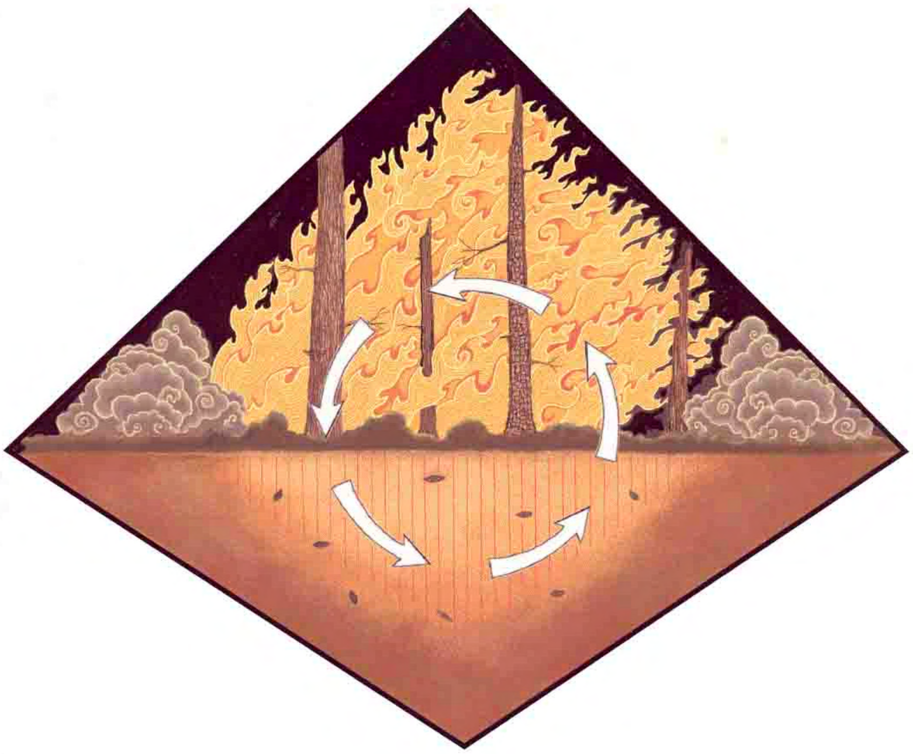
The Effects of Fire and Heat on Obsidian



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June 2002

The Effects of Fire and Heat on Obsidian

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Papers presented in Symposium 2

The Effects of Fire/Heat on Obsidian

at the 33rd Annual Meeting of the

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INTRODUCTION

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This document includes papers first presented at the April 23-25, 1999, Annual Meeting of the Society for California Archaeology (SCA) in Sacramento, California. A symposium entitled ***The Effects of Fire/Heat on Obsidian*** was carried out over a period of two days (Friday afternoon and Saturday morning). The symposium was split in this fashion to provide food for thought from the first day's presentations that could be discussed at meeting attendees' leisure during Friday evening and the early morning hours of Saturday before we resumed. It was anticipated that this "thinking" time would generate questions, comments, and discussion during the Saturday morning's session, and as hoped, it did.

This symposium included an international group of presenters, one traveled from Japan and one from England, while most completed much shorter trips from places in North America.

- Yuichi Nakazawa traveled from Hokkaido University, Japan, to make his presentation.
- Madeline Solomon, who's home base is in Sonoma County, California, traveled from England where she was studying at the time of the symposium.

Presenters who traveled from places in North America included.

- Arlene Benson, District Archaeologist, Tonopah Ranger District, Unites States Department of Agriculture, Humboldt - Toiyabe National Forest, Nevada.
- Krista Deal, District Archaeologist, Pacific Ranger District, Eldorado National Forest in the central Sierra Nevada Mountains of California. Krista's paper was augmented by contributions from Denise McLemore, Forest Archaeologist, Eldorado National Forest, Placerville, California.
- Carolyn Dillian, Department of Anthropology, University of California, Berkeley.
- Kirk Halford and Anne Halford, Bishop Office of the Bureau of Land Management, California. In addition to presenting a paper at the 1999 symposium and making a major contribution to this document, Kirk was instrumental in obtaining publication funding from the Bureau of Land Management.
- Ted Jones, Obsidian Laboratory, Anthropological Studies Center, Sonoma State University, Sonoma County, California. The paper presented at the 1999 symposium was enhanced by contributions from Cal Herrmann, Chemist, then enrolled in an archaeology course at Santa Rosa Junior College, California.
- Roger Kelly, National Park Service, San Francisco, California.
- Janine Loyd, Obsidian Laboratory, Anthropological Studies Center, Sonoma State University, Rohnert Park, California.

- Sue-Ann Schroder, Obsidian Laboratory, Anthropological Studies Center, Sonoma State University, Rohnert Park, California.
- M. Steven Shackley, Archaeological XRF Laboratory, Phoebe Hearst Museum, University of California, Berkeley.
- Nelson Siefkin, Redwood National and State Parks, National Park Service, Arcata, California.
- Carl Skinner, Geographer, United States Department of Agriculture, Forest Service, Pacific Southwest Research Station, Redding, California.
- Jim Smith, Battalion Chief, California Department of Forestry and Fire Protection, Fresno, California.
- Anastasia Steffen, University of New Mexico, Albuquerque, New Mexico.

The seventeen authors discussed, in fourteen papers, various attributes of fuel loads, fire and heat, and the affect that wildfires, controlled burns, campfires, and laboratory controlled fires/heating could and do have on obsidian, particularly archaeological specimens.

Certainly, the corpus of information contained herein will not stand throughout time as the definitive work on the effects fire has on obsidian -- and it is not intended to. It is the editors' goal that this document will provide baseline data and food for thought that will serve as a foundation for further research. Clearly, mixing together fire and obsidian can have serious implications with regard to temporal control via obsidian hydration dating, and perhaps less so with regard to geologic source determination of obsidian, which is often achieved through x-ray fluorescence (XRF) analyses of trace elements.

Each of the symposium participants brought important perspectives to the meeting, and each provided useful information. Some presenters laid the ground work for examining the effects of fire on hydration by describing the history of projects concerned with this topic, and others reported their unique studies that looked at how controlled fires and wild fires have affected obsidian hydration bands. Still, others researched fire's effect on trace minerals and specific gravity (density). Each presenter's contribution when added to the others combined to describe the current state of our understanding and create a platform for future research.

The symposium was organized and co-chaired by two past-presidents of the International Association for Obsidian Studies (IAOS): David A. Fredrickson (1997-1999) and Thomas M. Origer (1990-1992). Editing and assembling of the papers that comprise this document was greatly enhanced by Janine Loyd, the current Secretary-Treasurer (2002-2004) of the IAOS.

We sincerely thank all participants. Roger Kelly and Sue-Ann Schroder provided historical context. Arlene Benson, Krista Deal, Kirk and Anne Halford, Nelson Siefkin, Madeline Solomon, and Anastasia Steffen presented papers that focused on the effects of wild fires and controlled burns. M. Steven Shackley and Carolyn Dillian examined fire's effect on obsidian source determination. Carl Skinner and Jim Smith provided basic information about fire. Finally, Janine Loyd, Ted Jones, and Yuichi Nakazawa described laboratory studies.

Editing the authors' reports was an enlightening task. Each document was submitted as a reflection of the author's view of the appropriate document format, style, and organization. We, the editors and compilers, made certain changes for the sake of continuity; however, we strove to allow each author's predilections to emerge. In keeping with this sentiment, the artistic creativity of Nelson "Scotty" Thompson shines through on the colorful cover image. Additional assistance was obtained from Robert Douglass who brought some conformity to the individual chapter References Cited, which had

arrived in a number of formats. Toni Douglass contributed by retyping some tables that did not survive conversion from their original submission form to the final form requested by the publisher. Lastly, we thank all our office cohorts who kindly put earplugs in when the computers acted up and when the document decided to evolve in mysterious ways.

The editors rue that it has been a long process to bring this document to fruition. However, all authors "hung together" and we are happy to present this volume with their contributions. The reader is encouraged to be critical, for it is from constructive criticism that archaeology advances as a science. We look forward to comments and suggestions for future research, and we hope one day that we will be even closer to understanding all the effects that fire and heat can have on obsidian.

A SYNTHESIS OF PREVIOUS STUDIES THAT EXPLORED THE EFFECTS OF FIRE ON OBSIDIAN: WHERE WE'VE BEEN AND WHERE WE'RE GOING

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This document is an overview of several research projects that integrated into their investigations the effects of fire on obsidian. A few of these studies were conducted serendipitously after wildfires had burned large areas, and others were the results of planned research. I purposely have omitted any hydration number details in this paper, as the chart at the end, which shows comparison methods and results, will provide you with temperatures and other pertinent information that correlate with tests done by some of the following authors.

Previous Researchers

Faith Duncan. The annotated bibliography of fire effects and cultural resources compiled by Faith Duncan from the Cultural Resources Management Department at Mesa Verde National Park has provided researchers with a well-informed manual of what has been written about fires, along with abstracts of many different investigations (Duncan 1990). As an addition to Ms. Duncan's manual, I have prepared with this paper a supplemental reference list of investigations that focus specifically on fire effects to obsidian since her manuals last publication.

Irving Friedman and Robert Smith. In 1960, Friedman and Smith documented some results involving their research with obsidian. They determined the main factors that effected the rates of hydration on obsidian were temperatures and chemical compositions (Friedman and Smith 1960). This research has initiated a need to better understand the influence of temperature variances and its effects on obsidian artifacts.

Irving Friedman and Fred Trembour. From different reports that briefly discuss temperature variances and their effects, it's been established that fire alters hydration rims on obsidian. A 1983 report by Friedman and Trembour stated that induced hydration test flakes that were heated in an electric bench furnace to 540ºC (1000ºF) or more, compared with similar shallow heat cracks otherwise known as crazing found on obsidian from agricultural land in South America (Friedman and Trembour 1983).

Fred Trembour. Results from induced testing by Trembour in 1979 and 1990 from the 1977 La Mesa Forest Fire in Bandelier National Monument, New Mexico, reported that hydration rim alteration on obsidian ranged from slight increases at 170ºC (330ºF) to actually melting and vesiculation stages at temperatures of 760ºC (1400ºF) (Trembour 1990).

James Hatch, Joseph Michels, Christopher Stevenson, Barry Scheetz, and Richard Giedel. Although chart information was not available, similar hydration results came from experiments done with research on Hopewell obsidian studies by Hatch, Michels, Stevenson, Scheetz, and Giedel with a thermostatically controlled pot furnace involving obsidian from Guatemala with pre-hydrated surfaces. These studies also noted distortion and progressive diffusion to hydration rims beyond 750ºF (400ºC).

A second experiment done by Hatch et al., on freshly flaked obsidian with no hydration rims, heated at temperatures between 250ºC (480ºF) to 750ºC (1380ºF), concluded "…that exposure of fresh obsidian to this range of temperature has no effect on the subsequent formation of hydration rims, except to reduce the optical clarity of the rims themselves".

Results of the second study indicate that obsidian with detectable hydration rims and potential archaeological significance are at higher risks from heat altering its integrity than recently fractured obsidian.

Craig Skinner, Jennifer Thatcher, and M. Kathleen Davis. Skinner, Thatcher, and Davis also conducted lab tests on obsidian from Northwest Research Obsidian Studies Laboratory, which produced a 1997 report for the Surveyor Fire Rehabilitation Project in Deschutes National Forest, Oregon. These tests consisted of placing six flakes one at a time in a muffle furnace for one-hour intervals at different temperatures. Once again, the results were similar to Trembour's analyses which stated that hydration rims increased in thickness before they began a process of diffusion, when exposed to increased temperatures (Skinner, Thatcher, and Davis 1997).

Several research papers on how fires directly effect obsidian have been written as part of aftermath studies from major fires. Pre-burn analyses for obvious reasons were unattainable and temperatures could only be estimated when possible. This is the case from two reports on my chart. The Henry Fire on Holiday Mesa, in the Jemez Mountains, New Mexico, by Stephen Lentz, Joan Gaunt, and Adisa Willmer, and on the Surveyor Fire, in Deschutes National Forest in Oregon by Craig Skinner, Jennifer Thatcher, and Kathleen Davis.

Stephen Lentz, Joan Gaunt, and Adisa Willmer. In the phase 1 report on Fire Effects On Archaeological Resources from the 1991 Henry Fire in New Mexico, documentation showed that post-burn analyses on obsidian was done from six different sites. A total of nine obsidian artifacts was collected from five burned out sites along with one flake collected from a non-burned site to use for comparison purposes. In order to provide artifacts with a degree of variance in heat, three artifacts were collected from what was estimated to be relatively light fuel type sites, three from moderately fueled sites, and three from what was considered heavy or long burning sites. The artifacts were divided into these fuel loads by supplying two surface and one subsurface specimen for each category. The controlled sample was collected randomly from the surface.

The hydration results from the lightly fueled sites provided measurable bands on all three specimens. Measurements from the moderately fueled sites came from two of the three samples, as one band from the surface specimen was diffused. The heavily fueled sites produced only one surface artifact with measurable rim, and the controlled specimen unfortunately had no visible band on it to compare with.

Craig Skinner, Jennifer Thatcher, and M. Kathleen Davis. Research from the 1993 Surveyor Fire in Oregon involved 51 obsidian artifacts that were collected from a combination of surface and subsurface locations. Temperature estimates suggest that this fire burned at a much hotter rate due to the fact that 46 of the 51 specimens analyzed produced un-measurable rim readings.

None of the samples from the Henry Fire or the Surveyor Fire had pre-burn analyses done on them; therefore, it is impossible to know what condition the obsidian was in prior to each fire.

The next couple of studies on my chart are particularly relevant because they involve more details from controlled burns. These prescribed fires allowed for pre-burn and post-burn obsidian analyses. They also provided an opportunity to create various fuel type situations, and permit heat-sensing devices to be used for measuring temperatures on each site.

Carole Linderman. Carole Linderman, from the Department of Anthropology, University of Oregon, reported on a series of studies done in 1987 and again in 1989, from the McKenzie Ranger District of the Willamette National Forest in Oregon.

The fire in 1987 was known as the Bunchgrass Meadow Burn project, and its purpose was to test whether or not temperatures from lightly fueled fires had any adverse effects on surface obsidian artifacts. In order to do this; ten test plots were situated throughout the location known as Bunchgrass Meadow, after which two obsidian artifacts were placed within each plot. One was placed on the surface and the other specimen at the depth of 3.5 centimeters.

Ceramic tiles with heat sensitive plastic dots on them were used to measure three separate temperature levels. When temperatures went past the dot thresholds, the color would change and the dot would melt. None of the dots were designed to reach levels beyond 500ºF.

Post-burn hydration examination of thin sections revealed that none of the artifacts analyzed showed any alterations to rim measurements as the result of the lightly fueled Bunchgrass Meadow burn.

In June and again in October of 1989, Linderman's research continued within the McKenzie Ranger district, at a location known as Lambchop #4. This study was to test whether moderate to heavy fuel loaded archaeological sites could produce enough heat to alter obsidian artifacts. A similar research strategy to the Bunchgrass burn was used, except that a total of 30 plots substituted the previous ten plots, and 60 obsidian artifact samples was used instead of 20.

The June burn tested only five plots, employing ten of the obsidian samples. Heat sensitive dots were used once more, but they were glued directly onto each artifact instead of on ceramic tiles. After the test, only six of the ten artifacts were recovered for post-burn measuring, as four specimens could not be found. Of the six samples, three produced un-measurable rims.

In October, the remaining 20 Lambchop #4 plots were burnt, along with 50 more obsidian samples. Due to vegetation variances, several alterations were made for this burn. A major change to monitoring the temperature range was the substitution of heat sensitive paints, as the paints produced higher thresholds for melting points than the dots did. The paints were applied as the dots were, directly to the artifacts, and carried thresholds of up to 1400ºF.

Forty-eight of the 50 artifacts were recovered from the October burn and sent to the Sonoma State Obsidian Lab for analysis. Of the 48 samples, 41 produced no visible hydration rim at all. Four showed diffused rims, and only two from below the surface were virtually unaffected. One specimen rendered diffused hydration in both pre and post burn stages.

With better results from the fall burn than the summer burn, the indications show that fires fed by moderate to heavy fuel loads definitely altered the majority of the obsidian artifacts tested.

Dee Green, Kristen Bordwell, Randall Hall, and Andrew Goheen. In the fall of 1996, a controlled burn on the east side of the Warner Mountains in northeastern California was accomplished by Dee Green, Kristen Bordwell, Randall Hall, and Andrew Goheen of the U.S. forest service, Warner Mountain Ranger District, in Modoc National Forest. This investigation involved the systematic collection of 90 obsidian specimens that were sent for analysis to Sonoma State University Obsidian Laboratory prior to the prescribed burn.

After hydration rims were measured and the artifacts returned, they were divided equally and subsequently placed on the ground surface in each of the light, moderate, and heavily fuel loaded locations. In order to monitor heat temperatures, three different measurement devices were tested, that included crayons, patches, and tablets. After a couple of practice runs, the tablets proved to be the most successful. Therefore, tablets were placed under each obsidian sample in their prescribed area.

Results from post-burn hydration rim analyses determined that 5 of the 30 samples placed in the lightly fueled area were altered and un-measurable. In the moderately fueled site, 21 of the 30 specimens were unreadable, and from the heavily fueled burn, 20 out of 29 were adversely effected and rendered unreadable. One sample remained missing.

Conclusion

Although it appears that selection of heat sensitive measuring devices needs further consideration, the study done by Green et al., had the best results from heat sensitive tablets that measured heat up to 500ºC (932ºF).

Finally, I'd like to point out that although temperature thresholds vary somewhat, many researchers agree that hydration rims on obsidian become severely effected around 427ºC (800ºF), and temperatures that reach 760ºC (1400ºF) for any extended period of time produce no visible hydration rim. Temperature ranges between 204ºC (400ºF) and 260ºC (500ºF) produce changes in rim sizes to stages of diffusion, and temperatures below 204ºC (400ºF) show little or no change to obsidian hydration band integrity.

Future research in obsidian studies will hopefully develop more information directed towards better temperature controls, duration of controlled burn sites, and the development of procedures employed during prescribed burns in order to eliminate adverse effects.

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An Overview of Obsidian Studies within Western United States Parks

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Introduction

For over 20 years, National Park Service (NPS) in its western United States regional areas has attempted to understand effects of terrain fires upon cultural resources. The attached rough diachronic chart shows a 30+ year-long development of NPS and other agencies' activities to establish practice, policy, and procedures linking fire programs with cultural resource management. Wildland fire events, planned ignitions, study reports, many meetings and cross training sessions, and publications are interconnected building blocks, leading toward an expansion of multidisciplinary knowledge and collaboration.

My assignment, herein, is to address NPS management for projects and wildland fire events and describe what NPS has done regarding the treatment of cultural obsidian in these two situations. Of course, a lot of data about geological sources, age, and other analyses has been accomplished on NPS cultural obsidian, but here we are focusing on fire environments and obsidian.

National Park Service Reports

I reviewed here key NPS reports and other materials in our office focused specifically on culturally altered obsidian in fire environments. At this time, NPS and our Forest Service colleagues at Missoula, Montana are working to compile a volume about cultural resources in fire events this fiscal year - 'The Effects of Fire on Cultural Resources: A State of Knowledge Review'. We're happy to have the USFS serving as lead.

A wake-up call was the 1977 'La Mesa' fire at Bandelier National Monument. For the first time archaeologists and fire fighters worked together in the field, and this was the first time that impacts or effects of wildland fire suppression on very significant cultural resources were assessed. Written descriptions were prepared but not published until 1990. A pioneering laboratory study on artifacts including obsidian was done by F.N. Trembour, a United States Geological Survey scientist in Denver, and this was because NPS didn't have the necessary expertise in house. Results of close examinations of site specimens and a control sample heated in an electric bench furnace showed that significant loss of hydration by high heat occurred but that hydration is reestablished during long periods of time also (Trembour 1990:177).

During the mid-1980s, several colleagues and I formed a little office research committee in fire effects. Earlier, I had attempted informal field plot experiments in Yosemite National Park, followed by other test plots in Sequoia-Kings Canyon national parks by Jim Mayberry (Kelly and Mayberry 1979; Mayberry 1979). These early tests included 'salting' a prescribed burn with a variety of artifacts to observe any changes. But burn temperatures were not recorded and changes to artifacts were highly variable. We did, however, work up a laboratory test project, reported in 1985 by Peter Bennett and Michael Kunzman, regarding changes to artifacts from high temperatures (Bennett and Kunzman 1985). Their report has been widely cited but not formally published. Tested obsidian pieces were changed by temperatures over 500ºC, in terms of water loss and visual appearance. These results were similar to those from Trembour's (1990) laboratory work.

Wildland fire realities caught up with us at Mesa Verde and Yellowstone National Park in the Late 1980s with major fire events and suppression campaigns. Abundant information from post-fire site surveys came from Mesa Verde staff, but disappointingly, the Anasazi didn't use obsidian much and very little was found to study the effects of major fires (Eininger 1989). But at Yellowstone National Park the story was different. The Obsidian Cliffs quarry locality and its 59 loci, now a National Historic Landmark, was thoroughly examined immediately after the intense wildfire of 1988 (Johnson and Lippincott 1989) and a detailed study completed later (Davis, Aaberg, Schmitt, and Johnson 1995). Cultural and natural obsidian within the Yellowstone Fire Complex was described as 'opalized' when in contact with fuels, or 'shattered' due to thermal shock from retardant, or 'spalled' at flow sources, and some artifacts became 'oxidized'. But 80 specimens were successfully subjected to X-ray fluorescence analysis by R.E. Hughes to establish geochemical integrity for variations and XRF signature of this widely traded material for comparisons (Davis et al. 1995:40-44).

Meanwhile, in the 1990s we experienced a series of park wildland fires: A-Rock fire in Yosemite (Hull 1991); Rainbow Fire which included Devil's Postpile Monument (Hull and Hale 1993); a wildfire entering Pinnacles National Monument, the Ross Fire in Lava Beds National Monument, and another entering Whiskeytown National Recreation Area, the Malibu Fire at Santa Monica Mountains National Recreation Area, the Akerson Fire of 1966 in Yosemite (see Keefe, Kahl, and Montague 1998), and the 1997 Mt. Vision Fire in Point Reyes National Seashore.

Cultural resources staff participated in all of these campaigns, but only for the A-Rock, Rainbow, and Akerson fires were post-fire contracted surveys completed. NPS archeologist, Paul Gleeson, prepared a BAER Cultural Resources report for the Mt. Vision Fire. Three post-fire survey projects included field observations of fire effects upon surface obsidian, site by site, including some laboratory analyses. These analyses were reactive - after the fire - rather than predictive as based from laboratory test data, applied to fuels in proximity to cultural obsidian on sites.

From the A-Rock Fire in the Foresta locality of Yosemite, Kathleen Hull observed "silvery sheen or exterior bubbles" on numerous obsidian pieces on burned sites. She did visual examination of pieces to determine probable geological source and effects of high heat which were often "discoloration" and "patination" of surfaces (Hull 1991:29, 54, 97). After the Rainbow Fire within Devil's Postpile National Monument, Hull and Hale saw the same changes in obsidian flakes at five sites, and noted the integrity of hydration rims was compromised by heat, but spalling or discoloration was not observed (Hull and Hale 1993:38, 53). In either situation, it was possibly to identify, based on macroscopic examination, the likely geological source even from affected pieces. XRF analysis and other analytical procedures were not within the scope of the contracted project.

Recently, the Akerson Fire effects upon archeological obsidian has been described (see Keefe, Kahl, and Montague 1998). This report is a thorough description of post-fire survey results and also includes much information on obsidian collections (see Keefe, Kahl, and Montague 1998:97-113, and Table 9). Sixty-nine artifacts exposed to this fire were analyzed by Pacific Legacy's team that included Tom Jackson, Rob Jackson, and Tad Allred. Although gradations of burning intensity at sites was not clearly documented, it was clear that there was a "loss of scientific data, specifically regarding obsidian hydration rims and thus temporal information..." (Keefe, Kahl, and Montague 1998:113). But determination of the geological source for the same 69 specimens was possible, yielding identification of five sources, including the expected Bodie Hills and Casa Diablo localities. Surface artifacts in heavily burned sites were more highly altered than subsurface ones.

The Akerson Fire report also used a modified field observation recording form to standardize post-fire site survey visits, and this innovation is very welcome. Some 77 sites were thus documented and monitored, which gives an excellent body of post-fire effects data from Yosemite's high country, as contrasted with lower elevations of the A-Rock/Foresta Fire complex.

