ericson, J.E., Koerper, H.C., Drover, C.E., & Langenwalter, P.E., II (1989). Advances in obsidian hydration dating and obsidian exchange in prehistoric Orange County. Pacific Coast Archaeological Society Quarterly, 25, 45–60.

Farmer, M.F. (1937). An obsidian quarry near Coso Hot Springs, California. The Masterkey, 11, 7–9.

Gilreath, A., & Hildebrandt, W.R. (1997). Prehistoric use of the Coso Volcanic Field. Contributions of University of California Archaeological Research Facility, 56, 1–201.

Glascock, M.D. (1994). New World obsidian: Recent investigations. In P. Meyers & D.A. Scott (Eds.), Archaeometry of Pre-Columbian sites and artifacts (pp. 113–134). Los Angeles: The Getty Conservation Institute.

Glascock, M.D., Elam, J.M., & Cobean, R.H. (1988). Differentiation of obsidian sources in Mesoamerica. In R.M. Farquhar, R.G.V. Hancock, & L.A. Pavlish (Eds.), Archaeometry ‘88 (pp. 45–251). Toronto, Canada: University of Toronto Press.

Glascock, M.D., Braswell, G.E., & Cobean, R.H. (1998). A systematic approach to obsidian source characterization. In M. Steven Shackley (Ed.), Archaeological obsidian studies: Method and theory (pp. 15–65), Advances in Archaeological and Museum Science. New York: Plenum Press.

Glassow, M.A. (1985). Proposed archaeological element of the Santa Barbara County cultural resources management plan, unpublished manuscript on file. Santa Barbara, CA: Santa Barbara County Office.

Graham, C.C., Glascock, M.D., Carni, J.J., Vogt, J.R., & Spalding, T.G. (1982). Determination of elements in the National Bureau of Standards' geological standard reference materials by neutron activation analysis. Analytical Chemistry, 54, 1623–1627.

Greenwood, R.S. (1972). 9000 Years of prehistory at Diablo Canyon, San Luis Obispo County, California. San Luis Obispo County Archaeological Society, Occasional Papers, 7, 1–88.

Harbottle, G. (1982). Chemical characterization in archaeology. In J.E. Ericson & T.K. Earle (Eds.), Contexts for prehistoric exchange (pp. 13–51). New York: Academic Press.

Harrington, M.R. (1951). The colossal quarry. The Masterkey, 25, 14–18.

Harrington, M.R. (1957). A Pinto site at Little Lake, California. Southwest Museum Papers, 17.

Heizer, R.F., & Hester, T.R. (1978). Great Basin. In R.E. Taylor and C.W. Meighan (Eds.), Chronologies in New World archaeology (pp. 147–199). New York: Academic Press.

Hildebrandt, W.R., & Gilreath, A.J. (1988). Survey and evaluation of cultural resources on a portion of the Navy/CLJV contract (Residual Navy 2) lands within the Coso KGRA, Inyo County, CA. China Lake, CA: California Energy Co.

Hildreth, W. (1979). The Bishop tuff: Evidence for the origin of compositional zonation in silicic magma chambers. Geological Society of American, Special Paper, 180, 43–75.

Hildreth, W. (1981). Gradients in silicic magma chambers: Implications for lithospheric magmatism. Journal of Geophysical Research, 86, 10153–10192.

Hughes, R.E. (1988). The Coso volcanic field re-examined: Implications for obsidian sourcing and hydration dating research. Geoarchaeology, 3, 253–265.

Hughes, R.E., & True, D.L. (1985). Perspectives on the distribution of obsidians in San Diego County, California. North American Archaeologist, 6, 325–339.

Irwin, C.N., Ed. (1980). The Shoshoni Indians of Inyo County, CA: The Kerr Manuscript, Ethnology and History No. 15. Menlo Park, CA: Ballena Press Publications in Archaeology.

Jack, R.N. (1976). Prehistoric obsidian in California I: Geochemical aspects, In R.E. Taylor (Ed.), Advances in obsidian glass studies: Archaeological and geochemical perspectives (pp. 183–217). Park Ridge, NJ: Noyes Press.