As noted, wildland fires in NPS field units, which include wooded coastal ranges (e.g., Point Reyes, Mt. Vision), interior pinyon-juniper woodlands (e.g., Lava Beds), coastal chaparral (e.g., Santa Monica Mountains National Recreation Area) or interior ranges with pine-oak woodland (e.g., Whiskeytown National Recreation Area), either were lower temperature fires or did not include much site obsidian.

These several studies show us that wildfire events within NPS field units where archaeological obsidian is expected will result in loss of scientific data that could be derived from obsidian hydration analysis, but not necessarily geological source determinations. Morphological and typological work is possible on altered specimens also, but appearance, color, or surface patina will change with high heat. These effects, although potentially damaging research potential, would not appear to disqualify an archaeological resource from eligibility or listing on the National Register of Historic Places. But heavy fuel loads directly upon obsidian laden sites will mean greater data loss and possible fragmentation of finished artifacts or quarried materials; hence, fuel removal should be undertaken on such sites.

Conclusion

In summary, what do we need to do?

1. Use workable, standardized ways for field observation of fire effects, especially upon obsidian, during post-fire field surveys.

2. Continue to check post-fire collected specimens in the lab for quantifiable changes, particularly hydration levels.

3. Use mechanical fuel reduction measures as preventive methods when major sites are already known or when cultural obsidian on sites is documented during fire campaigns.

4. Use available Fire-Pro, BAER as well as cultural resources funding to study direct fire effects on obsidian and other artifactual media in prescribed fire projects to establish more controlled observations from the laboratory for application to field scenarios.

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Effects of Prescribed Fire on Obsidian and Implications for Reconstructing Past Landscape Conditions

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Introduction

This study was designed to measure the effects of prescribed fire on obsidian hydration bands, and to explore the possibility of using obsidian hydration data as an aid in reconstructing fire histories, which could then be used in reconstructing past landscape conditions.

Obsidian hydration band studies provide researchers in Sierran forests a primary means of establishing prehistoric site chronologies and depositional integrity. Obsidian from distinct volcanic flows has unique chemical compositions, allowing researchers to determine the source of obsidian tools and debris left on sites in prehistoric contexts. In addition, obsidian "hydrates," or absorbs moisture in ever thickening bands along freshly exposed surfaces, such as those created when stone tools are manufactured or refurbished, with obsidian from different sources hydrating at slightly different rates. The thickness of the band can indicate how long a surface has been exposed, allowing archaeologists to date obsidian that has been left at archaeological sites (although certain variables, such as soil moistures, soil pH, and temperatures can affect absorption).

In catastrophic wildfire situations, however, hydration bands become diffused and unreadable thus destroying a valuable analytical tool. The effects of prescribed fires are less well understood. Most researchers have assumed that less intense fires do not affect hydration bands; however, there has been little exacting data to support this assumption. Although there have been several experimental studies in the field with prescribed fire, and others which induced effects in the lab, previous experiments have generally measured maximum temperature or fire intensity, but not duration of heat, or only measured effects following a wildfire, without benefit of pre-fire data. Many of these studies have concluded that there are "temperature thresholds" above which artifacts are reportedly damaged -- temperatures which most researchers presume are not often reached in prescribed fires (Biswell 1989:213-220; Donaldson 1982:3). The current study measured temperature and duration of heat in the field in two prescribed burns (Figure 1) and assessed the effects on obsidian with previously measured hydration bands.

Studies by the Pacific Southwest (PSW) Forest Fire Laboratory have shown that prescribed fires in areas with heavy fuels often smolder for days. In these heavily fueled burns, all the organic material, regardless of duff moisture conditions, is usually consumed to mineral soil (Sackett and Haase n.d.). Soil temperatures in these conditions can easily range from 200 to over 780ºF, with temperatures from 80 to more than 200ºF at 12 inches below the surface (Sackett and Haase n.d.). In fact, elevated temperatures have been recorded nearly two feet below ground surface (Sackett and Haase 1993:2). Prior studies have shown that hydration bands on obsidian are initially affected at a threshold of about 260ºC (500ºF) (McIntyre n.d.:*9)*, and seriously affected by around 427ºC (800ºF) (Trembour 1979). These temperatures are within the range often reached in prescribed burns.

Our study was conducted in cooperation with PSW experiments by Steve Sackett, Sally Haase, and Gloria Burke on prescribed fire and sugar pine mortality. Obsidian specimens were placed in two

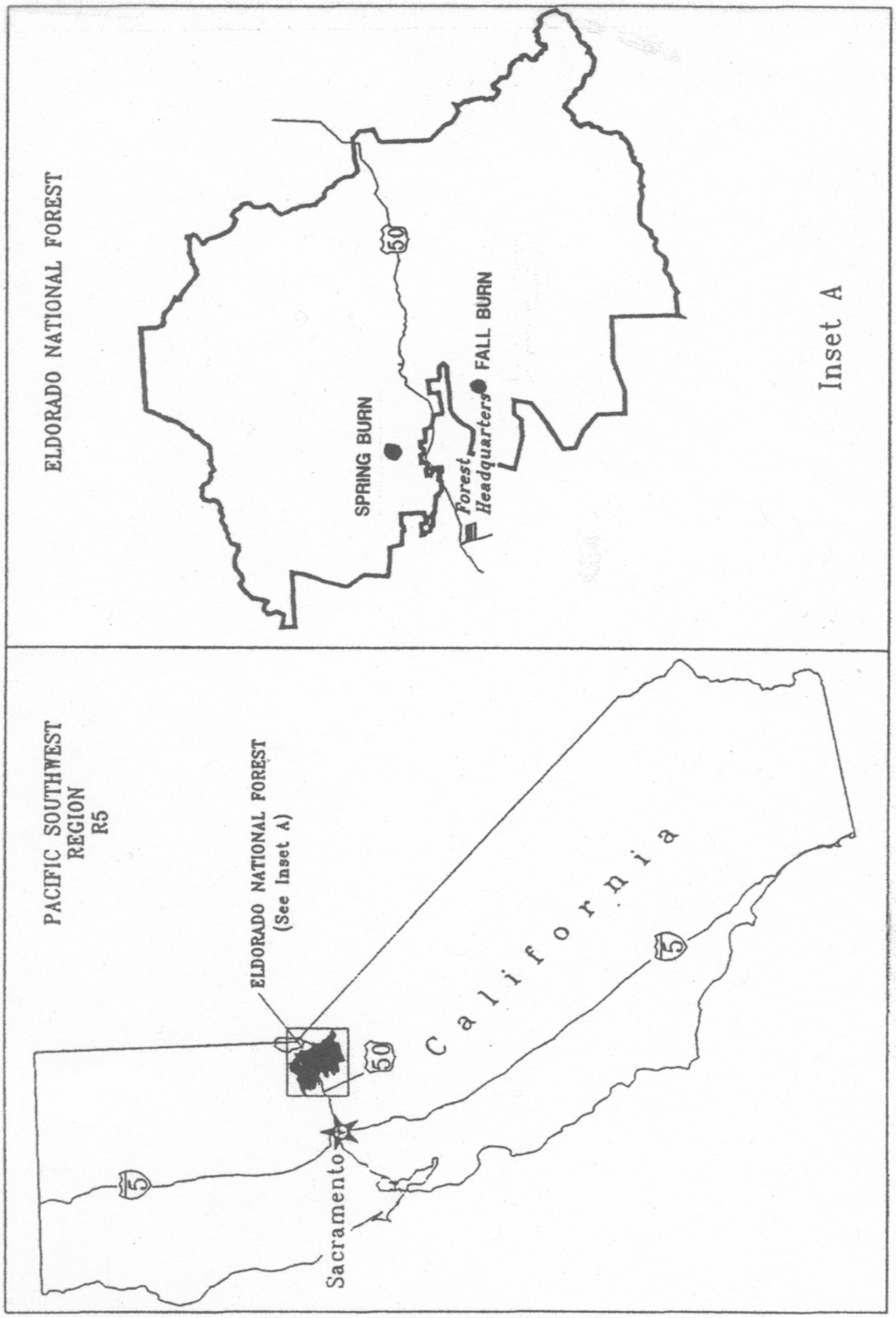


FIGURE 1. LOCATION OF SPRING AND FALL BURNS USED IN OBSIDIAN HYDRATION EXPERIMENT.

prescribed burns, situated in areas with different burn histories. Specimens with known hydration bands, obtained from 23 sites within the Pacific Ranger District of the Eldorado National Forest, were set at and below ground surface in a variety of fuel loading situations. Thermocouples were used to measure temperature and duration of heat. Obsidian samples were removed following the burns and resubmitted for hydration measurements. Preliminary results indicated that duration of exposure to heat, even at low temperatures, creates effects on obsidian hydration bands similar to effects of elevated temperature. These results have implications regarding the effects of prescribed burning in different fuel loads, as well as for potential landscape-level, reconstructive fire histories.

Prior Fire Effects Studies

The majority of prior studies of fire effects on archaeological resources have been conducted in the aftermath of wildfires (cf., Burgh 1960; Kelly and Mayberry 1979; Kelly 1984; Lentz et al. 1996; Lissoway and Propper 1988; NIFC 1995; Pilles 1982; Rogers and Francis 1988; Silvermoon 1987; Switzer 1974). Few of the studies on wildfire-affected obsidian have recorded the pre-burn hydration readings of the obsidian (for an exception, see Origer and Anderson 1994). Several prescribed fire experiments monitored pre-burn and post-burn effects to resources, although most of the effects noted were macroscopic (Linderman 1992; Picha et al. 1991; Pidanick 1982; Welch and Gonzales 1982). Laboratory experiments on the effects of fire on obsidian have primarily focused on the effect of varying temperatures on hydration bands, and most used freshly flaked obsidian for measuring effects (see Picha et al. 1991; Kelly and Mayberry 1979; Mazer et al. 1991; Stevenson et al. 1985; Trembour 1979). Although there have been a few exceptions, most wildfire, prescribed fire, and laboratory studies have focused on determining the temperatures at which archaeological resources are negatively affected, with negative effects generally defined macroscopically. These studies have resulted in statements such as those included in the National Interagency Fire Center course, "Introduction to Fire Effects RX340," which states that for prescribed burn temperatures in the range of 400 to 500ºC (752 to 932ºF), severe alterations to inorganic cultural material would not occur (NIFC 1995:4a.6).

Our Prescribed Fire Experiment

Sample Selection

The current study measured temperature and duration of heat in the field in two prescribed burns and assessed the effects on obsidian hydration band measurements. Obsidian which had been previously sourced and measured for hydration from sites on the Pacific Ranger District of the Eldorado National Forest, provided the samples used in this experiment. A total of 54 specimens from 23 sites within our study area was selected, with hydration bands ranging from 0.9 to 7.7 microns. Several criteria were used to select the samples. First, the specimens needed to be large enough to be recovered easily from the soil after the prescribed burn. Second, we wanted the total sample selected to reflect the same proportions of obsidian sources represented at sites on the Forest. Third, we wanted the samples to reflect the full temporal span represented on the Forest. Finally, in the hopes that obsidian might be useful for landscape level fire histories, we wanted the samples to be from geographically dispersed sites, stratified by elevation.

There are no known obsidian sources on the Eldorado National Forest; all the obsidian has traveled fair distances to get here, either through direct acquisition or trade. The majority of obsidian on the Pacific District is from Bodie Hills (77.6%), with lesser amounts from Mount Hicks (8.6%), Napa Valley (4.8%), Sutro Springs (4.0%), Mono Glass Mountain (1.7%), Pine Grove Hills (0.6%), with 0.3% each from the Truman-Queen, Grasshopper Flat/Lost Iron Wells, Fox Mountain, Coglan Buttes, Borax Lake and Casa Diablo sources. Obsidian from unknown sources comprises 0.9% of the district's obsidian. These numbers are similar to those for the rest of the Forest. For our experiment, we selected 43 samples from Bodie Hills, 3 from Mount Hicks, 3 from Napa Valley, 2 from Sutro Springs, 1 from Mono Glass Mountain, 1 from Truman-Queen, and 1 from Pine Grove Hills. Table 1 shows the total number of specimens burnt by source and Table 2 shows site and obsidian sample data for the materials used in this experiment.

Table 1. Total number of burnt specimens by obsidian source.

Source	Number Burnt	% of Total
Bodie Hills	43	79.6
Mount Hicks	3	5.6
Napa Valley	3	5.6
Sutro Springs	2	3.8
Mono Glass Mtn.	1	1.8
Truman-Queen	1	1.8
Pine Grove Hills	1	1.8
Total	**54**	**100**

Using cross-dating and prior research with assumed hydration rates for Bodie Hills obsidian (see Tremaine and Jackson 1995), we divided our samples into Early, Middle and Late Periods based on thickness of the hydration bands. Samples with readings of 2.5 microns or less were chosen to represent the Late Sierran Period, roughly 200 to 1,000 years ago. For the Middle Sierran Period, roughly 1,000 to 2,500 years ago, readings of 2.6 to 4.0 microns were used, and for the Early Sierran Period, beginning roughly 2,500 years ago, readings of 4.1 microns and greater were used. Our objective was to have equal numbers of Early, Middle and Late Sierran obsidian samples; 17 of the specimens had early period bands, 18 had middle period bands, and 19 had late period bands.

Elevation was divided into three categories, with low elevation sites between 3,000 and 4,500 feet, mid-elevation sites between 4,501 and 6,500 feet, and high elevation sites above 6,501 feet. Our goal was to have equal representation of low, mid-, and high elevation sites. Seven of the sites represented were at high elevations, eight were from mid-elevations, and eight were situated at low elevations.

Experimental Context

Two prescribed burns, one in the fall of 1996 (see Photograph 1) and another in the spring of 1997, with very different fire and burn histories, were utilized for this study, resulting in differing burn conditions, particularly with respect to smoldering time. Three fuel situations ("light," "woody", and "log") were selected for specimen placement within each of the areas to be prescribed burned. Each fuel situation had three study spots: two at ground surface (under the duff layer and atop mineral soil), and one approximately 2 to 3 inches below ground surface. Obsidian was placed so that each of the three fuel locations received samples of early, middle and late period pieces of obsidian. Each bag also contained obsidian from either high, mid-, or low elevation contexts, such that obsidian from each time period and each elevation range was subjected to each of the three fuel situations. In order to facilitate specimen recovery and post-burn identification of any altered pieces, the contents of each sample bag were photocopied prior to placement in the ground.

Table 2. Site and sample data for Eldorado National Forest prescribed burn experiment.

Site 05-03-55-	Number of Specimens	Sources Represented	Time Period	Elevation
36	2	B-1, S-1	E-1 M-1	High
50	3	B-2, M-1	M-1 L-2	Low
78	3	B-1, M-1, Mg-1	M-1 L-2	High
90	7	B-6, N-1	E-5 M-2	Mid
144	1	B-1	L-1	Mid
167	6	B-6	E-3 M-2 L-1	Low
197	3	B-2, S-1	E-1 M-1 L-1	High
199	2	B-2	M-1 L-1	Mid
211	1	B-1	M-1	Low
228	1	N-1	L-1	Low
249	2	B-1, M-1	L-2	Mid
263	3	B-2, N-1	E-1 M-1 L-1	High
270	1	B-1	E-1	High
274	3	B-1, Q-1, P-1	M-1 L-1	High
279	1	B-1	M-1	Low
280	4	B-4	E-2 L-2	Low
319	1	B-1	L-1	Mid
333	3	B-3	E-1 M-1 L-1	High
347	1	B-1	E-1	Low
356	1	B-1	M-1	Low
368	1	B-1	M-1	Mid
415	3	B-3	M-2 L-1	Mid
421	1	B-1	E-1	Mid
Total = 23	**54**	**B-43, M-3, N-3, S-2, Mg-1, Q-1, P-1**	**Early – 17** **Middle – 18** **Late - 19**	**High - 7,** **Mid - 8,** **Low - 8**

Source Codes: B = Bodie Hills, M = Mount Hicks, N = Napa Valley, Mg = Mono Glass Mountain, SS = Sutro Springs, Q = Truman Meadows-Queen, P = Pine Grove Hills.

Burning conditions were monitored at each of the study spots by PSW scientists Steve Sackett, Sally Haase and Gloria Burke using grounded, stainless steel, chromed-alumel thermocouples to measure soil temperatures. Thermocouples were placed into undisturbed soil, with subsurface cables running from the thermocouples to data loggers outside the fireline. Obsidian specimens were placed as close to the thermocouples as possible from the thermocouple/cable "cutbank" using forceps, rather than being inserted into the ground from above, in order to minimize fuels and ground disturbance which could affect fire behavior. Data logging for soil temperatures was conducted using seven channel, Campbell Scientific Model 21 microloggers, with data on soil moisture, temperature and duration stored on data-type cassette tapes (see Photograph 2).

The obsidian was retrieved following the burns and resubmitted for hydration readings. For consistency, the same individual who had completed the majority of the original hydration readings also read the hydration on the resubmitted samples, using identical equipment.

Fall Burn in Unmanaged Fuels

In the fall of 1996, we placed obsidian samples in a prescribed burn conducted by PSW which was designed to continue studies on the effect of prescribed fire on sugar pine mortality (Sackett and Haase n.d.). The burn site on Baltic Ridge covered a fairly flat acre on a ridge top saddle, at an elevation of 4,760 feet. Vegetation consisted of plants common to the yellow pine / black oak community; no prior fuels management, and no wildfires, had occurred in the study area during at least the last 86 years. Dead and down woody fuels -- those responsible for carrying the flames -- at the burn site were estimated at about 40 tons per acre. Fuels on the forest floor, or those fuels that will smolder after the flaming front has passed, ranged from 18 to 60 tons per acre within the one acre burn site. At our obsidian study area, the forest floor inventory of "light" fuels measured 20 tons per acre of fuel, primarily in the form of deep duff; "woody" fuels measured 31 tons per acre of fuel in the form of duff and 1/4-inch to 1-inch diameter twigs and branches; and "log" fuels measured 16 tons per acre by an 8-inch diameter log (Sackett 1997).

Half (27) of the total obsidian specimens were placed in the fall burn area (see Photograph 3). The fall obsidian was stratified by elevation and age, and divided into nine sample bags, with each bag containing an early, middle and late piece of obsidian from either all low, all mid- or all high-elevation sites. These were then evenly distributed at each of three fuel conditions. In each of the three fuel locations, six samples were placed on the ground surface below the duff layer, with three more placed two to three inches below the ground surface.

The prescribed burn was ignited at the northeast corner of the unit at 12:15pm on October 7, 1996. Relative humidity ranged from 27-40%, and winds were generally calm at about one mph. Soil moistures were very high, averaging 26.2% at depths of 0-2 inches and 25.9% at 2-4 inches. Fuel moisture content of the ¼-1-inch diameter fuels ranged within a low 7-8%. Flame lengths of one to three feet were common, with scorch heights in the heaviest fuel loads at 10-15 feet.

The fire reached the obsidian study locale shortly after 4:00pm, with the flaming front crossing the study area in about 10 minutes. As the flames reached the study area, temperatures jumped at all three surface thermocouples. Flame lengths at the light fuels ranged from 4 to 10 inches, at the woody fuels from 12 to 24 inches, and at the log fuels to about 10 inches. After the flames passed over the study site, the temperatures continued to rise as the area was subjected to deep duff glowing combustion (Sackett and Haase 1996). Temperatures at the ground surface reached their maximum 2½ hours later as the fire smoldered through the duff and woody fuels, with the highest temperatures recorded at ground surface under the log (971ºF). Surface woody fuels reached maximum temperatures of 590ºF; light surface fuels reached 584ºF. Temperatures dropped off gradually in the surface settings, with recorded temperatures as high as 200ºF as late as 2:00am in the surface log fuels. Temperatures continued to be elevated 44 hours later, still approaching 100ºF.

Subsurface temperatures took 6½ hours to reach their maximum temperatures after the flaming front passed, with log fuels topping out at a fairly low 163ºF and light fuels at 153ºF. The temperature at the subsurface woody fuels location was not recorded due to an equipment failure. Temperatures remained elevated and nearly constant at the subsurface sites (mostly over 100ºF) for the next two days (see the graph on the following page). Average soil moistures dropped to 5.7% at 0-2 inches, and to 16.7% at 2-4 inches. (Interestingly, soil moistures rose at depths between 6 and 14 inches; below this, measurements were not taken.)

The obsidian samples were retrieved two days after the fire had passed over the obsidian study area. Smoldering in the duff was still present. Nearly all surface fuels had been consumed, and a deep ash layer covered the site (see Photograph 4).

A 10-inch diameter log, which had been suspended 18 inches above the ground over the woody fuels location, had fallen to the ground adjacent to the obsidian samples. This log was still burning with a slow, glowing combustion from underneath.

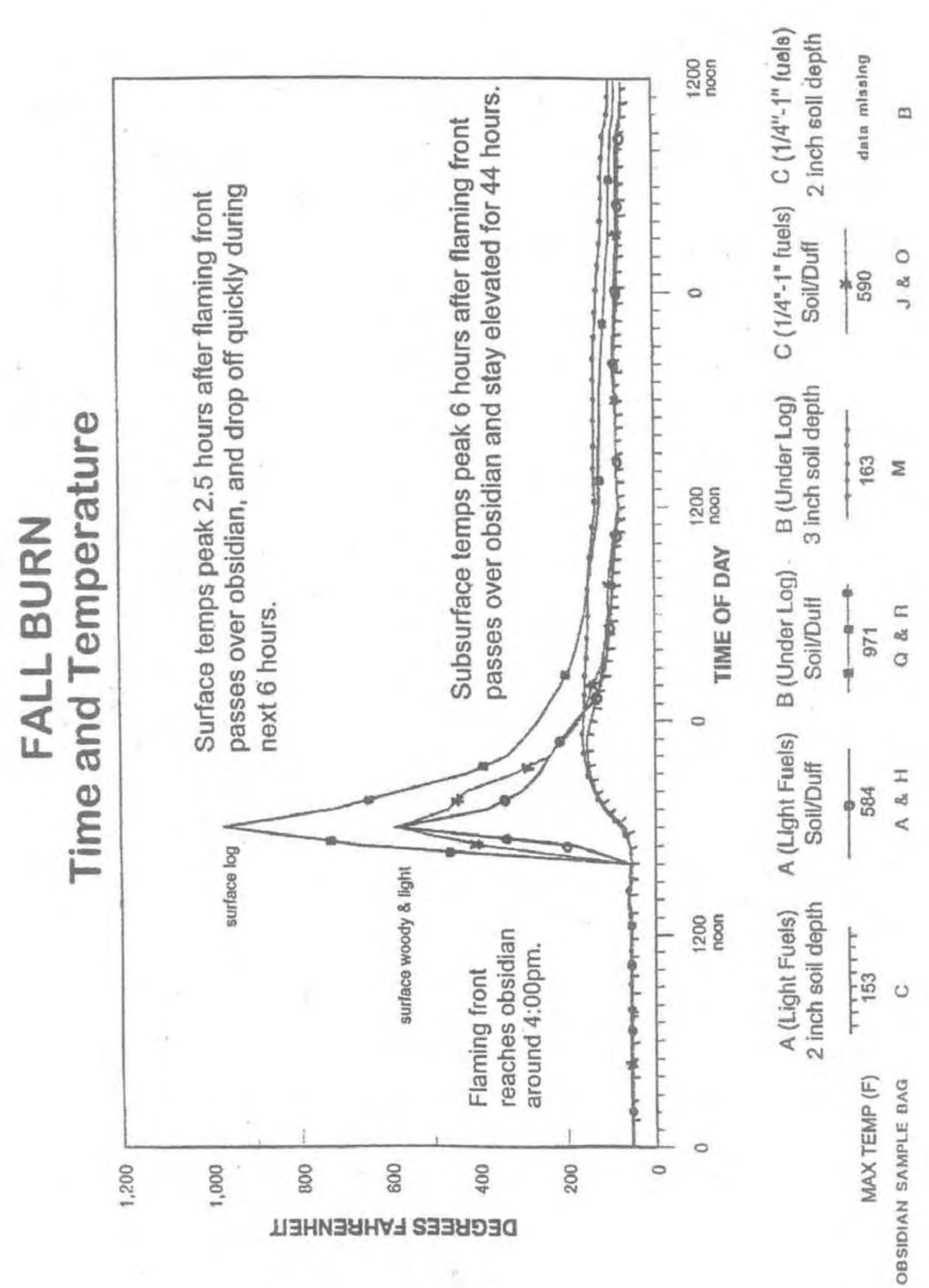
Fall Burn Results

Table 3 shows the results of the fall burn on the obsidian samples. Hydration bands were radically altered on 67% (18 of 27) of the obsidian samples placed in the fall burn. These changes generally resulted in the hydration readings dropping to "zero" (i.e., there was no visible hydration band, or the band was too vague and diffused to read), no matter how thick the original bands were. In the light fuels, 5 of 9 samples were altered (56%). For woody fuels, 6 of 9 (67%) were changed and in the log fuels, 7 of 9 (78%) were affected. The woody fuel samples could have experienced additional effects from the suspended log dropping near the samples, which increased the time of glowing combustion at the site. However, it is not known when the log actually dropped to the ground.

Surface samples suffered the greatest effects, with 14 of 18 (78%) altered. The surface effects might also be inflated by the log drop on woody fuels (all six surface samples in woody fuels dropped to zero hydration band widths); if the surface woody fuels samples had not been affected, the surface percentage affected drops to 44%. For the subsurface obsidian, 4 of 9 samples (44%) were affected. None of the subsurface woody fuels samples were altered, suggesting that the log dropped onto the ground perhaps as long as 12 hours after the flaming front had passed over the obsidian site.

Comments on the Fall Burn

These results were somewhat surprising. We expected to see minimal to no effects on the obsidian, since from a firefighter's perspective, this was a low intensity fire with flame lengths of only one to three feet -- a fire easily contained by a handline around the burn. If California Indians were frequently burning large portions of the landscape, presumably with low intensity fires, how is it that the greater proportion of collected surface obsidian samples produce good hydration readings? Perhaps their frequent, periodic fires substantially reduced ground fuels, and although those fires might behave essentially the same as our fall burn, they would probably have been f shorter duration and much less severe at the ground surface, at least in terms of the glowing and smoldering phase of the fire.



FALL BURN
Time and Temperature
Surface temps peak 2.5 hours after flaming front passes over obsidian, and drop off quickly during next 6 hours.
Subsurface temps peak 6 hours after flaming front passes over obsidian and stay elevated for 44 hours.
surface log
surface woody & light
Flaming front reaches obsidian around 4:00pm.
DEGREES FAHRENHEIT
1,200
1,000
800
600
400
200
0
0
1200 noon
0
1200 noon
0
1200 noon
TIME OF DAY
A (Light Fuels) 2 inch soil depth
A (Light Fuels) Soil/Duff
B (Under Log) Soil/Duff
B (Under Log) 3 inch soil depth
C (1/4"-1" fuels) Soil/Duff
C (1/4"-1" fuels) 2 inch soil depth
MAX TEMP (F)
153
584
971
163
590
data missing
OBSIDIAN SAMPLE BAG
C
A & H
Q & R
M
J & O
B

Table 3. Fall burn results.

Fuel & Burn Situation			**Early Period**		**Middle Period**		**Late Period**	
Fuels probe # – depth maximum temp.	**Bag**	**Elev.**	site # *pre-burn reading*	spec.#/ source *post-burn reading*	site # *pre-burn reading*	spec.#/ source *post-burn reading*	site # *pre-burn reading*	spec.#/ source *post-burn reading*
Light 2 – surface 584°F	A	high	none**		333 ***2.8***	175/B ***0***	263 ***2.3*** 78** ***1.9***	433-n/B ***0*** 300-c/M ***0***
Light 2 – surface 584°F	H	mid	90 ***5.7***	74-aa/N ***0***	415 ***4.0***	610-e/B ***3.9***	199 ***1.0***	303-e/B ***1.1***
Light 1 – 2 inches 153°F	C	low	280 ***4.7***	477-e/B ***0***	50 ***3.4***	34-d/B ***3.4***	167 ***1.0***	268-k/B ***1.2***
Woody 6 – surface 590°F	J	high	36 ***5.1***	589-bb/B ***0***	197 ***3.5***	301-q/B ***0***	274 ***2.0***	406-l/Q ***0***
Woody 6 – surface 590°F	O	low	167 ***4.1***	268-a/B ***0***	211 ***2.6***	307-a/B ***0***	280 ***2.4***	477-b/B ***0***
Woody 5 – 2 inches data missing	B	mid	90 ***4.5***	74-gg/B ***4.4***	368 ***3.2***	571-h/B ***2.8***	319 ***1.4***	590-c/B ***1.5***
Log 3 – surface 971°F	R	low	347 ***4.2***	562-m/B ***4.1***	167 ***3.4***	268-l/B ***0***	228 ***1.1***	584-a/N ***0***
Log 3 – surface 971°F	Q	mid	421 ***4.7***	613-c/B ***0***	90 ***2.8***	74-xx/B ***0***	249 ***1.4***	383-c/B ***1.5***
Log 4 – 2 inches 163°F	M	high	270 ***4.6***	405-a/B ***0***	36 ***3.5***	589-aa/S ***0***	333 ***0.9***	174/B ***0***

Source codes: B = Bodie Hills; M = Mount Hicks; N = Napa Valley; Q = Queen; S = Sutro Springs

Source total: Bodie (22/82%); Hicks (1/4%); Napa (2/8%); Queen (1/4%); Sutro (1/4%)

Fuel situations: 2 bags of samples at ground surface and one bag at 2-3 inches; each fuel situation also had samples from a high, mid-, and low elevation site.

Pre- and post-burn hydration band measurements in microns. Shaded entries mark radical changes.

** *No Early Period sample; two late sites are represented in Bag A*

Spring Burn in Managed Fuels

In order to mimic burn intensities and ground fuel conditions that might have occurred in a forest periodically burnt by Native Americans, the spring burn site was placed in an area that had been prescribe burned several times (in 1978, 1979 and 1985). This area was located at an elevation of 3,670 feet on a gentle slope with a southern aspect in the yellow pine / black oak belt. Dead and down fuels were estimated at four tons per acre (see Photograph 5). Average fuel loading of the forest floor was 21 tons per acre, with fuels at the burn site consisting of less than a half inch of pine needles mixed with a few pine cones, twigs and a few small logs. A well-developed duff layer was not present.

As in the fall burn, a total of 27 pieces of obsidian was placed in the spring burn site, again with nine total sample bags, each with an early, middle and late piece of obsidian from either high, mid- or low elevation sites. These were placed in similar fuels situations -- light fuels (less than one-half inch of pine needle cast), woody fuels (pine needles with ¼ to one-inch diameter twigs and branches) and log fuels (a 4-inch diameter deadfall log). Each fuel situation had a total of nine samples, with six placed on the ground surface and three placed below the surface at depths of 2-3 inches. Some live fuels (bearclover, 6-inch tall oak, bracken fern) were present in the burn plot. At the woody fuels site, pre-burn soil moistures varied from 18% to as high as 30% at 0-2 inches. The log fuels site had pre-burn soil moistures of nearly 20%, while the light fuels site had soil moistures varying from 14% to nearly 18% (Sackett and Haase 1999).

The 16 x 13 foot spring burn plot was ignited at 11:20am on May 17, 1997. Winds were calm, air temperature was 22ºC (72ºF), and the relative humidity was 52%. The fire burned at a rate of six inches per minute, passing over the obsidian samples roughly 20 minutes after ignition, with the last of the flaming front reaching the bottom of the burn plot in 36 minutes. Flame lengths of 3 to 12 inches were reached. The pine needles, cones and ¼ to one-inch fuels were completely consumed by the fire, and overall fuel loads reduced by half. Post-burn soil moistures dropped to between 12% and 20% in the woody fuels location, to 14% in the log fuels location, and between 11% and 16% in the light fuels.

Maximum surface temperatures were reached quickly, with the log fuels peaking at 885 degrees, the woody fuels at 137ºC (279ºF), and the light fuels at 79ºC (175ºF). Field notes on the burn day indicated that by 12:15pm, the surface temperatures were already dropping, but the subsurface temperatures were starting to rise. By 2:30pm, the three surface sites had temperatures of 27ºC (81ºF) in light fuels, 34ºC (94ºF) in woody fuels, and 35ºC (95ºF) in log fuels. Subsurface temperatures were noted at 23ºC (73ºF) in light fuels, 30ºC (86ºF) in woody fuels, and 36ºC (96ºF) in the log fuel site. Near ambient temperatures were reached one hour later, with sample retrieval initiated at 3:30pm. These smoldering, glowing combustion burn times differed radically from the fall burn, with its 80+ years of fuel buildup (see Photograph 6).

Spring Burn Results

The effects on the obsidian burnt in the spring are shown in Table 4. One-third of the spring samples (33% or 9 of 27) had hydration bands that were radically altered, resulting in band readings of zero (not visible), compared to the two-thirds affected in the fall burn. In the light fuels, a surprising 4 of 9 (44%) were changed, possibly due to volatile oils at the burn plot from nearby bearclover or from the relatively new pine needle cast. For woody fuels, only 1of 9 (11%) were substantially altered. In log fuels, 4 of 9 (44%) obsidian readings dropped to zero. Half of the spring surface samples (9 of 18) were altered by the burn. None of the subsurface samples were affected, compared to 44% in the fall burn. All of these figures are lower than those noted in the fall burn in unmanaged fuels.

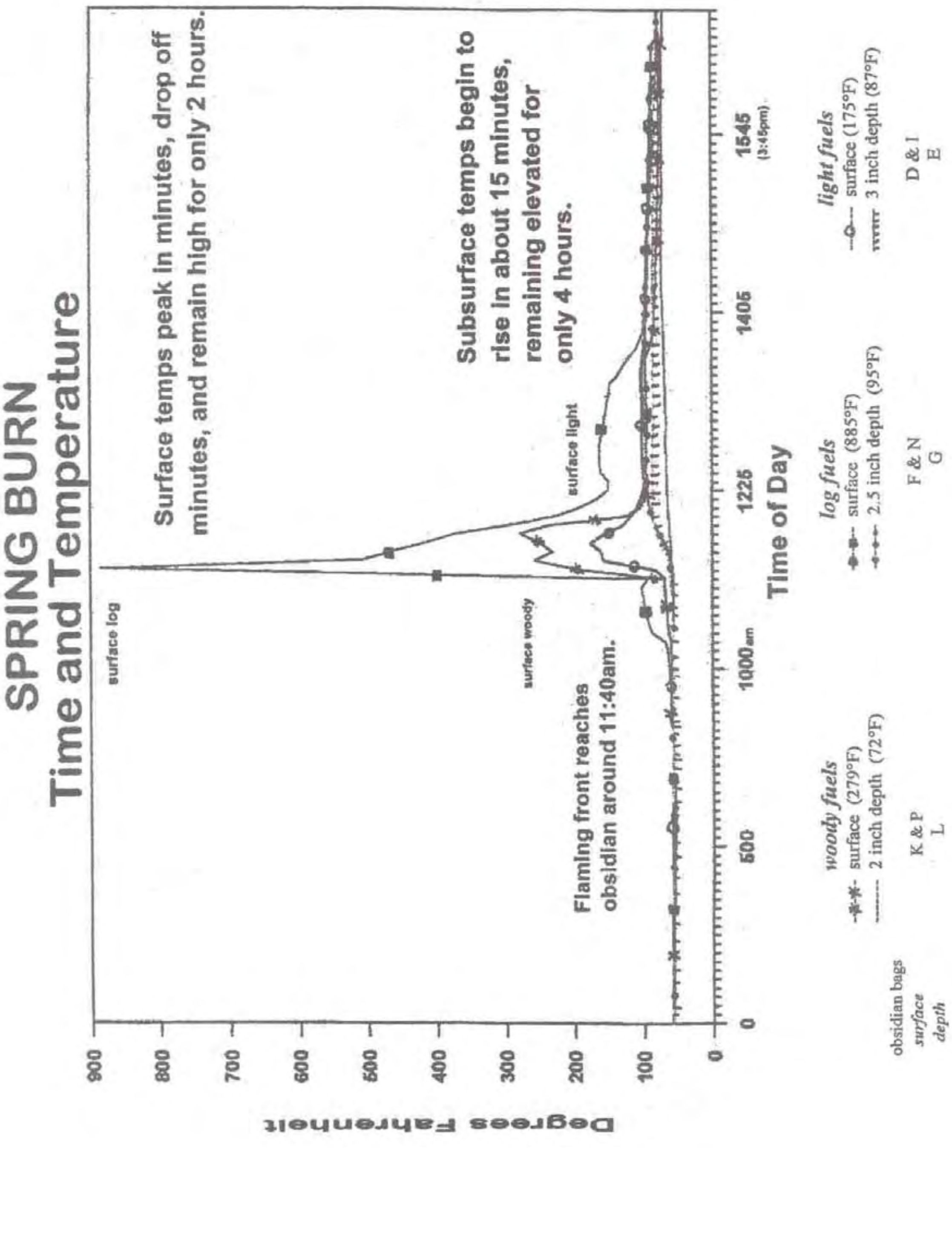

SPRING BURN
Time and Temperature
Surface temps peak in minutes, drop off minutes, and remain high for only 2 hours.
Subsurface temps begin to rise in about 15 minutes, remaining elevated for only 4 hours.
Flaming front reaches obsidian around 11:40am.
surface log
surface woody
surface light
Degrees Fahrenheit
900
800
700
600
500
400
300
200
100
0
0
500
1000am
1225
1405
1545
(3:45pm)
Time of Day
obsidian bags
surface
depth
woody fuels
surface (279°F)
2 inch depth (72°F)
K & P
L
log fuels
surface (885°F)
2.5 inch depth (95°F)
F & N
G
light fuels
surface (175°F)
3 inch depth (87°F)
D & I
E

Table 4. Spring burn results.

Fuel & Burn Situation	Bag	Elev.	Early Period		Middle Period		Late Period	
Fuels			site #	spec.#/ source	site #	spec.#/ source	site #	spec.#/ source
Probe # – depth Maximum temp.			*pre-burn reading*	*post-burn reading*	*pre-burn reading*	*post-burn reading*	*pre-burn reading*	*post-burn reading*
Light 1 – surface 175°F	D	high	333 ***4.1***	176/B ***4.1***	263 ***2.8***	433-e/N ***0***	78 ***1.8***	300-i/B ***0***
Light 1 – surface 175°F	I	low	167 ***4.4***	268-h/B ***4.4***	167 ***2.7***	268-d/B ***0***	50 ***2.5***	34-h/M ***0***
Light 2 – 2 inches 87°F	E	mid	90 ***5.9***	74-a/B ***5.8***	199 ***4.0***	303-b/B ***4.0***	144 ***1.9***	376-a/B ***1.8***
Woody 5 – surface 279°F	K	mid	90 ***4.1***	74-b/B ***4.1***	415 ***4.0***	610-f/B ***0***	249 ***1.3***	383-b/M ***1.3***
Woody 5 – surface 279°F	P	high	197 ***5.4***	301-b/B ***5.3***	274 ***3.8***	406-i/P ***3.8***	197 ***2.5***	301-o/S ***2.4***
Woody 6 – 2 inches 72°F	L	low	167 ***4.6***	268-j/B ***4.6***	356 ***3.2***	548-1/B ***3.2***	280 ***2.0***	477-f/B ***2.2***
Log 3 – surface 885°F	F	low	280 ***4.9***	477-d/B ***0***	279 ***2.8***	476-a/B ***0***	50 ***1.9***	34-c/B ***0***
Log 3 – surface 885°F	N	mid	90 ***4.5***	74-u/B ***4.6***	90 ***2.7***	74-ff/B ***2.7***	415 ***1.9***	610-a/B ***0***
Log 4 – 2 inches 95°F	G	high	263 ***7.7***	433-d/B ***7.5***	78 ***2.6***	300-d/Mg ***2.6***	274 ***2.4***	406-k/B ***2.4***

Source Codes: B = Bodie Hills; M = Mount Hicks; N = Napa Valley; Q = Queen; S = Sutro Springs; Mg = Mono Glass Mountain; P = Pine Grove Hills

Source Total: Bodie (21/78%); Hicks (2/7%); Napa (1/4%); Sutro (1/4%); Mono (1/4%); Pine Grove (1/4%)

Pre- and Post-burn hydration band measurements in microns. Shaded entries mark radical changes.

Comments on the Spring Burn

The effects of the spring burn were less in all fuel load situations, both in surface and subsurface contexts, than they were in the fall burn. Temperatures of 22ºC to 474ºC (72ºF to 885ºF) were within the range of those present in the fall. In both the fall and spring burns, the flaming front crossed the obsidian study areas in approximately 10 minutes. The major difference between the spring and fall burns was in the length of time each area remained in a smoldering, glowing phase of combustion. Where the fall burn site smoldered at elevated temperatures for several days, the spring burn site maintained elevated temperatures in the range of four to five hours. This difference in the length of time the obsidian was exposed to heat most likely accounts for the difference in effects between the two burns.

Comments on Both Burns

Every fire has a number of microenvironments within the burn which will affect fire behavior, including differences from one portion of the fire to another in the condition of the fuels (size and shape, moisture content, temperature, compactness and arrangement, continuity, chemistry), wind speed and direction, eddies in wind current, slope, and aspect. A change in any one of these might create different effects to particular obsidian samples from one study spot to another (i.e., woody fuels versus light fuels locations). Potential variations were minimized, however, by placing the specimens in a geographically restricted area (generally all within six feet of each other), and by the fact that the flames burnt over the study plots in roughly 10 minutes, limiting the time in which environmental conditions such as moistures and wind speeds could change. Variables present in both the fall and spring burns -- soil chemistry, roots, volatile oils, rocks (which might block or radiate heat) -- were not controlled for, and may have affected the results.

At least one aspect of the design of our experiment -- the equal distribution of samples to each of the three fuels situations -- would probably not occur in fires on sites in a natural setting. In general, in natural conditions, an area with less ground fuels would have reduced opportunities for artifacts to be situated under downed logs and woody debris. Likewise, in an area where fuels are heavy, fewer opportunities would exist for obsidian to be located under light fuels. Distributing the obsidian samples equally among all three fuels types (light, woody, and log) may therefore skew the interpretive potential of our results.

Although this experiment was only designed to quantify alterations in hydration readings, several macroscopic changes were noted on 74% of our samples. These included the presence of a light sheen or luster, often on only one face of the specimen; a light “pitting” of the surface of some of the obsidian; and the presence of adhesions on the samples. These changes were noted on specimens placed in all three fuel contexts (light, woody and log fuels), on obsidian subjected to temperatures ranging from 31ºC to 522ºC (87ºF to 971ºF) for varying lengths of time, and on specimens placed on the soil surface and to depths of three inches.

Implications for Interpreting Fire Histories and Determining Past Fuel Loads

This study was conducted with a limited number of samples in only two prescribed burns. Although our results are similar to other studies where effects increased as temperature and length of exposure increased (see Deal 1999), additional studies are needed to better understand the parameters of those effects, particularly for prescribed fire. For instance, there are likely to be other components of the fire environment, such as wood ash, soil chemistries or soil moistures, that are mitigating or contributing to observed effects. Even so, these results bring forward some interesting questions which have implications for ecosystem management: Can surface obsidian data suggest past fuel conditions? Can this data be used to reconstruct fire histories? Is this data consistent with the ethnographic record concerning Native American burning practices and historical landscape conditions?

Native American Burning and Historic Landscape Conditions

Native Americans shaped the landscape on a large scale, particularly through the use of fire (MacCleery 1994; Martinez 1993; Pyne 1982), which MacCleery (1994) points out as a fact contrary to popular images of the past:

> There is no question that enormous areas of the forests and grasslands we inherited (or invaded and stole, if you wish) were very much cultural landscapes, shaped profoundly by human action…. Indian use of fire as a management tool changed in profound ways the entire ecology of the forest and the plant and animal communities associated with it…. In fire-prone ecosystems in the West, Indian burning created an element of ecosystem stability that would not have existed without it (MacCleery 1994).

The degree to which Native Americans manipulated the local ecosystem of the Pacific District area is not known, but is expected to have been fairly extensive. Indians throughout California frequently set fire to areas to maintain montane meadows and increase forage, particularly for deer, whose numbers can increase by 400% in areas that have been burned (Taber and Dasmann 1957, cited in Mellars 1976:22). Other objectives of burning included clearing areas around habitations to watch for strangers and dangerous animals; facilitating travel and hunting; driving game; improving wild seed crops and maintaining populations of edible bulbs and tubers; improving certain characteristics of plants used in basketry; maintaining or enhancing the distribution of oaks; killing insects and pests; and maintaining springs and surface waters (Anderson 1992a, 1992b, 1993; Anderson and Moratto 1996; Biswell 1967; Kroeber 1925; Lewis 1973; MacCleery 1994; Matson 1972; McCarthy 1993; Mellars 1976; Wickstrom 1987; Shipek 1993; Sterling 1904; Williams 1993). However, when queried today on why their ancestors burned areas of the forest, the reason mentioned most often by California Indian elders in a recent study was the prevention of large, devastating fires (Anderson 1993b:25). Estimates for the number of acres burned annually in the state from both lightning and Native American ignitions range from 5.6 to 13.2 million (Smith et al. 1994:9), with the vast majority of acreage burned attributable to Native American burning practices. (During the last 80 years, far less than a million acres per year have burned in prescribed or wildland fires in California [Arno 1996:3]).

This deliberate setting of fires would have created an open landscape with less underbrush and an even spacing between trees. Small patches of vegetation in varying successional stages would be scattered throughout the forest (see Kilgore 1981:59). Shade intolerant species would have been favored over those that are shade tolerant, with pine (which is fire tolerant) increasing at the expense of incense cedar and fir, which are not fire tolerant (Johnston n.d.; McKelvey et al. 1996:1033; Pilles 1982:2; Warner 1980:91). Black oak stands would have been more extensive, as would some populations of grasses and annuals used as staple plant foods (Matson 1970:147). Meadows would have been expanded or maintained by fires, which prevented conifers from encroaching into them.

Fires continued to be set by the ranchers who moved into the Sierras in the mid- to late 1800s. Sheepmen set fires to facilitate the movement of flocks and the growth of browse (Sterling 1904); dairy ranchers to increase forage in pastures. Setting of fires by sheepherders was so prevalent, in fact, that travel in the late 1800s was often hampered in autumn by dense smoke (Johnston n.d.). The incidence of destructive stand-replacing forest fires in the late 1890s brought the first attempts to suppress fires, to protect both watersheds and valuable timberlands.

Several fire histories derived from trees located on the Pacific Ranger District in the yellow pine / black oak belt and in the red fir zone (Ferrell 1994; Gethen 1993, 1994, 1994b and Rice 1983) strongly support the presence of wide-scale, deliberate burning in the past. The oldest fire scar found in these studies dates to 1676, or just over 300 years ago. Average fire return intervals in the yellow pine / black oak belt were found to be from 6 to 7 years; in the red fir zone, average fire return intervals were 12.8 years. These studies indicated that the prehistoric frequency of lightning fires alone could not account for fire occurrence in the areas studied, with lightning ignitions only matching the number of fires expected in the area once fire suppression policies were enacted. Additionally, since low intensity fires can burn without injuring new wood in trees, fire frequencies based on fire scars may be too conservative (Biswell 1989:55), hinting that fires might have been present in the environment even more frequently than indicated by these studies (cf., Lewis 1980).

Low fuel loads, and the removal of ladder fuels by the frequent setting of fires, would make it unlikely that many large-scale stand-replacing fires occurred during the management of the land by Native Americans (McKelvey et al. 1996:1035; Anderson and Moratto 1996:196-202; Skinner and Chang 1996:1042). This may be further supported by the fact that numerous pieces of surface obsidian have been collected from the forest with measurable hydration bands.

Using Obsidian to Determine Past Fuel Loads

We know from fire-scarred trees across the Pacific District that fires were occurring in the past at frequent intervals, thus providing numerous opportunities for obsidian to have been altered by fire. Yet, when tallied from sites and isolated finds across the District, more surface and near-surface obsidian returns readable hydration bands than unreadable (91% vs. 9%). This implies that few if any hot, catastrophic fires, or long, smoldering fires occurred in those areas where the obsidian was found, possibly due to reduced fuel loads in and around the locations where the obsidian was deposited. Since fuels build up naturally in forested environments, we can assume that fuels were being reduced by periodic prescribed fires deliberately ignited by Indians or left to (safely) burn after lightning strikes. Assuming for the moment that this is true, can obsidian data be used to assess how long this sort of managed fuels reduction was occurring on a landscape scale?