Jack, R.N., & Carmichael, I.S.E. (1969). The chemical “fingerprinting” of acid volcanic rocks. California Division of Mines and Geology, Special Report, 100, 17–32.

Jackson, T.L. (1984). A reassessment of obsidian production analyses for the Bodie Hills and Casa Diablo Quarry Areas, In R.E. Hughes (Ed.), Obsidian studies in the Great Basin, Contributions of the University of California Archaeological Research Facility No. 45. Berkeley, CA: University of California at Berkeley.

Jenkins, D.L. (1985). Flood, sweat and spears in the Valley of Death: Site survey and evaluation in the Tiefort Basin, Fort Irwin, CA, Fort Irwin Archaeological Project Report 17. San Diego, CA: Dames and Moore.

Koerper, H.C., Ericson, J.E., Drover, C.E., & Langenwalter, P.E., II. (1986). Obsidian exchange in prehistoric Orange County. Pacific Coast Archaeological Society Quarterly, 22, 33–69.

Koerper, H.C., Langenwalter, P.E., II, & Schroth, A. (1991). Early Holocene adaptations and the transition phase problem: Evidence from the Allan O. Kelly Site, Agua Hedionda Lagoon. In J.M. Erlandson & R.H. Colten (Eds.), Hunter-gatherers of early Holocene coastal California, Perspectives in California Archaeology I (pp. 43–62). Los Angeles: Institute of Archaeology, UCLA.

Kroeber, A.L. (1925). Handbook of the Indians of California, Bureau of American Ethnology Bulletin 78. Washington, DC: Smithsonian Institution.

Lanphere, M.A., Dalrymple, G.B., & Smith, R.L. (1975). K-Ar ages of Pleistocene rhyolitic volcanism of the Coso Mountains, California. Geology, 3, 339–341.

Meighan, C.W. (1981). The Little Lake Site, Pinto points, and obsidian dating in the Great Basin. Journal of California and Great Basin Anthropology, 3, 200–204.

Moratto, M.J. (1984). California archaeology. New York: Academic Press.

Moratto, M.J. (1987). Holocene paleoenvironments and archaeology in the central Sierra Nevada. Abstracts with Program, 21st Annual Meeting of the Society for California Archaeology, Fresno, California.<zaq;2>

Neff, H. (1994). RQ-mode principal components analysis of ceramic compositional data. Archaeometry, 36, 115–130.

Nelson, E.W., Jr. (1891). The Panamint and Saline Valley Indians. American Anthropologist, 4, 371–372.

Ross, C.P., & Yates, R.G. (1943). The Coso quicksilver district, Inyo County, California. U.S. Geological Survey Bulletin, 936-Q, 395–416.

Scarr, C., & Healy, F., (Eds.), (1993). Trade and exchange in prehistoric Europe. Proceedings of a conference held at the University of Bristol, April 1992, Oxbow Monograph 33. Oxford: Oxbow.

Sigleo, A.C. (1975). Turquoise mine and artifact correlation for Snake townsite, Arizona. Science, 189, 459–460.

Singer, C.A., & Ericson, J.E. (1977). Quarry analysis at Bodie Hills, Mono County, California: A case study. In T. Earle & J.E. Ericson (Eds.), Exchange systems in prehistory (pp. 171–188). New York: Academic Press.

Smith, C.R. (1978). Tubatulabal. In R.F. Heizer (Ed.), California, handbook of North American Indians. Washington, DC: Smithsonian Institution.

Spence, M.W., Kimberlin, J., & Harbottle, G. (1984). State-controlled procurement and the obsidian workshops at Teotihuacón, Mexico. In J.E. Ericson & B.A. Purdy (Eds.), Prehistoric quarries and lithic production (pp. 97–105). Cambridge, UK: Cambridge University Press.

Steward, D.C. (1941). Culture Element Distributions XIII: Nevada Shoshone. University of California Anthropological Records, 4(2), 361–446.