In order to explore this possibility, we looked for the oldest surface hydration date (i.e., the thickest hydration band as measured in microns), for individual locations (in this case, archaeological sites and isolate locations) where surface obsidian hydration data was available on the Pacific District. We then assigned a *tentative* chronological date to the micron readings (see Table 5), with each one-tenth micron reading assigned a numeric value representing years before present (which might be thought of as relative dates, rather than absolute ones). Next we plotted the dates back to their location on the Pacific District (Table 6 and Figure 2). The dates indicated in Figure 2 could possibly indicate the amount of time that has transpired since an intense stand-replacing, high temperature fire, or a long duration smoldering fire, has occurred at each location. In fact, hydration might still be present on obsidian from these sites precisely *because* they were located in areas subject to frequent, periodic fires with very restricted fire residence times, resulting in low fuel loads.

Our experiment showed an increased tendency for obsidian hydration to be altered with increased smoldering times common with heavier fuel loads, particularly when obsidian was on the ground surface. Given that frequent fires were known to be occurring over the District, that any piece of surface obsidian could be altered in any one of those fires, and that much of the data in Figure 2 spans several thousand years, the proposition that these lands were managed by deliberate burning for an extended period of time is strengthened. One alternative scenario might be that hydration is present on obsidian at the locations in Figure 2 because people did not deliberately burn the places where they lived or worked. If this were so, over time, after specific areas were no longer used and fuels increased at the sites, it would be expected that fires from the surrounding terrain would easily spread into them and alter the obsidian hydration. Securing additional hydration readings from isolates, many of which were presumed to be lost or discarded away from habitation areas, might offer further insights regarding this possibility.

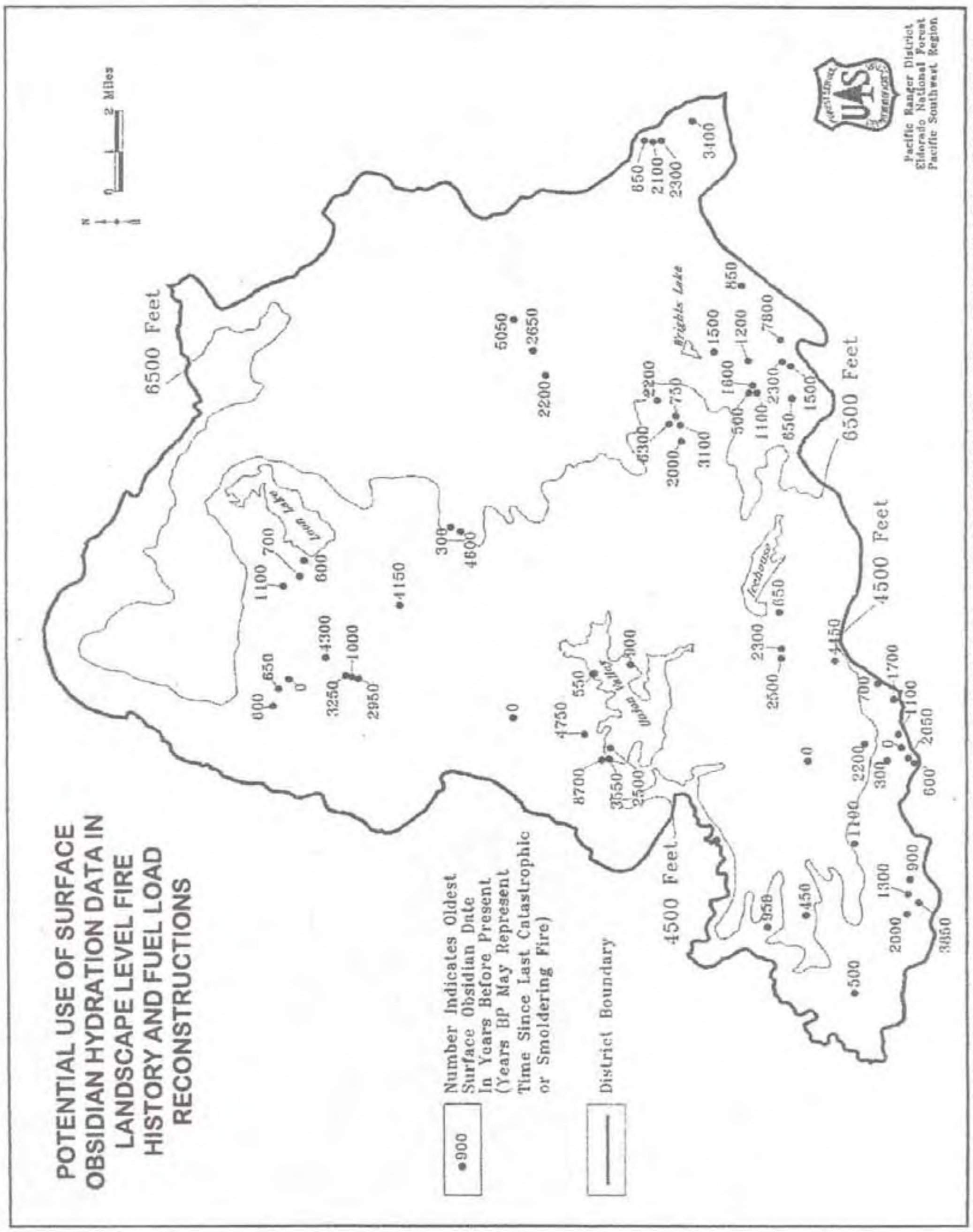


FIGURE 2. CONJECTURED YEARS BEFORE PRESENT SINCE A HIGH INTENSITY FIRE OR A SEVERE SMOLDERING FIRE HAS OCCURRED AT SPECIFIC LOCATIONS ACROSS THE PACIFIC DISTRICT.

Table 5 Tentative hydration band time conversions.

Late Sierran (200 –1000 BP)		Middle Sierran (1000 to 2500 BP)		Early Sierran (2500+ BP)			
micron reading	**years before present**	**micron reading**	**years before present**	**micron reading**	**years before present**	**micron reading**	**years before present**
0.9	200	2.6	1100	4.1	2650	6.5	6500
1.0	250	2.7	1200	4.2	2800	6.6	6600
1.1	300	2.8	1300	4.3	2950	6.7	6700
1.2	350	2.9	1400	4.4	3100	6.8	6800
1.3	400	3.0	1500	4.5	3250	6.9	6900
1.4	450	3.1	1600	4.6	3400	7.0	7000
1.5	500	3.2	1700	4.7	3500	7.1	7100
1.6	550	3.3	1800	4.8	3700	7.2	7200
1.7	600	3.4	1900	4.9	3850	7.3	7300
1.8	650	3.5	2000	5.0	4000	7.4	7400
1.9	700	3.6	2100	5.1	4150	7.5	7500
2.0	750	3.7	2200	5.2	4300	7.6	7600
2.1	800	3.8	2300	5.3	4450	7.7	7700
2.2	850	3.9	2400	5.4	4600	7.8	7800
2.3	900	4.0	2500	5.5	4750	7.9	7900
2.4	950			5.6	4900	8.0	8000
2.5	1000			5.7	5050	8.1	8100
				5.8	5200	8.2	8200
				5.9	5350	8.3	8300
				6.0	5500	8.4	8400
				6.1	6100	8.5	8500
				6.2	6200	8.6	8600
				6.3	6300	8.7	8700
				6.4	6400		

Note: These "time" conversions are only tentatively assigned an absolute value herein as an example of how hydration data might be used to aid in landscape reconstructions. The "time" before present, as plotted on Figure 2, might best be thought of as "micron years", or as years BP relative to each other. In either case, the data spans many thousands of years.

Several other things might affect the interpretation made here; for instance, any given piece of obsidian could have been underground, protected from the effects of fire, and brought to the surface more recently by burrowing rodents, or tree throw, or some other agent. The more samples with readable hydration bands from surface contexts at a particular location, the greater the confidence that the site was not subjected to smoldering or hot, stand-replacing fires. Although not quantified here, some of the sites shown in Table 6 did produce numerous obsidian hydration dates, thus increasing the confidence level for these particular areas. In any case, Figure 2 is provocative: the plotted dates, taken together, support the notion that fuels were being managed across the landscape for thousands of years. This conclusion is consistent with findings in ethnobotanical research regarding the length of time burning has been used for managing vegetation used as basketry materials (see Anderson 1999).

This hydration/mapping exercise serves as one example of how hydration data might be used on a landscape-level to aid in reconstructing fire histories and past fuel load conditions. And, if it holds that hydration data can be used as an indicator of the absence of heavy fuel loads or large fires in the past, then this sort of data is extremely valuable in providing information that goes well beyond the temporal limit of several centuries inherent in dating fires from tree cores.

Using Obsidian to Date Past Fire Events

Elevated temperatures apparently force resident moisture on exposed surfaces "into" obsidian, creating a wide, diffused band with unreadable or blurred margins (Jackson, personal communication, 1997; Trembour 1990*)*. Whether obsidian can rehydrate following exposures to high temperatures, and the rate at which the obsidian rehydrates, if it does at all, is currently under investigation by the Eldorado National Forest as a follow-up to this study, and by Tom Origer and his colleagues at Sonoma State University. At least one researcher has suggested that past fire events are recorded on obsidian in the form of re-established hydration bands, stating that the:

> ". . . diffusion effects of a high heat experience in obsidian are eventually 'recovered' from by a lengthy period at normal conditions where a semblance of [a] 'normal' rind is re-established in time" (Trembour 1990:177-178).

Should Trembour's statement be found to be true under natural field conditions, that is, the original hydration band would become re-established over time, then using obsidian hydration to reconstruct fuel loads or fire histories as discussed in the last section could prove less useful, unless other markers of fires are present on the obsidian.

Some obsidian previously collected from archaeological contexts has returned wide, unreadable, diffused bands, with a second distinct, readable band retained on the surface of the object (Jackson, personal communication; Origer, personal communication, 1997), suggesting the possibility that this obsidian has rehydrated after an event such as a fire, which led the initial hydration band to become unreadable and diffused. In the case of diffused bands, labs usually note their presence, but provide a micron reading on the distinct, thinner, secondary hydration band, if one is present. This micron reading is then generally taken to indicate the age of manufacture of the artifact (which, because of the thinner band, would return a younger date than the original date of manufacture). For instance, one site on the Pacific District produced 16 surface samples with diffused bands, each with a second readable band - this second band provided the micron reading returned from the lab. However, if it can be shown that obsidian *does* rehydrate after a fire, then the thickness of the second, readable band would likely mark a past high intensity fire event, rather than a past cultural (manufacturing) event. Additional research is needed to more precisely identify what the markers of fire are on obsidian.

Table 6. Pacific District sites and isolates with hydration data.

Site/Isolate Number	Maximum Reading	Tentative years BP	Site/Isolate Number	Maximum Reading	Tentative years BP
36	3.7	2200	263	7.8	7800
50	3.5	2000	270	4.6	3400
78	2.6	1100	274	3.8	2300
85	--	--	275	3.6	2100
87	5.5	4750	276	1.8	650
90	8.7	8700	279	2.8	1300
96	--	--	280	4.9	3850
113	4.3	2950	283	1.5	500
127	2.7	1200	284	1.7	600
136	2.4	950	289	5.2	4300
143	1.7	600	290	5.3	4450
144	1.9	700	292	2.6	1100
146	4.5	3250	296	1.5	500
153	2.3	900	302	5.7	5050
165	1.8	650	309	2.2	850
167	4.1	2650	319	1.6	550
169	1.7	600	333	4.1	2650
172	2.6	1100	334	4.0	2500
174	3.1	1600	340	3.8	2300
178	2.3	900	347	1.9	700
197	5.4	4600	356	3.2	1700
198	1.1	300	368	3.7	2200
199	5.1	4150	369	--	--
210	3.0	1500	378	1.8	650
211	2.6	1100	415	4.0	2500
228	1.1	300*	421	4.7	3550
240	3.5	2000	427	2.5	1000
248	4.4	3100	Isosate-181	1.8	650
249	2.0	750	Isolate-231	--	--
255	6.3	6300	Isolate-232	1.4	450
259	3.8	2300	Isolate-233	1.2	350
261	3.0	1500	Isolate-238	3.7	2200

Note: *The micron readings are from surface finds only, and represent the thickest (i.e., oldest) micron readings from each surface context, converted to a tentative date in years before present (BP). For surface obsidian with two cuts, the thinner (youngest) reading was reported, based on the assumption that the material might have been scavenged from an older site prior to its deposition where it was found.*

Management Implications

It has been estimated that in the last 85 years, between 8.5 and 17 fire cycles have been missed in Sierran ponderosa pine stands due to fire suppression, from 4.3 to 10.6 fire cycles in mixed-conifer stands, and 1.3 to 5.7 fire cycles in Sierran red fir (United States Department of Agriculture 1995:3-73). These lost fire cycles represent a tremendous fuel buildup in Sierran forests, with a resultant increase in fire intensity and severity (United States Department of Agriculture 1995:3-73-99). Locations outside of managed fuels areas are now at great risk of increased resource damage when wildland fires occur. Since fire suppression activities result in the greatest disturbance to sites, and consequently the greatest loss of data, it is imperative that we work toward removing fuels to reduce these effects. Minimally, fuels should be reduced on sites themselves, to reduce data loss through burning or suppression activities.

Our experiment shows that prescribed burning will result in some predictable data loss to obsidian bearing readable hydration bands, particularly when located on or near the surface. If prescribed burns are planned in areas that have not had prior fuels management projects, these losses can be anticipated to be the greatest. However, if fuels can be reduced on sites prior to burning, either through hand removal of downed fuels or thinning via hand or mechanical means when appropriate (see Jackson 1993; Jackson et al. 1994), then this data loss is reduced. Often, however, fuels are so dense that the nature or even presence of surface artifactual materials is unknown. Collecting surface samples prior to burning (if even possible in dense fuel situations) would secure the data that could be affected by the prescribed burn.

Conclusion

This experiment helps to meet an expedited compliance process agreed upon between the California State Historic Preservation Office and Region 5 of the USFS, which called for continued research into the effects of prescribed burning. The experiment not only generated data regarding the effects of burning on obsidian, but also applied that data toward ecosystems management issues such as past fuel loads and fire histories. Given that increased ground fuels equate to increased smoldering time and increased data loss, the results of this experiment point to the merits of removal of fuels from sites, prior to the occurrence of a smoldering fire, a high-intensity fire, or large-scale suppression activities.

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Photograph 1. Fall burn fuels condition. Twenty-seven obsidian samples were placed in the fall burn study site in an area where no recorded wildland fires or prescribed burns had occurred. The woody fuels samples were placed under the suspended log on the right, the log fuels samples were placed under the small fallen log in the center, and the light fuels samples were placed under the duff on the left side of the frame. Forceps were used to place the obsidian in order to minimize disturbance to fuels.

Photograph 2. Thermocouples were placed into the soil by the obsidian samples to monitor soil temperatures. A cable led from the thermocouples to a datalogger, located outside the fireline. The datalogger was set to record temperatures at the obsidian samples at designated time intervals.

Photograph 3. Fall burn sample locations, all in flames. Light fuel samples are to the left underneath the duff, log fuel samples are in the center under the small fallen log to the right of the stump, woody fuel samples are beneath twigs and branches underneath the suspended log on the right.

Photograph 4. Fall burn, 40 hours after flames burned across the obsidian study site. Obsidian samples placed in light fuels were near the pin flag on the left, obsidian in log fuels were near the pin flag at the center, and woody fuels samples were underneath log to right. The log at the log fuels sample location was completely consumed, and the suspended log overhanging the samples at the woody fuels site had dropped to the ground, where it continued to smolder from underneath. The ground was still hot two days after ignition when the obsidian samples were retrieved. The obsidian was then resubmitted to the lab for hydration measurements.

Photograph 5. The spring burn study site was located in an area where the fuels had been previously reduced (in 1978, 1979 and 1985) using prescribed fire. Twenty-seven obsidian samples were placed in the spring burn study site, using the same procedures as in the fall burn.

Photograph 6. Fire burning over spring burn samples (located near pin flags). Light fuels obsidian samples are in the center background, woody fuels samples are near the center of the photo, and log fuels samples are situated under the small logs in the right foreground. Obsidian samples were retrieved later in the day.

THE TRENCH CANYON PRESCRIBED BURN: AN ANALYSIS OF FIRE EFFECTS ON ARCHAEOLOGICAL RESOURCES WITHIN THE SAGEBRUSH STEPPE COMMUNITY TYPE

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Abstract

Prescribed fire is becoming a common tool on Public Lands to manage fire behavior, fuel loading and vegetation community associations. The effects of this management practice on archaeological resources are of concern. This paper will focus on the effects of a prescribed burn on the hydration birefringent rim of obsidian artifacts. In particular, this analysis addresses the differential effects of fire within three quantified fuel zones within late seral Great Basin sage (Artemisia tridentata ssp. tridentata) and upland sagebrush steppe community types.

Introduction

Wildfires and prescribed burns in forested habitats have been shown to cause significant impacts to archaeological resources (Anderson and Origer 1997; Deal and McLemore 1997; Jackson 1997; Lentz et al. 1996; Trembour 1990). Impact levels are highly variable and are mainly related to fuel types, densities, fire intensity and duration. As prescribed fires are increasingly used as a tool in ecosystem management, continuing research is needed to quantify the potential effects of such management fires on cultural resources.

While some investigations have been concluded in forested habitats (Connor et al. 1989; Deal 1997; Duncan 1990; Eininger 1990; Lentz et al. 1996) very little research has been reported from analyses conducted in the sagebrush steppe ecotype. One exception is Green et al. (1997) who reported on prescribed fire analyses within the upland sagebrush steppe community type, dominated by mountain big sage (*Artemisia tridentata* ssp. *vaseyana*). Research of fire effects on cultural resources has been focused on post fire assessments with little pre-fire control data. Controlled analyses need to be conducted to objectively evaluate and quantify fire impacts on cultural resources.

This paper provides an assessment of the effects of prescribed burning, under controlled conditions, on cultural resources in the Trench Canyon area located within Mono Basin, Mono County, California (Figure 1). The burn area is on public lands administered by the Bureau of Land Management, Bishop Field Office. Five archaeological sites were recorded during an archaeological investigation of the project area in 1997. These sites consist primarily of obsidian flaked stone assemblages and, to a lesser degree, ground stone material.

It has been shown that freshly exposed surfaces on obsidian nodules or artifacts, such as those caused during the manufacture of tools, begin to absorb water, which diffuses into the interior resulting in the formation of a microscopically visible birefringent front or hydration band (Skinner and Thatcher 1998). Through time, the front penetrates deeper into the artifact providing an indicator of the age of the exposed surface. In the Inyo-Mono region, obsidian hydration has become an extremely important analytical tool for assessing a site's chronological attributes and can provide important information regarding questions as far ranging as hunter-gatherer mobility, exchange, technology, subsistence and changing land-use patterns. For cultural resource management purposes this dating method can be used as an index to evaluate a site's significance and potential eligibility for the National Register of Historic Places (NHPA). It has been shown that moderate to high intensity fires can negatively affect the measurable hydration rind on an artifact causing a vague to unreadable diffusion front (Origer 1996).

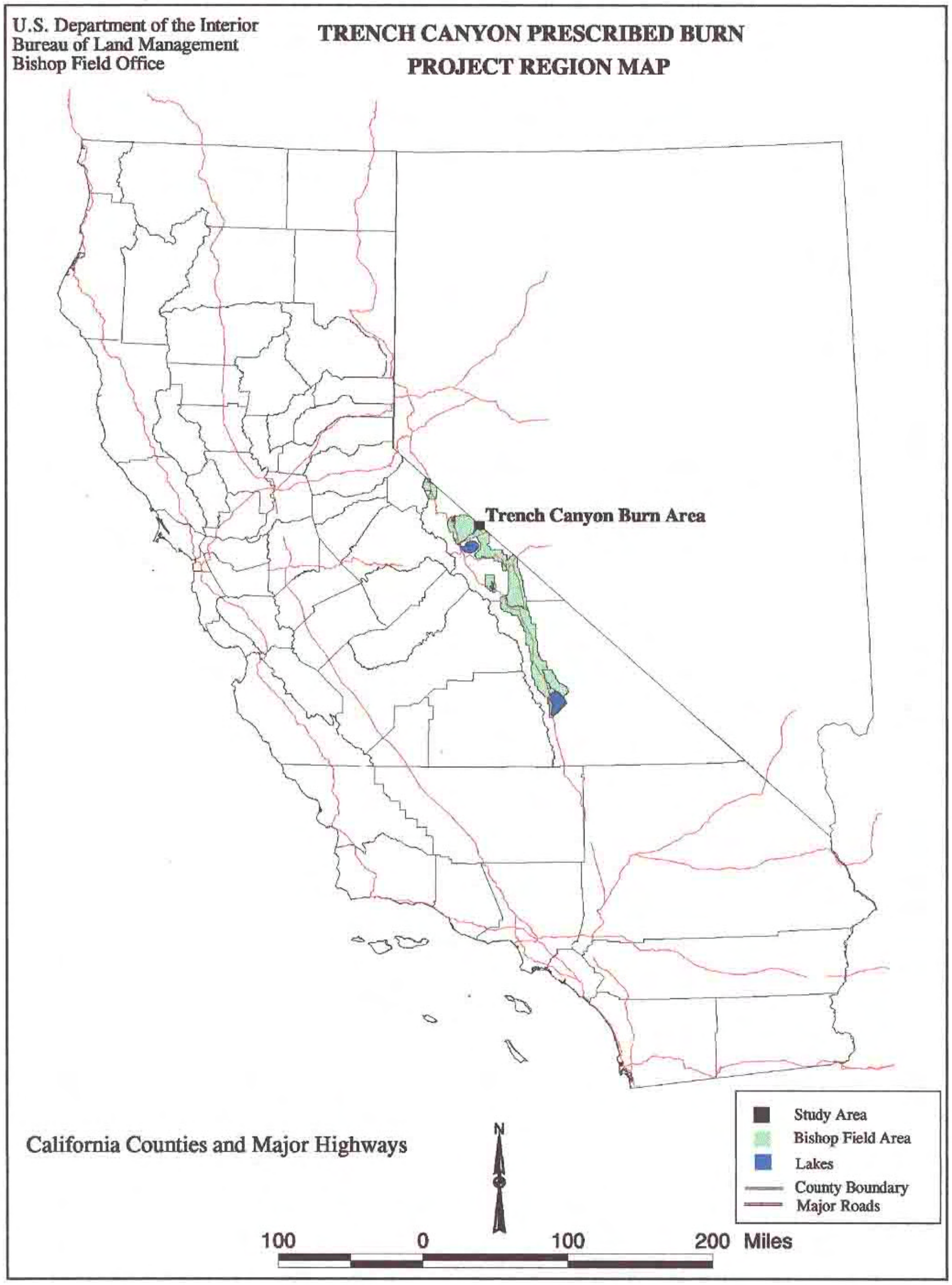

Figure1. Project region map.

This analysis is focused on one prescribed fire event within a sagebrush steppe habitat and addresses the effects of this event on obsidian flaked stone artifacts. The emphasis is on the differential effects of fire, within the variable fuel types in the project area, to the hydration diffusion front on obsidian artifacts. To assess the impacts, a control test of six 1 m^2 test plots was conducted. Test plots were placed within three quantified fuels types, i.e., heavy, moderate and light. A sample of 180 obsidian artifacts that had been previously subjected to hydration analyses was selected. Each plot was set up with a sample of 30 artifacts, 10 each at the 0 cm, 5 cm, and 10 cm levels.

A fire prescription was developed to reduce the high density of Great Basin sagebrush (*Artemisia tridentata* ssp. *tridentata*) in the project area. This vegetative component is suppressing the regenerative potential of the native perennial grass understory primarily comprised of Great Basin wild rye (*Leymus cinereus*). To aid in prescription development, weather conditions were collected for one year utilizing a Remote Area Weather Station (RAWS). These data were employed to develop the final parameters (e.g., temperature, wind speed, fuel moisture, etc.) under which the prescribed burn should be conducted. The vegetation goal of this project is to restore a sagebrush-grass mosaic into a site dominated by dense, monotypic stands of sagebrush and subsequently increase the compositional and structural diversity to the site.

Great Basin wild rye (*Leymus cinereus)* is generally considered to be well adapted to fire (Mason 1981; Sheeter 1968; Stubbendiek et al. 1986). Crowns have coarse stems that tend to insulate perennating buds located at, or just below, the ground surface. As a result, the majority of plants survive fire to become components of the post-burn plant community. Surviving plants sprout from basal buds, and in some ecotypes, from rhizomes (Wright et al. 1965). Some post-fire seedling establishment is also expected to occur. To increase the positive effects of post-fire regeneration of Great Basin wild rye, the fire was timed to occur during periods of plant dormancy. Fall is documented to be the most optimal time to achieve rapid recovery of this species (Vallentine 1961; Wright et al. 1982; Zschaechner 1985).

Questions directing the assessment of the effects of fire on obsidian artifacts, under the prescription developed for Trench Canyon, include:

- What are the impacts of prescribed burning within the sagebrush steppe habitat on prehistoric archaeological resources, with a focus on obsidian artifacts?
- What are the differential effects between low, moderate and high density fuel zones?
- What are the differential effects of fire between surface and subsurface artifacts?
- Do fires within the sagebrush steppe ecotype significantly impact the data potential of prehistoric archaeological resources rendering determination of NHPA eligibility difficult?

Based on previous research, it is hypothesized that prescribed fire within the Trench Canyon sagebrush steppe habitat will not adversely affect the data potential and significance of prehistoric flaked stone assemblages located on the fringes of the heavy fuel zone. It is predicted that no subsurface artifacts will be affected in the low and moderate fuel zones (as described below), while a loss of up to 70% of the hydration rinds is expected to occur in the 0-5 cm level in the heavy fuels. This analysis will test these hypotheses with a goal to facilitate archaeological survey strategies and management prescriptions for controlled burns in the similar vegetation types in the future.

Previous Fire Studies

Previous fire effect studies have been conducted under wildfire, controlled and laboratory conditions (see Deal 1997; Jackson 1997 for overviews). The conclusion is that the two most important variables affecting obsidian hydration are fire intensity and duration. In general, hot fires (> 260˚C) will have an adverse effect on the hydration band, but low intensity fires which occur for long durations can also have negative effects. Smoldering roots, stumps or duff have been shown to affect artifacts, and temperature maximums may occur well after the fire has burned through an area leaving hot, smoldering ground litter (Deal 1997:7; Deal and McLemore 1997). The threshold for the loss or diffusion of the birefringent front begins at about 260˚C (500˚F) and is seriously affected at 427˚C (800˚F) (Deal 1997; Green et al. 1997). The main effect on obsidian hydration is that the birefringent front expands causing a diffuse and unreadable hydration band (Rob Jackson, personal communication 1998; Deal 1997; Origer 1996). Burned specimens often show macroscopic surface alterations such as spalling, sooting, weathering and may take on a waxy chatoyance (Jackson 1997; Origer 1996).

The most adverse effects to obsidian hydration occur to artifacts on the surface where temperatures as high as 7051˚C (13001˚F) have been recorded in the chaparral and subsurface temperatures can reach excesses of 931˚C (2001˚F) (Hull n.d.:21-22), though temperatures generally are significantly lower under prescribed fire conditions. Fuel loading, vegetation type and topography are some of the key variables affecting a fire's intensity. Surface fuels, such as duff and pine needles, will carry fire along the ground causing increased soil temperatures and result in increased subsurface temperatures which can adversely affect hydration readings. But various studies show that artifacts below 5 cm show only moderate effects from fire (Anderson and Origer 1997; Deal 1997). Artifacts below 10 cm show no measurable effects (Anderson and Origer 1997; Reynolds 1998).

The Research Area

The Trench Canyon study area is located along the California/Nevada border (Figures 1 and 2) in the northeast corner of Mono Basin, Mono County, California. Mono Basin is a structural depression formed at the base of the eastern piedmont of the Sierra Nevada Range. During the terminal Pleistocene (~35,000-12,000 B.P.), the hydrographically closed basin was inundated by pluvial Lake Russell (present day Mono Lake) which covered an ~650 km^2 area and reached elevations as much as 200 meters above the current lake level of 1,944 meters (Grayson 1993; Stine 1990). Remnant lake shores flank the project area. Today, Mono Lake covers an area of roughly 180 km^2. Trench Canyon is a small, remnant embayment of ancient Lake Russell, characterized by well developed sand dunes formed of aeolian lake deposits. The project area is within a level to sloping basin (0-15% slope) with a south/southwest aspect at an elevation of approximately 2,074 meters. The soils consist of Quaternary lake and aeolian deposits, characterized by clayey soils in the basin fringed by the dune and gravely lake shore deposits. It is on the dune complexes, on the perimeter of the basin, that the archaeological sites occur (Figure 2). Average precipitation ranges from 20-30 cm, and the dominant vegetation includes Great Basin sagebrush (*Artemisia tridentata* ssp. *tridentata*), Great Basin wild rye (*Leymus cinereus),* needle and thread grass (*Hespirostipa comota*) and annual and perennial buckwheat (*Eriogonum)* species. Great Basin sagebrush, which dominates the basin, reaches heights up to two meters with canopies spreading one to two meters in diameter and bases up to 20 cm in diameter.

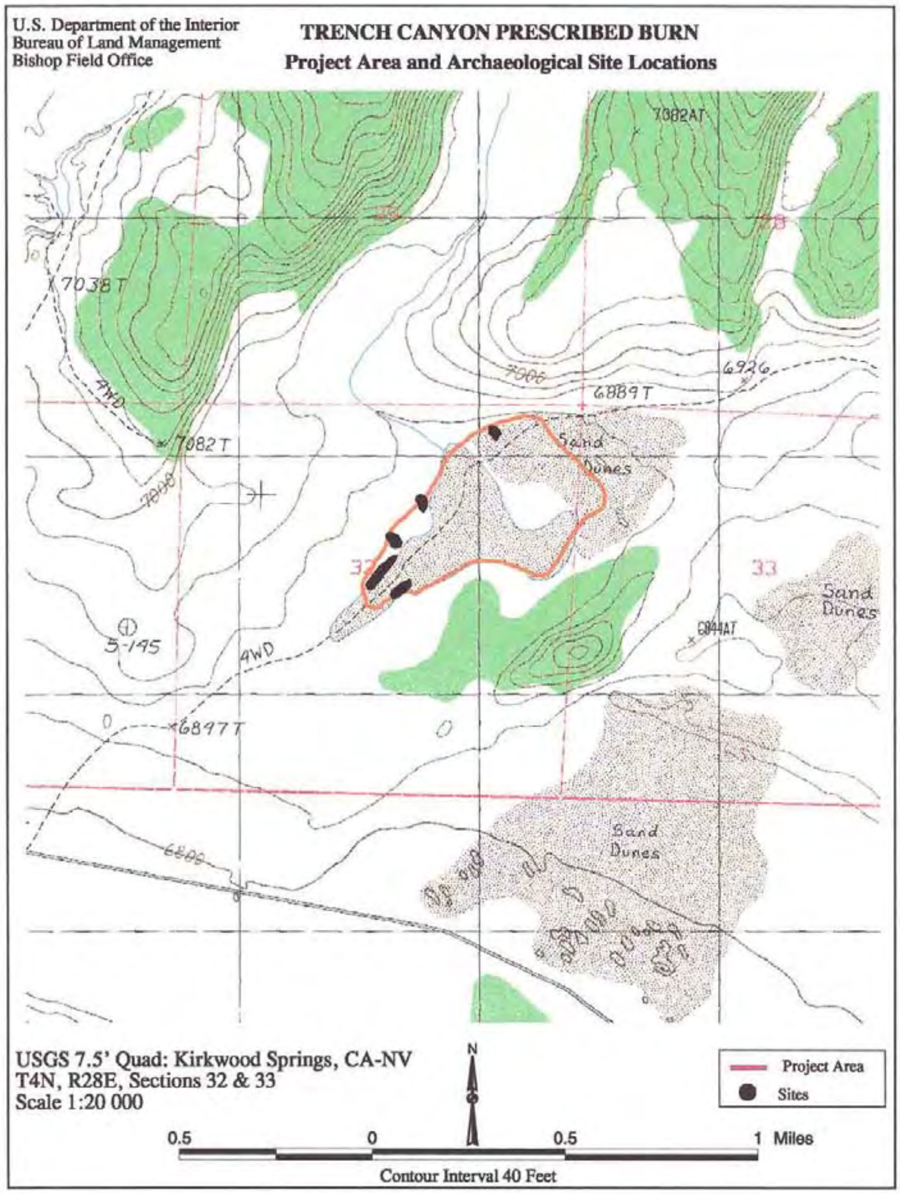

Figure 2. Archaeological site locations

Trench Canyon Archaeological Evaluations

A Class III archaeological inventory was conducted in the project area in 1997. Five prehistoric sites were recorded, all located in the dune areas on the fringe of the basin (Figure 2). The sites range in size from 1,508 m^2 (97-29-S3) to 5,655 m^2 (97-29-S6). The sites consist primarily of obsidian flaked stone assemblages. The flaked and tool stone profiles indicate that mid and late stage biface thinning were the main reduction activities at the sites. Ground stone material occurs in small proportions (i.e., ≤ 3 items) and are ephemeral in nature, with grinding surfaces showing limited use wear. Active aeolian sand deposits suggest that subsurface remains may occur, but during test plot setup no subsurface deposits were encountered.

Forty-five obsidian toolstone and flaked stone specimens were submitted to the Northwest Research Obsidian Studies Laboratory (Skinner and Thatcher 1998) from the project area. Of these, 25 specimens were subjected to X-ray fluorescence (XRF) and all 45 to hydration analyses. Two samples were submitted from site 97-29-S1, thirty from 97-29-S3, three from 97-29-S4 and ten from 97-29-S5. The XRF analyses identified the representation of five sources in the sample, dominated by Mt. Hicks, which is located in the closest proximity to the project area to the northeast (Mt. Hicks n=20 (80%), Bodie Hills n=2 (8%), Casa Diablo (Lookout Mtn.) n=2 (8%), Silverpeak n=1 (4%)). The hydration analyses provide a range of readings from 3.2 to 12.2 µm (mean= 4.8 µm, SD=2.1 µm). The majority (67%) of the hydration readings fall in the 3.0 to 3.9 µm range. These data, along with a few diagnostic points (n=3, 1 Rosegate [4.4 and 3.5 µm], 1 Elko form? [6.1 µm], 1 dart stemmed form? [7.7 µm]), indicate that the project area was visited by hunter-gatherer groups from the Paleo-Indian to the Haiwee periods (ca.12,000 to 650 B.P.), with the most prevalent period of use during the Newberry/Haiwee interface (ca. 1,350 B.P.). The high frequency of sites in the project area and the temporal dimensions indicated by the hydration analyses suggest that the Trench Canyon area provided an important resource patch for hunter-gatherers moving through the area.

Methods - Fuel Types

The study area can be classified, in a broad sense, as a brush-dominated fuel group, fitting into "Fire Behavior Fuel Model 6" (Anderson 1982:9), with 100 (1-3" diameter) and 1,000 (> 3" diameter) hour fuels. One hour (< ¼") and 10 hour (1/4-1") fuels are also prevalent. This group was further separated into three sub-types. To determine the three quantifiable fuel sub-types that occur within the study area, a total of six 25 meter transects was established within vegetation zones that exhibited heavy (dense), moderate and low fuel cover. Vegetation and duff (litter) cover was then measured using the Line Intercept Method (Canfield 1941), which measures cover intercepts along the course of a line (tape). Foliage and basal cover are derived using this method. Fuel categories were then determined based on the following criteria: Heavy fuel types were those areas that contained 60-100% shrub cover (*Artemisia tridentata* ssp. *tridentata* and *Chrysothamnus naueseosus).* Moderate fuel types contained 20-60% shrub cover and low fuel types contained less than 20% shrub cover (see Table 1 and Figures 3 and 4).

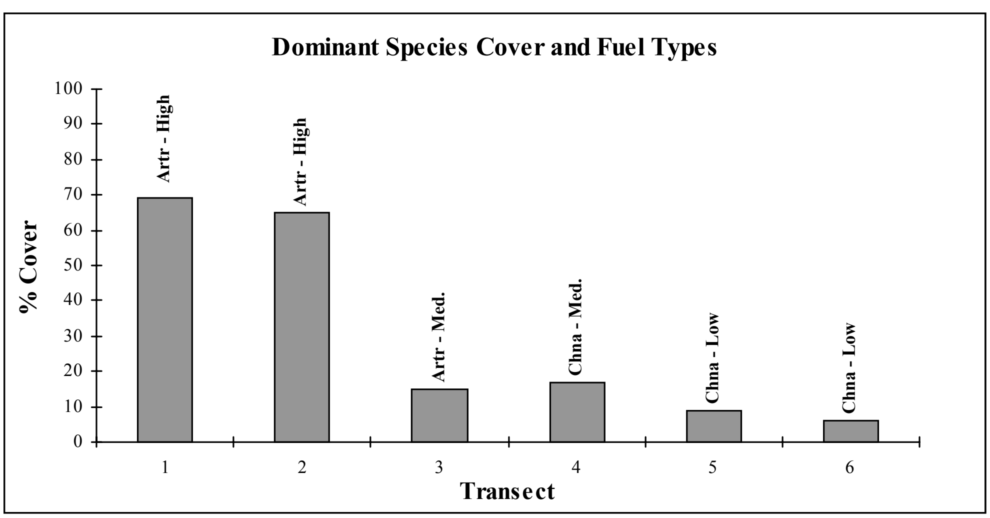

Figure 3. Dominant species cover and fuel types.

Table 1. Dominant species within the heavy, moderate, and light fuel types.

Transect	Plant Species	Fuel Type	% Cover
1	*Artemisia tridentata* ssp. *Tridentata*	Heavy	**69**
2	*Artemisia tridentata* ssp. *Tridentata*		**65**
	Acnatherum hymenoides		0.02
	Leymus cinereus	Heavy	0.004
3	*Artemisia tridentata* ssp. *Tridentata*		**15**
	Chrysothamnus nauseosus		**9**
	Eriogonum davidsonii		4
	Achnatherum hymenoides		3
	Lupinus purshii		1
	Leymus cinereus	Moderate	0.2
4	*Chrysothamnus nauseosus*		**17**
	Achnatherum hymenoides		7
	Artemisia tridentata ssp. *Tridentata*		**4**
	Eriogonum davidsonii		0.2
	Leymus cinereus	Moderate	0.02
5	*Chrysothamnus nauseosus*		**9**
	Achnatherum hymenoides		5
	Hespirostipa comota		4
	Eriogonum davidsonii		0.04
	Leymus cinereus	Light	0.08
6	*Hespirostipa comota*		8
	Chrysothamnus nauseosus		**6**
	Artemisia tridentata ssp. *Tridentata*		**5**
	Achnatherum hymenoides	Light	1
	Leymus cinereus		1

Shrub species percent cover values are in bold-face type.

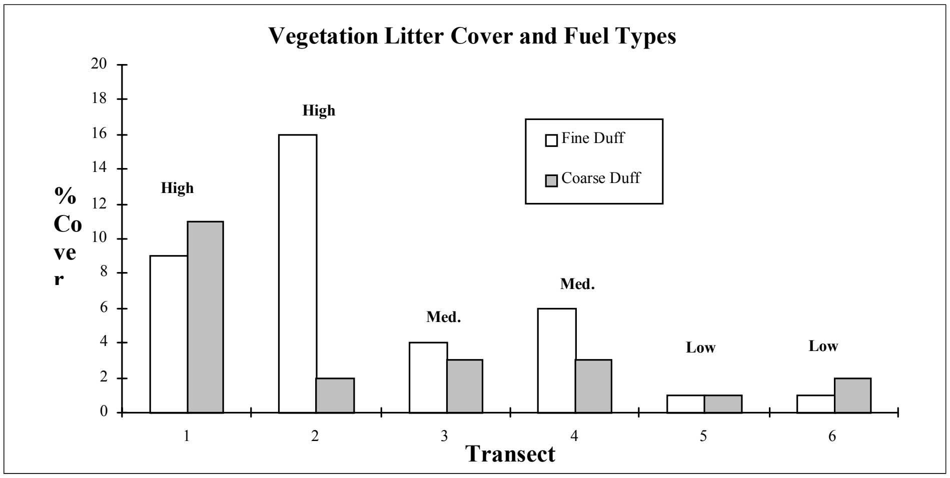

Figure 4. Vegetation litter cover and fuel types.

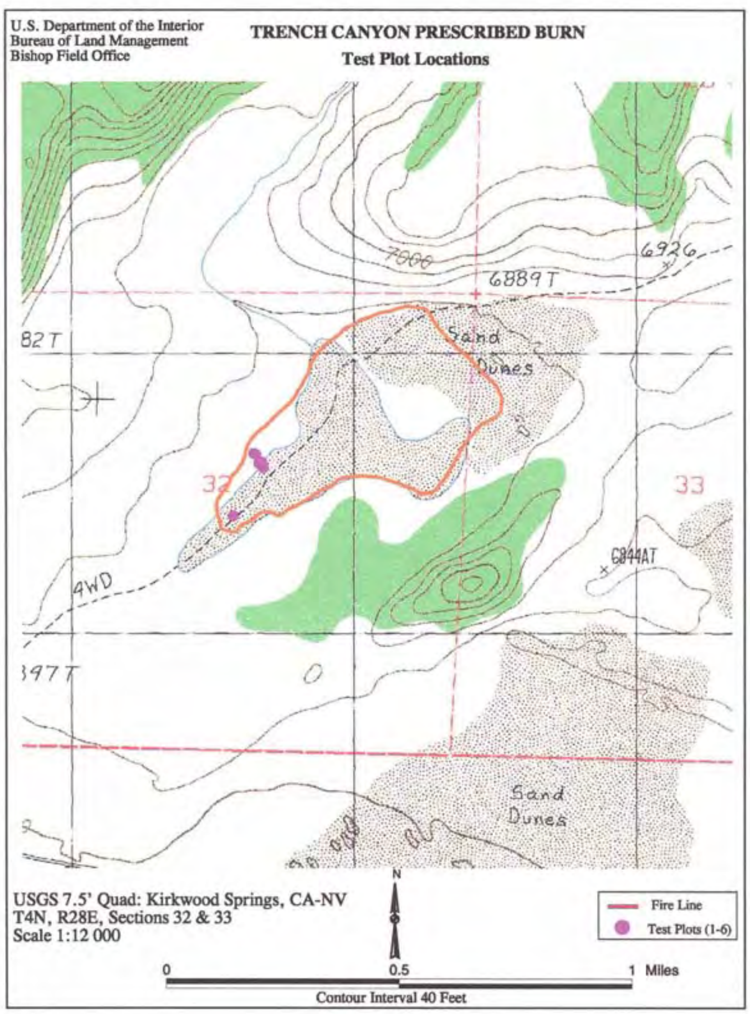

Figure 5. Test plot locations.

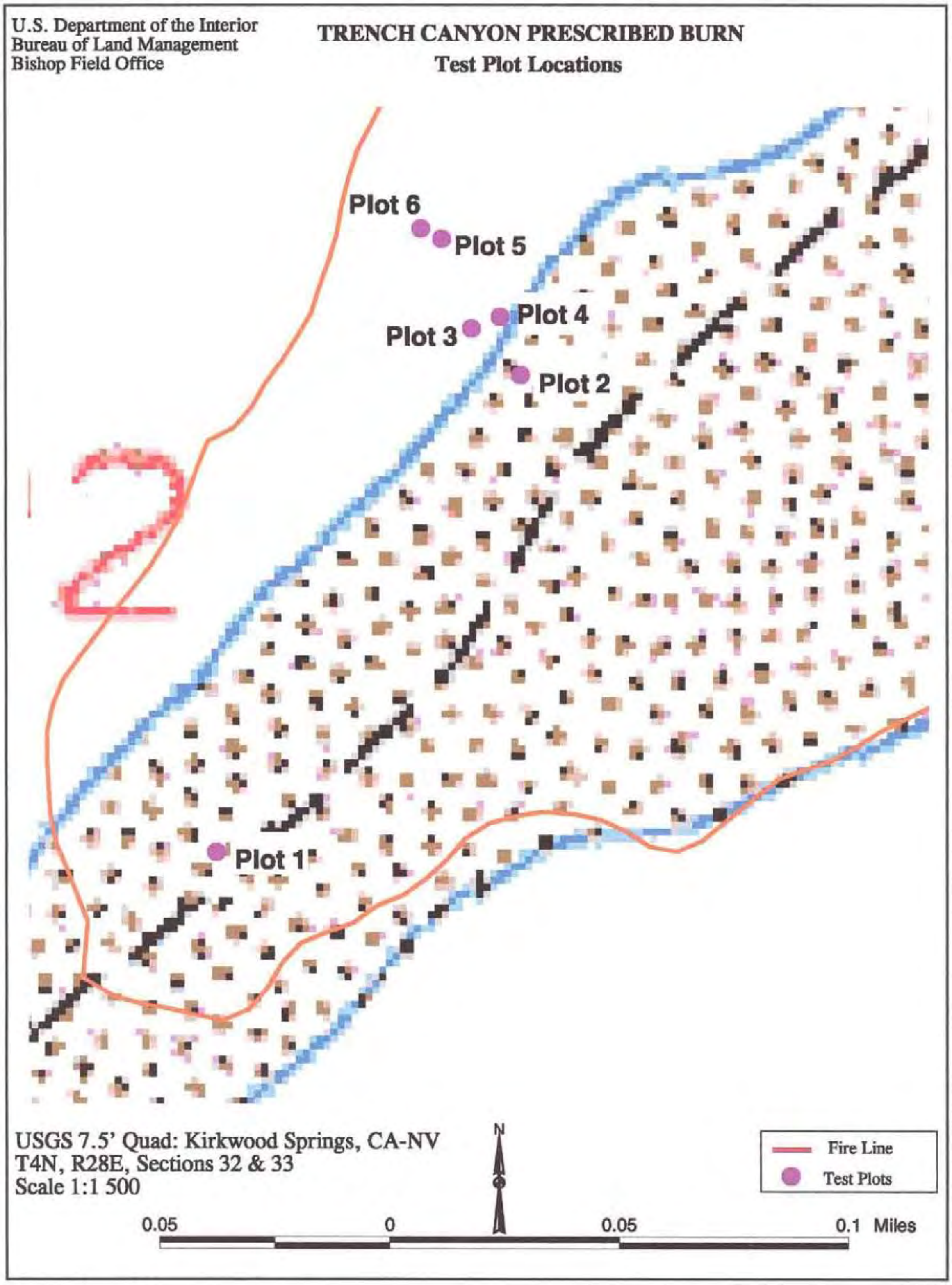

Figure 6. Test plot locations

Obsidian Artifact Analyses

To test the research hypotheses, a sample of 180 obsidian artifacts was distributed in the burn area within six one-meter square test plots (Figures 5 and 6). Pre-burn obsidian hydration analyses were conducted by Pacific Legacy (specimens 1-140) and the Northwest Obsidian Research Laboratory (specimens 141-180). Each artifact was photocopied to facilitate post burn recovery. Thirty samples were distributed within every plot with ten each at the 0 cm, 5 cm, and 10 cm levels (Figure 7). Test holes were excavated to 10 cm using an 8 cm diameter soil plug remover. Samples were arranged in three rows beginning from the northwest corner of the plot and placed numerically in a west to east sequence (Figure 7). Two plots each were placed within the three fuel types. Rebar designated the northwest corner of the plot. Each plot was mapped using a GPS unit on phase processor mode providing submeter accuracy. All plots were set up one day prior to the burn.

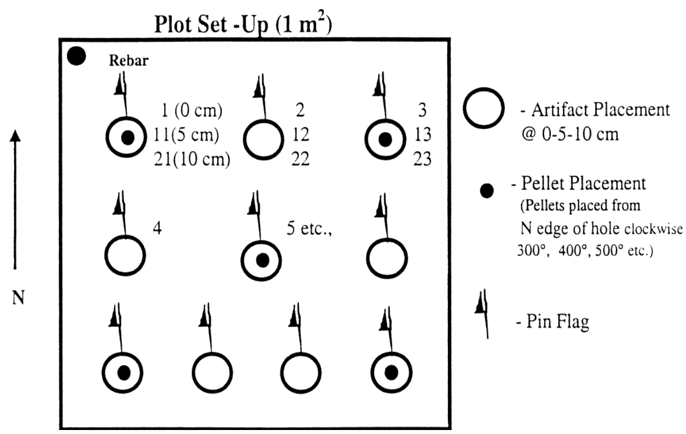

Figure 7. Plot set-up.