Steward, J. (1938). Basin Plateau aboriginal sociopolitical groups, Bureau of American Ethnology. Washington, DC: Smithsonian Institution.

Theodoratus, D.J. (1977). Ethnographic report on Coso Hot Springs, Inyo County, CA. Sacramento, CA: California Office of Historic Preservation.

Thomas, D.H., Pendleton, L.S.A., & Cappannari, S.C. (1986). Western Shoshone. In W.L. D'Azevedo (Ed.), Great Basin, Handbook of North American Indians II. Washington, DC: Smithsonian Institution.

Voeglin, E. (1938). Tubatulabal ethnography. University of California Anthropological Records, 2, 1–84.

Vogt, J.R., Graham, C.C., Glascock, M.D., & Cobean, R.H. (1982). A study of Mesoamerican obsidian sources using activation analysis. Journal of Radioanalytical Chemistry, 69, 271–289.

Warren, C.N., & Crabtree, D.H. (1986). Prehistory of the southwestern California area. In W. D'Azevedo (Ed.), Great Basin, handbook of North American Indians II (pp. 183–193). Washington, DC: Smithsonian Institution.

Whitley, D.S., Gummerman, G., IV, Simon, J.M., & Rose, E.H. (1988). The late Prehistoric Period in the Coso Range and its environs. Pacific Coast Archaeological Society Quarterly, 24, 2–10.

Yohe, R.M., II (1998). The introduction to the bow and arrow and lithic resource use at Rose Spring (CA-INY-372). Journal of California and Great Basin Anthropology, 20, 26–52.

Zigmond, M.L. (1981). Kawaiisu ethnobotany. Salt Lake City, UT: University of Utah Press.

Received September 5, 2003
Accepted for publication April 5, 2004

APPENDIX: ARCHAEOLOGICAL SITE INFORMATION

Collection 1

CA-SBr-5789

Relative shallow flaked stone scatter with deeper deposits, the result of bioturbation of silty clay sand and gravel, with evaporite in Joshua tree woodland at 2940 ft elevation (Red Buttes, CA 7.5E, T9N, R7W).

Joshua Ridge obsidian source in the Coso Mountain range is located approximately 103 miles at 355EN. The age of the site is 3490 ± 440 yr B.P., based on obsidian hydration at linear rate of 344 yr/micron. Site records located at the San Bernardino County Archaeological Information Center, San Bernardino County Museum, San Bernardino, California (Susan Bupp, Tetra Tech, Inc., San Bernardino, California, personal communication).

CA-Ker-3556

Shallow flaked stone scatter in silty sand mixed with gravels in Joshua tree woodland at 2390-ft elevation (Leuhman Ridge, CA 7.5E, T1ON R8W). Joshua Ridge obsidian source in the Coso Mountain Range is located approximately 91 miles at 356EN. Age of site is 3635 ± 490 yr B.P., based on obsidian hydration at linear rate of 344 yr/micron. Site records located at Southern San Joaquin Valley Archaeological Information Center, California State University, Bakersfield, California (Susan Bupp, Tetra Tech, Inc., San Bernardino, California, personal communication).

Collection 2

CA-Ker-3361 (EAFB #1232)

The 3700 m^2 site is a temporary prehistoric camp (Leuhman Ridge 7.5E, T1ON R7W) at 2580-ft elevation with chert, basalt, rhyolite, and quartz flakes with hearth features and ground stone. A possible quartz quarry with several outcrops of quartz was identified on the western portion of the site scattered with numerous quartz debitage flakes. Soil is sandy with pea gravel. Creosote bush, Joshua tree, shrubs, forbs, and grasses form the vegetation of the site. Joshua Ridge is located approximately 100 miles 350NE. Site records are at CSU Bakersfield Archaeological Information Center.

CA-Ker-2053

The site is in gravelly loam-sand in creosote scrub at 2570-ft elevation (Leuhman Ridge, CA 7.5E, T1ON R7W). Joshua Ridge obsidian source in the Coso Mountain Range is located approximately 102 miles 350NE. Site records are at CSU Bakersfield Archaeological Information Center.