Temperature measuring devices used to determine the fires heat intensity included Omega temperature pellets ranging from 149˚C (300˚F) to 843˚C (1550˚F) (Table 2). Each pellet was placed in a stainless steel cup and then situated in the northwest, northeast, center, southwest and southeast holes with the artifacts located in the center (Figure 7). Pellets were arranged with the 149˚C (300˚F) pellet situated on the north edge of the hole, and the remainder of the pellets distributed in a clockwise direction around the fringe of the hole. Table 2 shows the range of pellets utilized and their vertical placement. Three hundred degree centigrade (572˚F) and 204˚C (400˚F) pellets were placed in each level; 260˚C (500˚F), 316˚C (600˚F), and 482˚C (900˚F) pellets were placed from 0-5 cm; 649˚C (1200˚F) and 843˚C (1550˚F) pellets were placed only on the ground surface. A close range of pellets around 260˚C (500˚F) was employed (i.e., 149˚C, 204˚C, and 316˚C) due to previous studies which indicate that 260˚C (500˚ F) appears to be the threshold at which the hydration rind is initially affected with serious effects occurring around 427˚C (800˚F) (Deal 1997; Trembour 1979). An Omega HH 12 dual input handheld digital thermometer with a 1093˚C (2000˚F) range was used to record real time temperatures in Plot 1. Two 1260˚C (2300˚F) thermocouple elements were placed, one each, at the 0 cm and 5 cm levels in the center of the plot. Two hundred and fifty feet of thermocouple wire, with a sheath rating of 200˚C (392˚F), was laid at least 10 cm below the surface and strung along the fire break/road to the west end of the burn area where readings were collected every 30 seconds as the fire reached Plot 1.

A RAWS unit was placed at the study area one year prior to the burn. Data were collected hourly at the station and downloaded via satellite into data tables accessible by computer. Temperature, wind speed and direction, relative humidity and fuel moisture were monitored and utilized by the Bishop Field Office fire managers to develop a prescription for the Trench Canyon burn. Prescription parameters and burn day data are summarized in Table 3 and discussed in the following section.

Table 2. Temperature measuring devices.

Omega Pellets (˚F)	**Color**	**Placement**
149˚C (300˚F)	Orange	0-10 cm
204˚C (400˚F)	Dark Green	0-10 cm
260˚C (500˚F)	Light Blue	0-5 cm
315˚C (600˚F)	Dark Red	0-5 cm
482˚C (900˚F)	Lime Green	0-5 cm
649˚C (1200˚F)	Yellow	0 cm
843˚C (1550˚F)	Purple	0 cm

* Omega HH 12 digital thermometer, 1093˚C (2000˚F) range, dual input.

* XC-24-K-12, 12”, 1260˚C (2300˚F) thermocouple elements.

* EXFF-K-24, 500’ of 24 gauge thermocouple wire with 200˚C (392˚F) sheath rating.
SMP-K-MF, thermocouple connectors rated to 218˚C (425˚F), with waterproof sleeves.

Results - The Burn Day

The prescribed burn was conducted late in the fall on November 20, 1998, by a Forest Service fire crew. On November 19, during plot setup, it was noted that in the early morning the ground was covered with heavy frost, and soils were frozen down to 10 cm in the Plots 1 and 2 within the heavy fuel zone. Table 3 summarizes the parameters developed for the fire prescription and burn data collected from the RAWS. As detailed in the table, burn day conditions did not fully fit within prescription parameters. Two key variables, wind speed and fuel moisture, were not within prescription. The fuel moisture for the 10 hour fuels, which can be equated with the smallest plants of the Great Basin sagebrush which dominates the project area, were four times (24.3%) above the prescribed percentage (6%).

The burn day was clear and cold in the morning with high cirrus clouds moving in over the Sierra. Burning began at 10:45 a.m. on the northeast edge of the project area within moderate and light fuel zones. A team of 10 firefighters using drip torches began a strip burn procedure. Due to the low wind speed and the disperse nature of the fuels, the fire was unable to carry. As a result, the fire needed to be carried by hand with burners lighting individual bushes as they moved in a line from east to west. Due to a lack of success in the moderate to light fuels, the burners moved into the heavy fuels at 1200. In the heavy fuel zone, the fire reached a hot enough intensity to completely consume much of the large brush and ground litter, but the fire crew was still compelled to carry the fire front by hand. By 1400 the relative humidity began to rise causing the fire intensity to become much reduced and fire crew assisted burning was halted by 1530.

Table 3. Trench Canyon prescribed burn: fire prescription.

Scheduling				**Burn Day**	
Total Burn Area Size	100 Acres			30 Acres	
Season	Fall			11-20-98	
Time of Day	0700-1300			1100-1500	
Acceptable Prescription Range					
	Low	**High**	**Desired**	**Low (time)**	**High (time)**
Temperature (°F)	50	80	70	10.0 (0638)	56.0 (1338)
Relative Humidity (%)	15	30	20	9.0 (1338)	61.0 (0638)
Night Time Recovery (%)	20	70	50	32.0 (1738) (11-19-98)	61.0 (0638)
Mid-flame Wind Speed (mph)	8	20	10	2.0 (1138)	7.0 (1338)
Wind Direction	SW			SSE	SSE to SSW
Fuel Moisture (%)				**During Burn**	
1 Hour Fuels (< ¼” diameter)	4	5	4	6.1 (1338)	8.4 (1538)
10 Hour Fuels (¼-1” diameter)	4	6	4	24.3 (1438)	24.7 (1138)

Of the 100 acres scheduled for burning, 30 acres were successfully ignited (Figure 8). During the most intense period of the burn (at 1300), flame lengths reached heights of 15 feet, and most fuels were fully combusted. The fire was carried through test Plots 2-6 at 1340 and reached Plot 1, at the northwest end of the project area, at 1407, by which time the fire’s intensity had begun to decrease dramatically. During the peak period of the fire, the heavy fuels (i.e., Great Basin sagebrush) burned hot and fast, with each bush burning intensely for roughly three minutes consuming all of the leafy branches leaving only remnant bases and smoldering roots. The fire left a mosaic effect with islands of fully consumed vegetation interspersed with partially burned and unaffected islands. Roots and bases of Great Basin sage continued to smolder through the following day. Stands of rabbitbrush were fully consumed and burned with a flashy, high intensity. In general, fuels within the project area can be classified as flashy fuels which burned for short periods of time, but with a fairly high intensity. Fire in the moderate to low fuel zones had to be carried from plant to plant to effect any type of combustion.

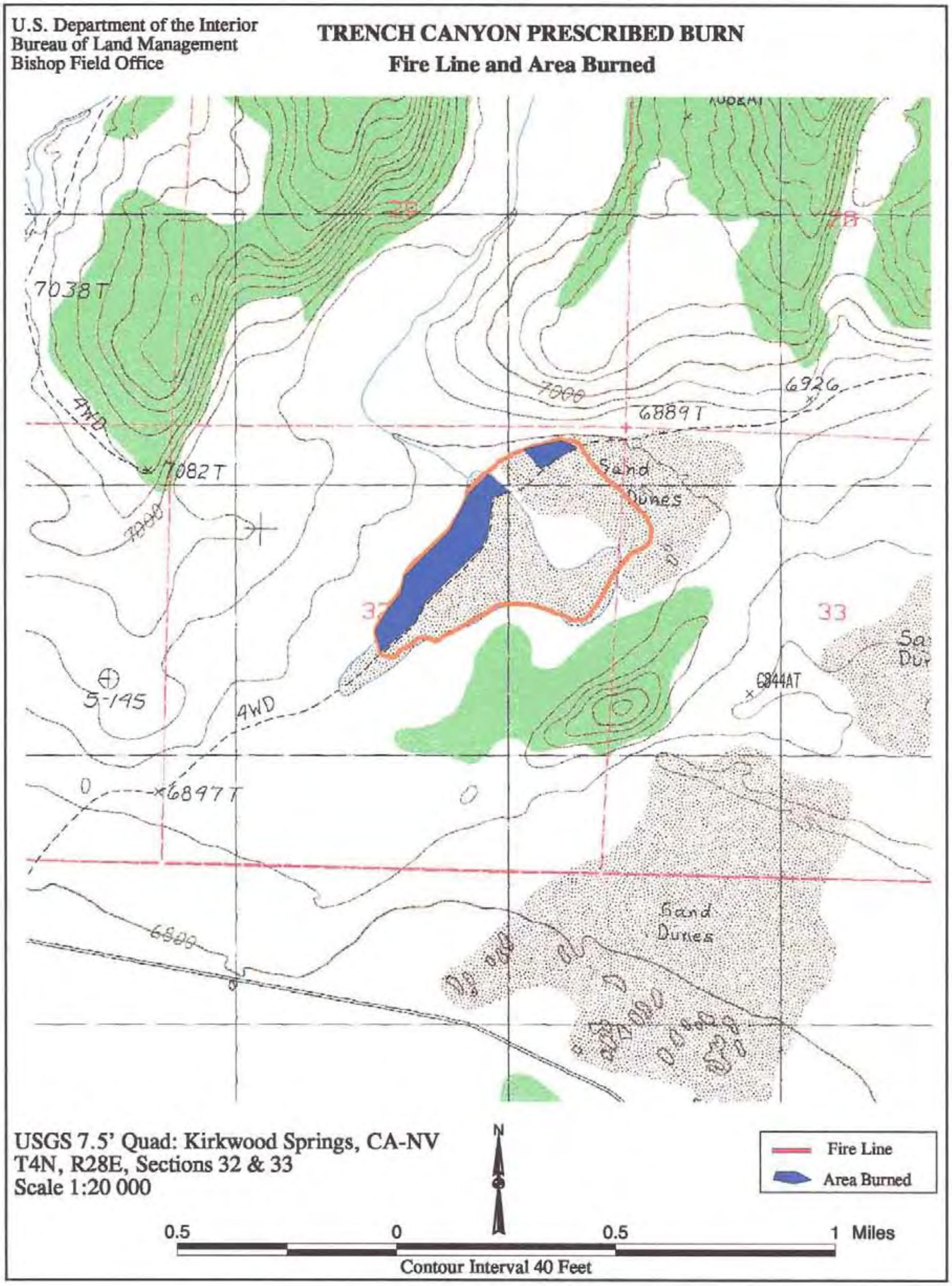

Figure 8. Fire line and area burned.

Real time, surface and subsurface, temperature data were collected in Plot 1 using the Omega HH 12 handheld digital thermometer. Beginning at 1407, when fire reached the plot, temperatures readings were collected every 30 seconds for 25 minutes. These data are presented in Figure 9. Surface temperatures reached their peak within three minutes, at a maximum of 85.2˚C (185.4˚F), and dropped steadily indicating the flashy nature of the fuels. Within 13 minutes, temperatures leveled off to near pre-ignition readings. Subsurface (5 cm) readings averaged 6.2˚C (43.2˚F) with minor fluctuations. At 5530 an upward spike indicates that subsurface temperatures were beginning to rise slightly as a result of heat conductance through the sandy soils. In general, these data indicate low fire temperatures in the vicinity of Plot 1 resulting from rising relative humidity and cooler ambient air temperatures that were occurring by 1400. These factors, coupled with low wind speeds, kept the big sage in the vicinity of Plot 1 from fully igniting and only reaching low temperatures.

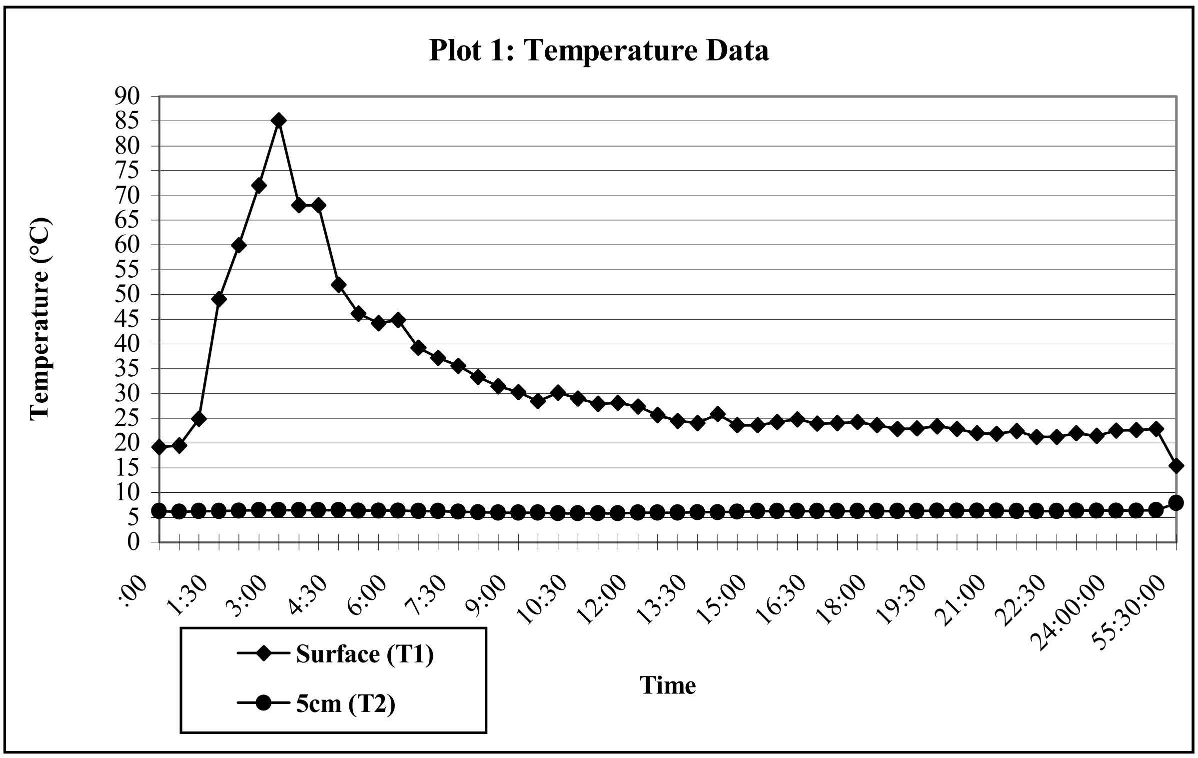

Figure 9. HH12 digital thermometer temperature data from surface and subsurface (5 cm) thermocouples placed in plot 1.

Post-Burn Plot Assessments

The day after the burn, data from the six test plots were collected and are outlined in Table 4 below. Of the six plots, only three showed any effects of fire in the form of burnt fuels and partially melted and melted temperature pellets. Pellets up to 316˚C (600˚F) melted with a total of 18 pellets in three plots being affected (Figure 10). Pellets in the 482˚C to 843˚C (900˚ to 1550˚F) range were completely unaffected. As shown in Figure 10, Plot 2, located in heavy fuels, was the most affected plot. Eleven pellets were melted (Table 4), all located on the western and central portions of the plot where a large (1.5 m x 1.5 m) big sage was located. The large shrub, along with coarse and fine duffs

Table 4. Post burn plot data.

Plot # 1:	**Heavy Fuels**				Date: 11-21-98
Level	0cm	5cm	10cm		
Pellets (°F)				Total Melted	Pellet Condition Key
300	N	N	N	0	M = melted
400	N	N	N	0	PM=partially melted
500	N	N	N/A	0	N=None
600	N	N	N/A	0	N/A=no pellet
900	N	N	N/A	0	
1200	N	N/A	N/A	0	
1550	N	N/A	N/A	0	
Total	0	0	0		

Plot Condition Information

Vegetation in the plot appeared completely unburned, including fine and heavy duff. All pin flags were remaining, though the flags were melted and shriveled. No pellets on the surface were melted. Soils moist and frozen in some holes down to 5cm and moist to 10cm.

Plot # 2:	**Heavy Fuels**				Date: 11-21-98
Level	0cm	5cm	10cm		
Pellets (°F)				Total Melted	Pellet Condition Key
300	2-M (SW,C), 1PM (NW)	N	N	3	M = melted
400	3-M (SW,NW,C)	N	N	3	PM=partially melted
500	1-M (SW) , 1-PM (C)	N	N/A	2	N=None
600	3-PM (SW,NW,C)	N	N/A	3	N/A=no pellet
900	N	N	N/A	0	Location in Plot
1200	N	N/A	N/A	0	NW=Northwest
1550	N	N/A	N/A	0	C=Center
Total	11	0	0		SW=Southwest

Plot Condition Information

Plot burned over fairly well. All fine duff burned, but not all coarse duff was completely combusted. Large sage on W side fully consumed. All pin flags melted except SE corner. NW, SW corners and center of plot got up to 600°. Pellets on NE and SE unmelted. Roots still smoldering on W side of plot. The area surrounding the plot did not burn as intensely as other locations in the heavy fuel zone.

Plot # 3:	**Moderate Fuels**				Date: 11-21-98
Level	0cm	5cm	10cm		
Pellets (°F)				Total Melted	Pellet Condition Key
300	1-M (SW)	N	N	1	M = melted
400	1-M (SW)	N	N	1	PM=partially melted
500	2-PM (SW,SE)	N	N/A	2	N=None
600	1-PM (SW)	N	N/A	1	N/A=no pellet
900	N	N	N/A	0	Location in Plot
1200	N	N/A	N/A	0	SW=Southwest
1550	N	N/A	N/A	0	SE=Southeast
Total	5	0	0		

Plot Condition Information

Plot untouched except SW corner where a sage plant was partially burned and flags melted. Ricegrass and coarse duff on N side of plot unburned. Roughly 50% of vegetation on south side was burned. Heat remaining in sage roots. Pellets on surface melted to 600° in the SW corner near the sagebrush.

Plot # 4: Moderate Fuels				Date: 11-21-98
Level	0cm	5cm	10cm	
Pellets (°F)			Total Melted	Pellet Condition Key
300	N	N	N	0	M = melted
400	N	N	N	0	PM=partially melted
500	N	N	N/A	0	N=None
600	N	N	N/A	0	N/A=no pellet
900	N	N	N/A	0	
1200	N	N/A	N/A	0	
1550	N	N/A	N/A	0	
Total	0	0	0		

Plot Condition Information

The plot was untouched by fire and no flags were burned. Vegetation within .5 meters of the S and E sides of the plot was 50% consumed, while 2 meters to the E all vegetation was burned. Three small obsidian specimens were lost at the 5cm level and 4 in the 10cm level due to sandy soils.

Plot # 5: Light Fuels					Date: 11-21-98
Level	0cm	5cm	10cm		
Pellets (°F)				Total Melted	Pellet Condition Key
300	N	N	N	0	M = melted
400	N	N	N	0	PM=partially melted
500	N/A	N/A	N/A	0	N=None
600	N	N	N/A	0	N/A=no pellet
900	N	N/A	N/A	0	
1200	N/A	N/A	N/A	0	
1550	N/A	N/A	N/A	0	
Total	0	0	0		

Plot Condition Information

The plot was unburned. Smaller vegetation (12" diameter) within .5 meters of the plot were burned. Fuels in this area are highly dispersed. Two small artifacts in the 5cm level were not recovered. Very sandy, well drained soils with low soil moisture.

Plot # 6: Light Fuels					Date: 11-21-98
Level	0cm	5cm	10cm		
Pellets (°F)				Total Melted	Pellet Condition Key
300	2-PM (NW, SW)	N	N	2	M = melted
400	N	N	N	0	PM=partially melted
500	N/A	N/A	N/A	0	N=None
600	N	N	N/A	0	N/A=no pellet
900	N	N/A	N/A	0	Location in Plot
1200	N/A	N/A	N/A	0	NW=Northwest
1550	N/A	N/A	N/A	0	SW=Southwest
Total	2	0	0		

Plot Condition Information

All vegetation around the plot burned, including one large sagebrush located less than .5 meters to the east. All of the flags within the plot melted, but grasses within the plot were only marginally effected. The 300° pellets on the W side of the plot, near the sage that burned, partially melted.

in the plot, had combusted though the coarse duffs were not fully consumed. The base of the large sage smoldered through the day. Plots 1 (heavy fuels), 4 (moderate fuels) and 5 (light fuels) were unaffected by the fire. A small sagebrush (< 0.5 m tall) on the southwest corner of Plot 3 was partially burned and pellets up to 316˚C (600˚F) were partially melted on the south edge of the plot (Table 4). A total of five pellets melted in this plot, four located in the southwest corner near the burnt sage. Plot 6 was the only other plot to be affected with two 300˚ pellets being partially melted on the west side of the site. This was caused by a sagebrush shrub which combusted 0.5 m to the west of the plot. These results show, in general, the moderate effect of the prescribed fire on the test plots.

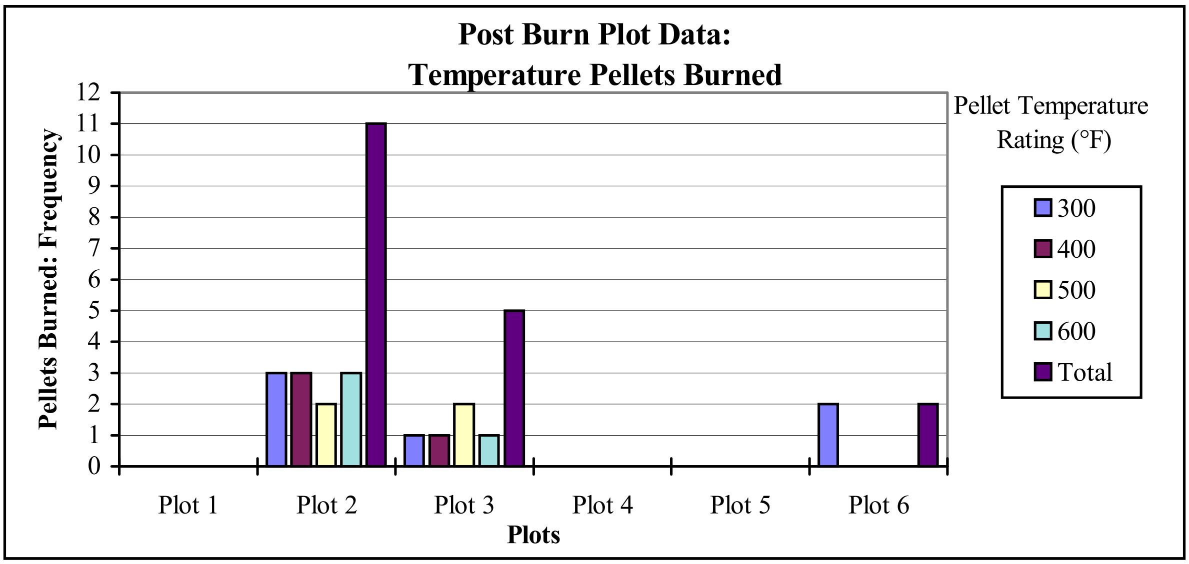

Figure 10. Post burn plot data.

Obsidian Artifact Analyses

Of the 180 artifacts planted in the six test plots, 172 (96%) were recovered. A total of eight subsurface artifacts was not recovered in the light and moderate fuel zones due to small artifact size (< 1 cm diameter) and sandy soils. Use of a light mesh in each subsurface level could alleviate this problem. Due to the low intensity of the burn, only 127 of the artifacts were submitted for post burn hydration analyses. Artifacts excluded were from unburned plots and mainly from the 10 cm level.

In general, due to the low intensity and duration of the burn, very few artifacts were adversely affected. For this reason, other levels of variance were sought that may indicate fire effects. A paired t-test for dependent variables was used to assess inter-lab variability before assessing fire effects. Sixty-one unaffected subsurface samples were tested, excluding six samples with diffuse hydration as outliers. The test showed a significant variance between pre and post-burn hydration readings: Paired t-test, $n = 61$, Mean Difference = 0.306 µm, SD Difference = 0.355 µm, $t = 6.718$, $df = 60$, CI = 99%, $p = < 0.001$. Due to the significant level of inter-lab variability in hydration values, only diffuse hydration and no visible band readings were used as a gauge of fire effects.

The results from Plot 2, the most intensively burned location, are shown in Figure 11. For the purposes of plotting hydration values, diffuse hydration was given a value of zero. As shown in Figure 11, four (40%) of ten surface artifacts show diffuse hydration indicating the effects of the fire on surface samples and no effect to subsurface samples, excluding specimen 50 as an outlier. Figure 12 shows the percentage of diffuse hydration for all surface samples from each plot and a pooled percentage for all subsurface specimens submitted for post-burn analyses. Plots 2 and 3 were the most affected by the fire as indicated by both the number of pellets melted (Figure 10) and diffuse hydration readings. Figure 13 shows plots of the pre and post-burn hydration results for all surface samples from the six test plots and shows, again, that the greatest variation occurs in Plots 2 and 3.

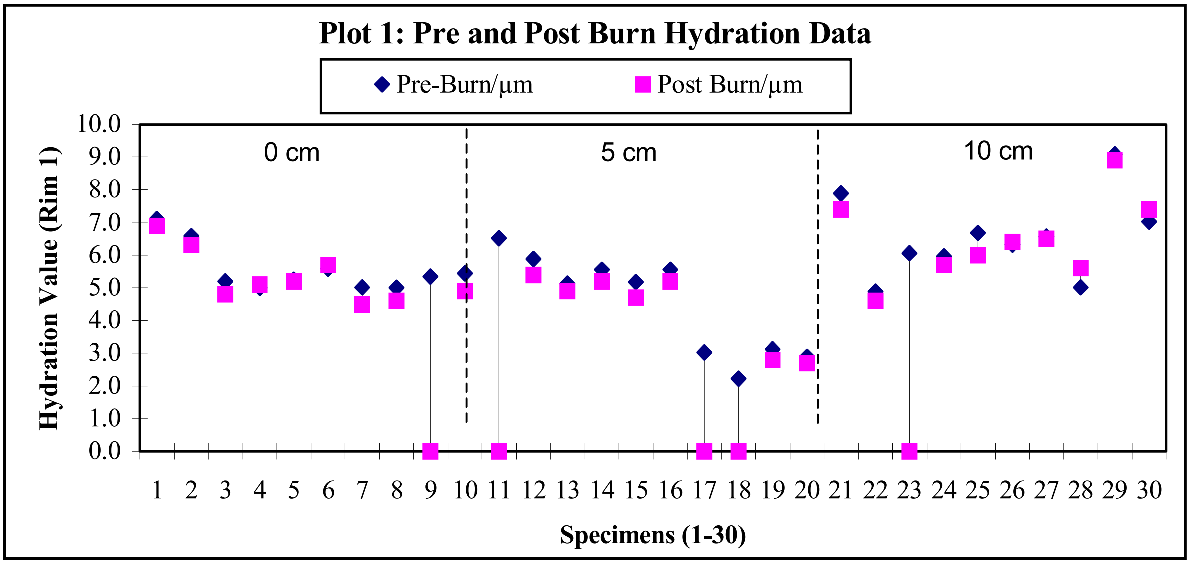

Figure 11. Plot 2: pre and post-burn hydration data.

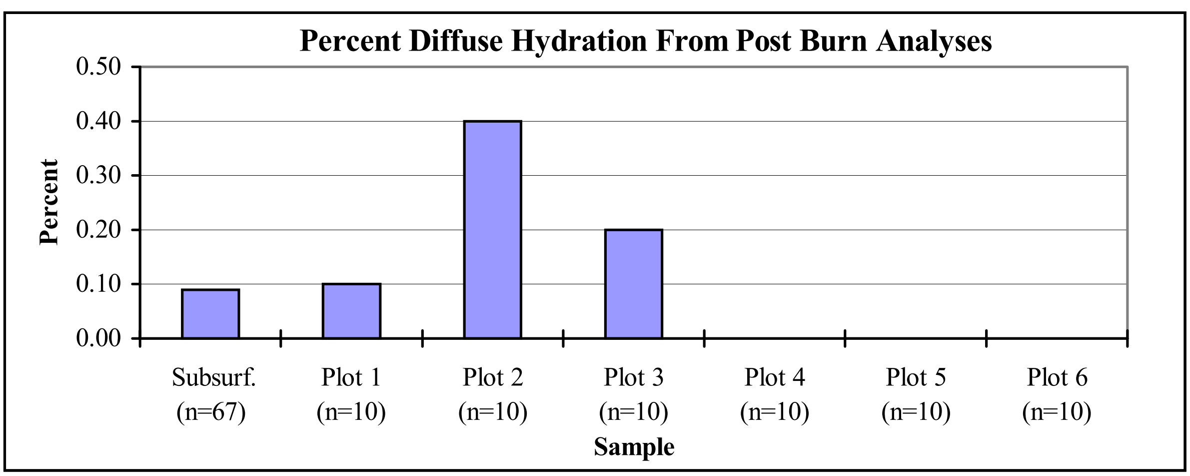

Figure 12. Percent diffuse hydration from post-burn analyses.

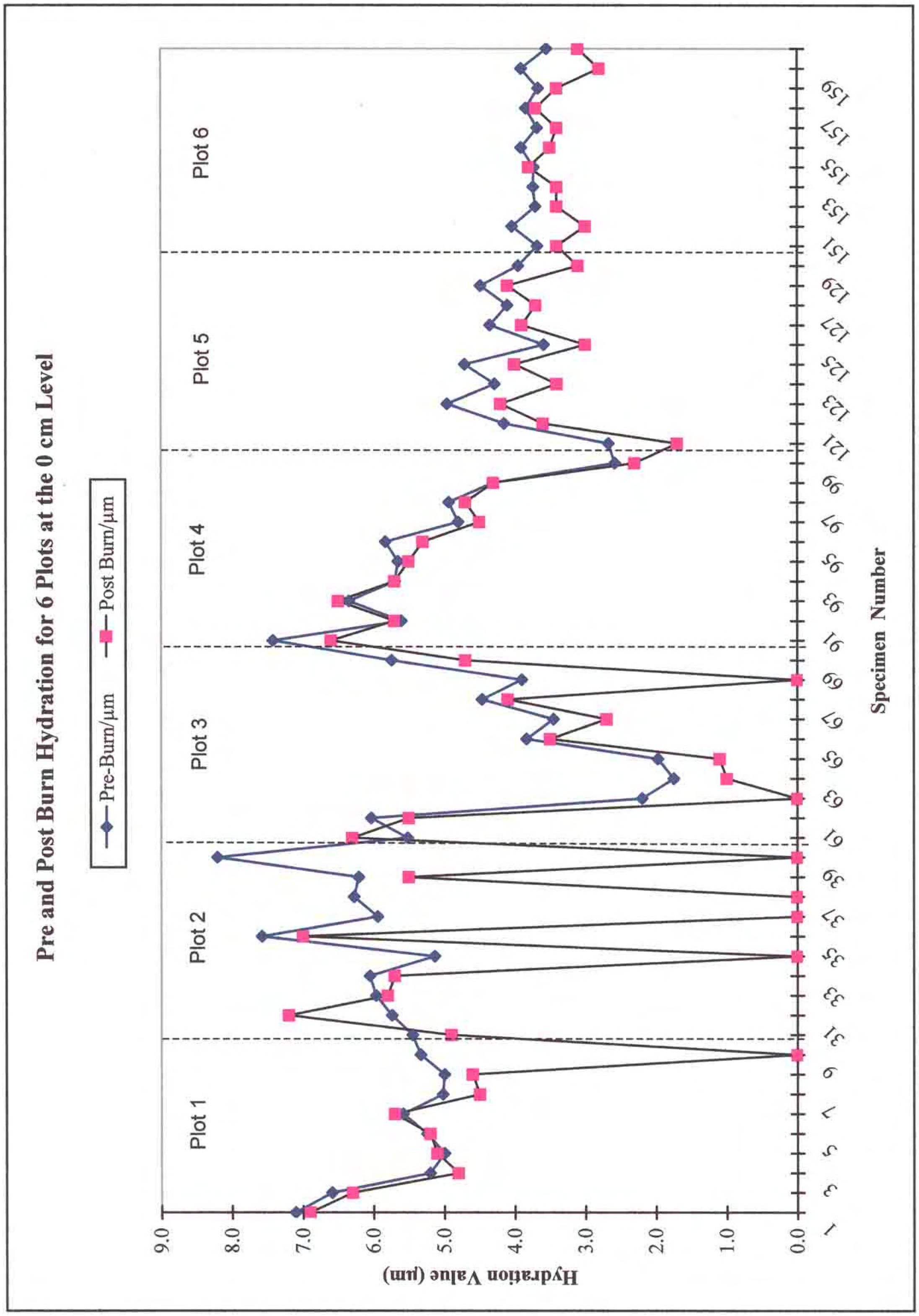

Figure 13. Pre and Post Burn Hydration for 6 Plots at the 0 cm Level.

Conclusions

The goal of this study has been to determine the effects of prescribed fire on archaeological resources within the sagebrush steppe community type, with a focus on obsidian flaked and tool stone artifacts. A set of hypotheses were developed for this study to test the premise that managed fire in the sagebrush steppe habitat can be designed to minimize impacts to archaeological resources. In the case of the Trench Canyon prescribed burn, it was expected that obsidian artifacts within the heavy fuel zone would be adversely affected on the ground surface and down to a depth of 5 cm. It was expected that in the moderate and light fuel types that no subsurface materials would be affected with only limited effects to surface specimens. Under this scenario, it was predicted that the five archaeological sites within the project area would not be adversely affected due to their location in moderate and light fuel zones.

Due to the fact that the burn was not accomplished under the parameters of the prescription, the research hypotheses can not be fully assessed. But important conclusions can be derived from this analysis. Though the burn intensity was lower than would be expected under the prescription, it is clear that surface temperatures within the heavy fuels can reach hot enough temperatures 204-260˚C (400-500˚F) to adversely impact hydration rinds of surface artifacts as was shown in Plot 2. It can also be concluded that prescribed fire in the sagebrush steppe, if conducted under the conditions of this event, will have little impact in all fuel types, and impacts to flaked and ground stone artifacts would be insignificant. Further, it can be suggested that sites within moderate and light fuels, even under prescribed conditions, would not be adversely affected due to a lack of fuel densities high enough to promote fire spread without human intervention. From a cultural resource management perspective, it can be concluded that prescriptions can be developed for the sagebrush steppe community type that will have limited to no adverse impact to prehistoric sites lacking organic remains.

Whether the vegetative goals of this burn have the desired effects under the reduced fire intensity that occurred at Trench Canyon still remains to be assessed. Previous studies indicate that post-fire abundance of Great Basin wild rye does not change significantly for the first several years (Everett et al. 1984; Ward 1977). In big sagebrush/Thurber needlegrass communities in Nevada, densities of Great Basin wild rye were found to remain constant at 0.02 plants per square meter for two years after a mid-season wildfire (Ward 1977). It is anticipated that the Trench Canyon site will follow a similar pattern with regard to recruitment of new cohorts, however existing plants are likely to re-sprout vigorously under the implemented burn.

Though the data are not conclusive, they suggest that the spatial placement of artifacts in relationship to fuels is important. As shown in Plots 2 and 3 (Table 4), 94% of the pellets affected were located near burnt shrubs and smoldering roots. These data suggest that fire effects can vary even within limited areas (i.e., 1 m^2). Temperature pellets as close as 1 m from burnt vegetation were unaffected. These data suggest that artifacts near burning shrubs and smoldering roots should show the greatest effect. This assumption will need to be more fully assessed, but indicates that fire effects can be reduced by curtailing fuel loading in and around archaeological sites prior to burning.

As prescribed fire becomes more aggressively utilized to manage fire behavior and to attain desired ecosystem conditions, the effects of this management practice must be closely monitored for potential adverse effects to cultural resources. This study represents one prescribed burn in one environmental context, under one set of weather conditions within the sagebrush steppe vegetation community in Trench Canyon, California. Fire behavior is complex, often unpredictable and ever changing, and no one analysis can address all the variables that may influence a specific fire event and its effects to archaeological resources. But from this analysis, it is clear that fire and cultural resource personnel can work together to develop prescribed fire parameters which can reduce the impacts to archaeological resources and in the long-term, protect these resources by curtailing fuel loading which leads to both hot and long duration fire events.

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FIRE AND GLASS: EFFECTS OF PRESCRIBED BURNING ON OBSIDIAN HYDRATION BANDS

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Abstract

Results from a series of field and laboratory experiments on the effects of prescribed burning in a Ponderosa pine-mixed conifer forest on obsidian hydration bands are reported and discussed. Field experiments conducted at Boggs Mountain Demonstration State Forest, Lake County, California, during Spring 1998 involved placing obsidian specimens with previously measured hydration bands at soil surface in the path of several small broadcast burns and one slash pile burn. In laboratory experiments obsidian specimens with previously measured hydration bands were heated at temperatures ranging from 100 to 300°C (38 to 149ºF) for periods ranging from 1.3 to 24 hours. Maximum temperature, duration of exposure to elevated temperatures, sample placement, geochemical obsidian source, specimen weight and pre-experiment hydration band depth were the primary experimental variables. Post-experiment hydration band measurements were obtained for a sub-sample of specimens exposed to various experimental conditions.

Hydration analysis results from this study confirm previous findings that maximum temperature and duration of exposure to elevated temperatures are primary factors that determine whether hydration bands become damaged and unmeasurable after exposure to prescribed burn conditions. Geochemical obsidian source, specimen weight and pre-experiment hydration band depth had no discernible influence on the results in this study.

Field and laboratory results indicate that exposure to broadcast burn conditions in a Ponderosa pine-mixed conifer forest with fuel loads under four tons/acre, relative humidity above 35%, wind speeds of 0-20 mph, 100 hour fuel moisture content above 28%, and soil moisture above 45%, is unlikely to cause hydration bands to become damaged and unmeasurable. Exposure to slash pile burn conditions under the same weather, fuels,, and soil conditions is likely to damage some bands on specimens located at the soil surface, however. Fire severity may be a more useful measurement than fire intensity in determining thresholds beyond which hydration bands are consistently altered or damaged.

Laboratory experiment results indicate that exposure to elevated temperatures below 100°C (212°F) for less than 24 hour does not change hydration bands. This finding has potential relevance for field studies, as soil temperatures during fire remain below 100°C as long as moisture remains in the soil. Further research is necessary to determine whether results from laboratory heating experiments are directly applicable to prescribed burn field conditions.

Introduction

Obsidian hydration analysis is often employed to establish the chronology and integrity of prehistoric archaeological deposits in California. Under natural conditions the freshly exposed surface of a piece of obsidian absorbs minute amounts of moisture or hydrates over time. This process results in the formation of a distinct hydration band that can be measured under polarized light at a magnification of 200-300. As an obsidian artifact ages the width of its hydration band increases. Measuring the band thus gives an estimate of the age of the artifact. Obsidian hydration is best considered as a relative rather than an absolute dating technique. In addition to time, hydration rates are affected by several variables; for example, the geochemical source of the obsidian, temperature regimes to which artifacts have been exposed, pH, and chemistry of the surrounding sedimentary matrix (Tremaine 1989).

Fire can also affect obsidian hydration bands. Specimens recovered after exposure to wildfires often have damaged hydration bands that are diffuse and unmeasurable or not visible at all. Many wildfires have high spatial heterogeneity, so that a post-fire landscape may be a mosaic of severely, moderately and lightly burned areas. Post-fire research has correlated the degree and frequency of damage to obsidian hydration bands with the intensity of the wildfires in particular areas. Obsidian artifacts recovered from lightly burned areas may not be affected by the fire, while those exposed to more severe conditions may have damaged, unmeasurable bands (Origer 1996).

Obsidian artifacts may also be exposed to fire through prescribed burning, the intentional use of landscape fire in order to achieve specific management goals; for example, wildfire hazard prevention, fuel load reductions, and habitat restoration. While some researchers have suggested that the low temperatures and fire intensities involved in prescribed burns do not alter or affect hydration bands, several recent studies have shown that obsidian hydration bands may become damaged and unmeasurable after exposure to prescribed burn conditions (Deal 1997; Green 1997).

This study addresses the effects of prescribed burning in a Ponderosa pine-mixed conifer forest in California's North Coast Ranges on obsidian hydration bands through a series of field and laboratory experiments. The primary research questions addressed are:

1. Under what conditions does exposure to prescribed burns damage obsidian hydration bands?

2. Can one determine minimum fire temperature or burn intensity thresholds above which hydration bands are consistently altered or damaged?

3. What factors (e.g., fire temperature, duration of exposure to elevated temperatures, soil moisture or chemistry, obsidian source, hydration band width, obsidian specimen weight) are most influential in affecting obsidian hydration bands?

4. Can field results be replicated in laboratory experiments so that directed laboratory research can help answer these questions?

The California Department of Forestry and Fire Prevention (CDF) initiated the study. Initial project funding was provided through Contract #8CA97015 with the Anthropological Studies Center, Sonoma State University. The data were originally presented in a paper given at the 1999 Society for California Archaeology (SCA) Annual Meetings in Sacramento, and a version of this report is on file with the CDF.

Setting

Field experiments were conducted at Boggs Mountain Demonstration State Forest (Boggs Mt. DSF) during spring 1998. Boggs Mt. DSF is located about 0.5 miles northeast of the community of Cobb, Lake County California (Figure 1). Ponderosa pine-mixed conifer is the predominant vegetation type, although small areas of meadow and chaparral vegetation are found within the 3500 acre forest. Ponderosa pine (*Pinus ponderosa*), Douglas fir (*Pseudostuga menziesii*), sugar pine (*Pinus lambertiana*), canyon live oak (*Quercus chrysolepsis*), black oak (*Quercus kelloggii*) and madrone (*Arbutus menziesii*) are the primary arboreal species in the study area. Associated species include manzanita (*Arctostaphylos* spp.), ceanothus (*Ceanothus* spp.), coffeeberry (*Rhamnus californica*), wild rose (*Rosa californica*) and various grasses and herbs.

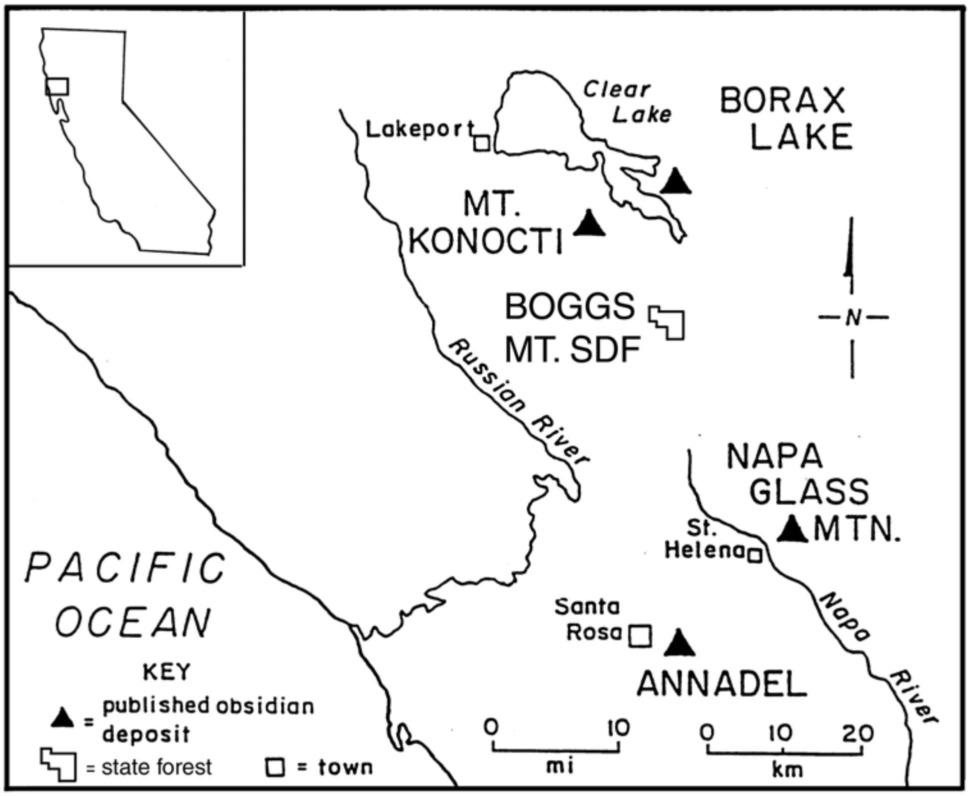

Figure 1. Location map showing Boggs Mt. DSF and the Borax Lake, Mount Konocti, Napa Glass Mountain (a.k.a. Napa Valley) and Annadel obsidian deposits.

The study area fits the Forestland Fuels model 9 (Table 1; Anderson 1982). Surface fuels are continuous beneath a non-continuous overstory of hardwoods and conifers. The duff layer is 0-3 inches deep and surface fuel depth is mainly less than 12 inches with scattered concentrations under three feet. Estimated fuel loading is 3.46 tons per acre (Table 2).

CDF conducts prescribed burning at Boggs Mt. DSF in order to reduce the risk of damaging wildfires. Specific goals of the program include reducing ground fuels and brush, disrupting vertical fuels continuity, thinning areas of overcrowded young trees and creating a mosaic of burn intensities while protecting overstory conifers and hardwoods. Initial forest underburning is conducted between

Table 1. Estimated proportions of fuel types at Boggs Mt. DSF (Sayers 1997).

Fuel type	Proportion
Conifer needles and hardwood leaves	Over 70%
Dead wood	Under 20%
Manzanita spp.	Under 20%
Miscellaneous bunch grasses	Under 20%

the first autumn rains and March or the beginning of spring bud swell. Subsequent prescribed burns may be conducted between July and February on a 5-15 year rotation. Planned fuel consumption is 2.25 tons per acre. The prescription calls for low to moderate intensity fires (with flame lengths less than three feet) that leave a remaining duff layer at least 0.25 inch deep and do not cause rock spalling. Additional protective measures, e.g., avoiding ground disturbing activities and excluding heavy equipment within a 25 foot buffer zone, are mandated for identified archaeological sites (Sayers 1997).

Table 2. Estimated fuel loading at Boggs Mt. DSF (Sayers 1997).

Fuel type	Estimated fuel load
1 hour (<0.25 in. diameter)	2.90 tons per acre
10 hour (0.25-1 in. diameter)	0.41 tons per acre
100 hour (1-3 in. diameter)	0.15 tons per acre
Total	3.46 tons per acre

While no detailed fire history is available, it is thought that before the current fire suppression era the characteristic fire regime in the forest was one of frequent low to moderate severity fire with isolated patches of high severity fire. Historic narratives recount the absence of dense thickets and the predominantly 'open' character of the forests. Remaining old-growth trees in the area often show multiple scars from past fires. Estimated pre-suppression fire return intervals are on the order of three to fifteen years (Sayers 1998).

Methods

Sample Selection. Culturally modified obsidian flakes with previously measured hydration bands and previously identified geochemical sources were selected from archaeological collections from the CA-MEN-1930, CA-SON-120 and CA-SON-1471 sites for the experiments. Obsidian source, specimen size and depth of hydration band were the primary selection criteria – a range of specimen sizes and hydration band depths and a balanced representation of geochemical sources were sought. Obsidian sourcing follows the determinations (made by visual inspection) that were reported in the analyses of the archaeological collections (Jones and Hayes 1989; Stewart 1989; Gary 1987). Specimen weights, measured on an analytic balance, provide an estimate of the relative sizes of the specimens. The hydration band measurements reported in the original analyses are described as the 'first' hydration band measurements here. First hydration band measurements for specimens from the CA-MEN-1930 collection were conducted at the Anthropology Department, San Jose State University. Those for specimens from the CA-SON-120 and CA-SON-1471 collection were done at the Obsidian Hydration Laboratory (OHL), Sonoma State University.

Specimens for the field experiments were selected from the CA-MEN-1930 collection. An additional criterion was that the obsidian pieces be large enough to be recovered easily after the burns. Specimens are from the Borax Lake and Mount Konocti sources (Figure 1). Specimen weights range from 0.19 to 2.30 g. First hydration band measurements range from 1.7 to 5.0 µm. Specimens for the laboratory experiments were selected from all three collections. Borax Lake, Mt. Konocti, Napa Valley, and Annadel sources are represented. Specimen weights range from 0.05 to 11.13 g, and first hydration band measurements range from 1.0 to 6.2 µm.

Field Experiments. Field experiments were conducted at Boggs Mt. DSF in April and May 1998. Steve Sayers, Forest Manager, conducted one slash pile burn and several small broadcast burns in square test plots that measured approximately 50 yards on each side. The basic procedures involved placing obsidian specimens at soil surface before each burn. Soil surface was defined as the soil/duff interface, the top of the mineral soil layer immediately beneath the bottom of the duff layer. Each obsidian specimen was placed directly on top of several heat sensitive temperature pellets with a range of temperature ratings. The pellets melt when exposed to the rated temperature. Surgical forceps were used to place the pellets and obsidian pieces in order to avoid disturbing the duff layer and thereby altering fuels and fire behavior at the sample sites. Specimen locations were marked with pin flags. Sayers recorded weather conditions and fuel moisture content in the field. Soil samples were collected and soil moisture content was subsequently determined in the laboratory. The burns were ignited with drip torches. Fire characteristics and behavior were noted. After the fires had extinguished and the areas had cooled, the immediate area around each pin flag was excavated to recover the obsidian specimens and any non-melted temperature pellets.

The test plot for the April broadcast burn was in an area that has never been prescribed burned and had not been disturbed for at least the past fourteen years (Figure 2). There were moderate 1 hour and 10 hour fuels, some fuels larger than 1 inch diameter and a duff layer 1-2.5 inches deep. A total of 32 obsidian specimens was exposed to the April broadcast burn conditions, 16 placed at soil surface and 16 placed at 2-inch sub-surface contexts, in two transects across the test plot. Temperature pellet ratings ranged from 101°C (214°F) to 550°C (1022°F).

Two test plots were used for the May broadcast burns. One was an undisturbed area similar to the April burn test plot. The second, on a slope that had been prescribed burned four years previously, had low concentrations of 1 and 10 hour fuels, sparse fuels larger than 1 inch diameter and a 1-2 inch deep duff layer. Areas of log, woody and light fuels concentrations were identified in the test plots (see Deal 1997). Log fuels areas were covered by dead fuels more than three inches in diameter, woody fuels areas were covered by dead and live fuels between 0.5 and 3 inches in diameter, and light fuels areas had fuels primarily less than 0.25 inches in diameter.

A total of 40 obsidian specimens was exposed to the May broadcast burn conditions. Twenty-five specimens were placed in the 'undisturbed' plot: 10 in log fuel areas, 5 in woody fuel areas and 10 in light fuel areas. Fifteen specimens were placed in the previously burned plot: 5 in woody fuel areas and 10 in light fuel areas. Temperature pellet ratings ranged from 55°C (131°F) to 299°C (570°F).

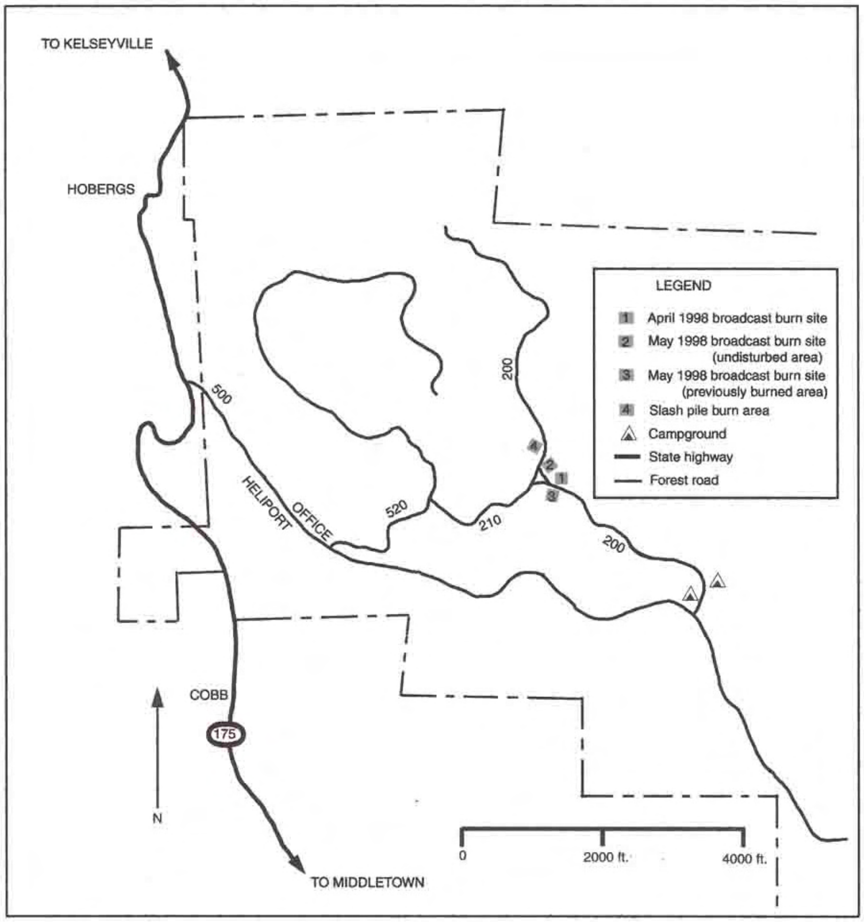

Figure 2. Location map showing test plots for broadcast and slash pile burn experiments conducted at Boggs Mt. DSF in April and May 1998.

For the May slash pile burn ten obsidian specimens were placed at soil surface directly on top of temperature pellets with ratings ranging from 101 to 550°C (38 to 288°F). A slash pile about 15 feet long by six feet wide by four feet high was then constructed with woody and log fuels over the study area. The slash pile fire was raked several times during the burn in order to push the unburned fuels toward the center of the pile and replicate ordinary slash pile burn conditions.

Laboratory experiments A total of 90 obsidian specimens with previously measured hydration bands was exposed to heat under a series of different conditions in the laboratory. Temperature, duration and placement were varied in the laboratory runs (Table 3). Specimens placed 'in crucibles' were placed in individual ceramic crucibles and heated in a recently calibrated Fischer Scientific muffle furnace. Specimens placed 'in sand' were buried in oven-dried sand in a Pyrex dish. Specimens placed 'on sand' were placed on top of a sand-filled Pyrex dish. Specimens placed in and on sand were heated in a recently calibrated Fisher Scientific drying oven. Experimental procedure involved putting the specimens in their containers into the pre-heated furnace or oven for the specified time period and then removing the specimens to cool in laboratory drying jars for several hours.

Table 3. Temperatures, durations, and placements used in laboratory experiments.

Temperature	Duration	Placement (# specimens)
100°C	24 hours	In sand (5); on sand (5)
125°C	24 hours	In sand (5); on sand (5)
200°C	2 hours	In crucibles (10)
200°C	2 hours	In sand (5); on sand (5)
200°C	10.25 hours	In crucibles (10)
200°C	12 hours	In crucibles (10)
200°C	12 hours	In sand (5); on sand (5)
300°C	1.3 hours	In crucibles (10)
300°C	12 hours	In crucibles (10)

Obsidian hydration

Second (post-experiment) hydration band measurements were obtained for a control sample and a sub-sample of obsidian specimens exposed to experimental burn conditions and laboratory heating regimes. A total of 73 specimens was submitted to the OHL for hydration analysis (Table 4). A single analyst, Tom Origer, conducted all the hydration band measurements following standard procedure. A thin-section slide was prepared from each specimen. Each hydration band was measured at six locations along the edge of the thin-section. The hydration band measurement is reported as the mean of these six measurements. Additional specimen characteristics (e.g., weathered [w] or good condition [g]) were occasionally noted in the hydration analyses.

The hydration band measurements have an accuracy of ± 0.2 µm due to the limitations of the equipment. The standard margin of error for comparing two measurements of a single specimen is thus ± 0.4 µm (Origer 1998). Four descriptive categories are used to report the hydration analysis results (Table 5). Completed hydration specimen slides and hydration band measurements are on file at the OHL. The obsidian specimens have been returned to their respective archaeological collections.

Results

Control Samples Nine of the ten control samples, which were not exposed to fire or subjected to heat, showed no change between the first and second hydration band measurements. One sample showed a change of -0.6 microns (Table 6).

Field Experiments. Weather conditions, fine fuels moisture and soil moisture conditions for the April and May 1998 burns were within the prescribed range (Table 7). Moisture content of 10 and 100 hour fuels was higher than prescribed. The April broadcast burn was ignited at noon. Flames reached the transects along which the specimens were placed within five minutes. Flame lengths averaged one foot. Maximum flame lengths were two feet. The fire's rate of spread was about two feet per minute. By 1315 the fire was almost completely extinguished; only one isolated log was still smoldering. The ground surface was blackened, yet some still-green vegetation remained in the test plot after the fire. Many one hour fuels were charred but not consumed. The duff layer was not appreciably thinner than before the fire. The fire killed many live fuels with trunks less than three inches in diameter and thus effectively disrupted vertical fuel continuity in the plot. The duff and underlying mineral soil were damp and cold to the touch immediately after the fire. None of the temperature pellets placed under the obsidian specimens had melted, indicating that temperatures had not risen above 101°C (214°F) on the soil surface and in the 2-inch sub-surface areas during the burn.

Fire behavior in the May broadcast burns was similar to that for the April burn. Maximum flame lengths were two feet and rate of spread was *ca*. two feet per minute. The fires burned through the test plots within *ca*. one hour. Most of the plastic on the pin flags melted in the flames. A few isolated logs and tree stumps were still smoldering when the obsidian specimens were retrieved from the test plots four hours later. The ground surface was blackened, yet some vegetation remained green. The duff and soil were cool to the touch but not cold.

Table 4. Obsidian specimens submitted for post-experiment hydration analysis.

Experiment			Number of specimens
Control sample			10
Field experiments			
April 1998 broadcast burn			0
May 1998 broadcast burns			10
May 1998 slash pile burn			8
Laboratory experiments			
Temperature	**Duration**	**Placement**	
100°C	24 hours	In sand	5
125°C	24 hours	In sand	5
200°C	2 hours	In sand	5
200°C	12 hours	In crucibles	10
200°C	12 hours	In sand	5
200°C	12 hours	On sand	5
300°C	1.3 hours	In crucibles	5
300°C	12 hours	In crucibles	5
Total			73

Table 5. Descriptive categories used to report hydration analysis results.

Category (abbreviation)	Description
No change (NC)	Second hydration band measurement is within the standard margin of error (+/- 0.2 μm) of the first hydration band measurement.
Changed hydration band measurement (CH)	Second hydration band measurement differs from the first hydration band measurement by more than the standard margin of error (+/1 0.2 μm).
Diffuse hydration band (DH)	No second hydration band measurement can be determined because the hydration band has become diffuse and unmeasurable.
No visible hydration band (NVB)	No second hydration band measurement can be determined because no hydration band is visible on the specimen.

In the log fuels areas several 55°C (131°F) and one 79°C (174°F) but no 101°C (214°F) pellets had melted, indicating that soil surface temperatures increased to 55-101°C during the burn. In the woody fuels areas all the 79°C pellets (the lowest rated pellets used in these areas) were recovered. Soil surface temperatures in these areas did not exceed 79°C during the burn. In the light fuels areas all the 55°C pellets placed were recovered, suggesting that soil surface temperatures stayed below 55°C. Fire characteristics in the two plots were so similar that the two burns can be considered as a single burn experiment. A sub-sample of ten obsidian specimens from the May broadcast burn was submitted to the OHL for second (post-experiment) hydration band measurements. Five specimens showed no change and five showed a change in hydration measurements greater than the 0.4 μm margin of error (Table 8).

The May slash pile burn was ignited at 1300. Flames lengths soon reached 7-8 feet. Within 45 minutes fuels in the center of the pile were mostly consumed and flame lengths had decreased to 1-2 feet. The fire was raked to push the unburned fuels towards the center, and flame lengths rapidly increased again. The raking was repeated several times through the afternoon, and the fire smoldered into the evening. The following day the former slash pile was a thick layer of ash and charcoal, still too hot to retrieve the obsidian specimens. Most fuels had been fully consumed. All the plastic flags had melted and most of the wires were bent and discolored but still in place.

Two days later eight of the ten specimens were recovered from the burn site. The recovered specimens were found adjacent to the pin flags by which they had been placed before the slash pile construction and fire; the raking may have displaced the two specimens that were not recovered. None of the 101°C (214°F), few of the 399°C (723°F) and all but one of the 500°C (932°F) temperature pellets were recovered. Soil surface temperatures may have reached 400 to 500°C (752 to 932°F) during the burn.

Table 6. Obsidian hydration analysis results for control samples, by specimen.

Specimen number	Result	H1 (μm)	H2 (μm)
1	NC	3.8	3.7
2	NC	2.9	2.9
3	CH	4.4	3.8
4	NC	1.9	2.3
5	NC	3.4	3.8
6	NC	2.4	2.5
7	NC	3.4	3.5
8	NC	2.2	1.9
9	NC	3.3	3.3
10	NC	3.0	3.0

Key: H1 = first (pre-experiment) hydration band measurement. H2 = second (post-experiment) hydration band measurement. NC = no change. CH = changed hydration band measurement.

Table 7. Prescription and experimental burn conditions at Boggs Mt. DSF.

Condition	Prescription	April 1998 burn	May 1998 burns
Relative humidity	20-60%	50%	36%
Air temperature	4.5-18°C (40-65°F)	18°C (65°F)	20.5°C (69°F)
Wind direction	180° - 360°	180° - 240°	180° - 240°
Wind speed	0-5 mph	0-2 mph	0-2 mph
1 hour fuels moisture	6-10%	10%	6%
10 hour fuels moisture	8-13%	22%	6-28+%
100 hour fuels moisture	10-14%	28+%	28+%
Soil moisture	> 20%	53%	47%

Note: Prescription data from Boggs Mt. DSF Vegetation Management Plan (Sayers 1997).

Table 8. Obsidian hydration analysis results for a sub-sample from May 1998 broadcast burns.

Specimen #	Placement	Temperature	Result	H1 (μm)	H2 (μm)
54	Log fuels	55-101°C	CH	1.7	2.5 (g)
56	Log fuels	55-101°C	NC	4.0	3.9 (g)
61	Log fuels	55-101°C	CH	4.5	3.3 (g)
66	Woody fuels	< 79°C	NC	3.5	3.8 (g)
71	Woody fuels	< 79°C	NC	2.9	2.9 (g)
74	Light fuels	< 55°C	CH	3.2	1.1 (g)
77	Light fuels	< 55°C	NC	2.6	2.4 (g)
81	Light fuels	< 55°C	CH	3.1	3.8 (g)
85	Light fuels	< 55°C	CH	3.0	3.5 (g)
88	Light fuels	< 55°C	NC	2.3	2.6 (g)

Key: H1 = first (pre-experiment) hydration band measurement.

H2 = second (post-experiment) hydration band measurement.

NC = no change. CH = changed hydration band measurement.

(g) = good condition.

All eight specimens were submitted to the OHL for second (post-fire) hydration band measurements. Three specimens showed no change, and two had hydration band measurements which differed from the first (pre-experiment) measurements by more than the standard margin of error. Two specimens had diffuse and unmeasurable hydration bands, and one had no visible hydration band (Table 9).

Laboratory experiments. A sub-sample of 45 specimens exposed to various laboratory heating regimes was submitted to the OHL for second (post-experiment) hydration band measurements (Table 10). Hydration band measurements for five specimens heated at 100°C (212°F) for 24 hours in sand were unchanged (Table 11). Four of the five specimens heated at 125°C (257°F) for 24 hours in sand showed no change and one specimen showed a decreased hydration band depth of -0.6 microns (Table 12).

Four of the five specimens heated at 200°C (392°F) for two hours in crucibles showed no change, while the fifth had a diffuse, unmeasurable hydration band (Table 13). Of the ten specimens heated at 200°C for 12 hours in crucibles five showed no change, two had increased hydration band measurements (of +2.5 and +1.3 μm), two had diffuse hydration bands and one had no visible hydration band (Table 14). All the specimens heated at 200°C for 12 hours in and on sand had diffuse, unmeasurable hydration bands (Tables 15, 16).

Table 9. Obsidian hydration analysis results for specimens from the May 1998 slash pile burn, by specimen.

Specimen #	Temperature	Result	H1 (μm)	H2 (μm)
44	> 399°C	DH	1.8	DH
45	> 399°C	NC	3.6	3.4
46	> 399°C	CH	2.2	3.5
47	> 101°C	NC	4.2	3.9
48	> 399°C	NC	3.5	3.7
49	> 399°C	CH	2.4	3.1
50	> 500°C	NVB	3.7	NVB (w)
51	> 399°C	DH	2.3	DH

Key: H1 = first (pre-experiment) hydration band measurement.
H2 = second (post-experiment) hydration band measurement.
NC = no change. CH = changed hydration band measurement.
DH = diffuse hydration band. NVB = no visible hydration band.
(w) = weathered.

Table 10. Specimens submitted for hydration analysis after exposure to laboratory heating regimes.

Temperature	Duration	Placement	Number of specimens
100°C	24 hours	In sand	5
125°C	24 hours	In sand	5
200°C	2 hours	In sand	5
200°C	12 hours	In crucibles	10
200°C	12 hours	In sand	5
200°C	12 hours	On sand	5
300°C	1.3 hours	In crucibles	5
300°C	12 hours	In crucibles	5
Total	–	–	45

Table 11. Hydration results for specimens heated at 100°C for 24 hours in sand.

Specimen #	Result	H1 (µm)	H2 (µm)
123	NC	4.8	5.0
124	NC	3.3	3.7
125	NC	3.5	2.7
126	NC	1.6	1.7
127	NC	5.5	5.4

Key: H1 = first (pre-experiment) hydration band measurement.
H2 = second (post-experiment) hydration band measurement.
NC = No change.

Table 12. Obsidian hydration analysis results for specimens heated at 125° C for 24 hours in sand.

Specimen #	Result	H1 (µm)	H2 (µm)
113	CH	4.2	3.6
114	NC	2.7	2.9
115	NC	3.8	3.6
116	NC	4.0	3.9
117	NC	2.8	2.7

Key: H1 = first (pre-experiment) hydration band measurement.
H2 = second (post-experiment) hydration band measurement.
NC = No change. CH = changed hydration band measurement.

Table 13. Obsidian hydration analysis results for specimens heated at 200°C for 2 hours in crucibles.

Specimen #	Result	H1 (µm)	H2 (µm)
164	NC	1.8	1.8
165	NC	2.8	2.8
166	DH	5.6	DH (~ 6.0 w)
167	NC	2.0	2.0
171	NC	2.2	2.5

Key: H1 = first (pre-experiment) hydration band measurement.
H2 = second (post-experiment) hydration band measurement.
NC = No change. DH = diffuse hydration band. (w) = weathered.

Table 14. Obsidian hydration analysis results for specimens heated at 200°C for 12 hours in crucibles.

Specimen #	Result	H1 (μm)	H2 (μm)
93	NC	1.9	1.8
94	NC	2.3	2.2
95	DH	1.0	DH
96	CH	1.1	3.6
97	NVB	1.5	NVB
98	NC	3.4	3.6
99	NC	2.3	2.0
100	CH	4.5	5.8
101	DH	2.7	DH
102	NC	1.6	1.8

Key: H1 = first (pre-experiment) hydration band measurement.
H2 = second (post-experiment) hydration band measurement.
NC = No change. CH = changed hydration band measurement.
DH = diffuse hydration band. NVB = no visible band.

Table 15. Obsidian hydration analysis results for specimens heated at 200°C for 12 hours in sand.

Specimen #	Result	H1 (μm)	H2 (μm)
143	DH	3.3	DH (~3.3)
144	DH	2.9	DH
145	DH	6.2	DH (w)
146	DH	1.8	DH
147	DH	1.8	DH

Key: H1 = first (pre-experiment) hydration band measurement.
H2 = second (post-experiment) hydration band measurement.
DH = diffuse hydration band. (w) = weathered.

All five specimens heated at 300°C (572°F) for 1.3 hours in crucibles submitted for hydration analysis had diffuse hydration bands (Table 17). Of the five specimens heated at 300°C for 12 hours in crucibles one showed a diffuse hydration band and four had no visible hydration band (Table 18).

Table 16. Obsidian hydration analysis results for specimens heated at 200°C for 12 hours on sand.

Specimen #	**Result**	**H1 (μm)**	**H2 (μm)**
148	DH	2.4	DH (~ 2.5)
149	DH	2.4	DH
150	DH	2.4	DH
151	DH	1.4	DH
152	DH	1.7	DH

Key: H1 = first (pre-experiment) hydration band measurement.
H2 = second (post-experiment) hydration band measurement.
DH = diffuse hydration band.

Table 17. Obsidian hydration analysis results for specimens heated at 300°C for 1.3 hours in crucibles.

Specimen #	**Result**	**H1 (μm)**	**H2 (μm)**
133	DH	1.2	DH
134	DH	2.8	DH
138	DH	1.2	DH
139	DH	2.1	DH
140	DH	5.5	DH

Key: H1 = first (pre-experiment) hydration band measurement.
H2 = second (post-experiment) hydration band measurement.
DH = diffuse hydration band.

Table 18. Obsidian hydration analysis results for specimens heated at 300°C for 12 hours in crucibles.

Specimen #	**Result**	**H1 (μm)**	**H2 (μm)**
104	NVB	4.7	NVB (w)
105	NVB	6.0	NVB (w)
107	DH	3.2	DH
110	NVB	1.4	NVB
112	NVB	2.2	NVB (w)

Key: H1 = first (pre-experiment) hydration band measurement.
H2 = second (post-experiment) hydration band measurement.
DH = diffuse hydration band. NVB = no visible hydration band.
(w) = weathered.

Discussion

As in previous field and laboratory studies (Linderman 1993; Lentz et al. 1996; Deal 1997; Green 1997; Skinner et al. 1996; and studies in this volume), damage to obsidian hydration bands became more prevalent and severe as maximum temperature and duration of exposure to elevated temperatures increased (Table 19). Temperature and duration were the primary factors determining whether exposure to fire or heat damaged the bands; neither geochemical source, specimen weight nor first (pre-experiment) hydration band width had a discernible influence on the obsidian hydration analysis results.

Table 19. Summary of obsidian hydration analysis results from Boggs Mt. DSF control, field and laboratory experiments.

Treatment			**Results (number specimens submitted for analysis)**	
Control sample			NC: 90%; CH: 10%	(10)
Field experiments				
May 1998 broadcast burns			NC: 50%; CH: 50%	(10)
May 1998 slash pile burn			NC: 37.5%; CH: 25%; DH: 25%; NVB: 12.5%	(8)
Laboratory experiments				
Temp.	Duration	Placement		
100°C	24 hours	sand	NC: 100%	(5)
125°C	24 hours	sand	NC: 80%; CH: 20%	(5)
200°C	2 hours	crucibles	NC: 80%; CH: 0%; DH: 20%	(5)
200°C	12 hours	crucibles	NC: 50%; CH: 20%; DH: 20%; NVB: 10%	(10)
200°C	12 hours	sand	NC: 0%; CH: 0%; DH: 100%	(5)
200°C	12 hours	On sand	NC: 0%; CH: 0%; DH: 100%	(5)
300°C	1.3 hours	crucibles	NC: 0%; CH: 0%; DH: 100%	(5)
300°C	12 hours	crucibles	NC: 0%; CH: 0%; DH: 20%; NVB: 80%	(5)
Total			NC: (35); CH: (11); DH: (21); NVB: (6)	(73)

Key: NC = no change. CH = changed hydration band measurement. DH = diffuse hydration band. NVB = no visible hydration band.

The significant proportion of specimens showing hydration band measurement changes of more than 0.4 microns after exposure to experimental conditions is an unanticipated result. The changed measurements may be direct results of exposure to elevated temperatures or they may reflect other factors, e.g., inaccuracies in the first (pre-experiment) hydration band measurements or changes in hydration band width during specimen curation. Re-measuring the bands from the original slides used for the first (pre-experiment) measurements may help resolve this uncertainty. Since the significance of the changed measurements remains unclear at present, the following discussion relies on the presence of unmeasurable (diffuse hydration = DH and no visible band = NVB) hydration bands to indicate that exposure to fire or laboratory heat has affected the bands.

All specimens analyzed after exposure to the May 1998 broadcast burn had clearly defined, measurable hydration bands. Maximum recorded temperatures at the sampling sites did not exceed 101°C (214°F). Laboratory results provide additional detail. All the analyzed specimens heated at 100°C and 125°C (212°F and 257°F) for 24 hours also had intact, measurable hydration bands. Together these results suggest that it is unlikely that obsidian hydration bands will be damaged by exposure to temperatures under 100°C for periods less than 24 hours. The significance of the threshold of 100°C lies in the fact that water boils at this temperature. Soil temperatures will not rise above 100°C as long as any moisture remains in the soil (DeBano et al. 1998).

While soil surface temperatures may rise above 200°C for short periods during cool-burning prescribed fires in mixed conifer forests, maximum temperatures at two inches below soil surface often remain far below 100°C (Figure 3). This suggests a preliminary hypothesis – relatively cool-burning prescribed fires in mixed conifer forest vegetation types will not cause hydration bands of obsidian specimens located at least two inches below soil surface to become damaged and unmeasurable.

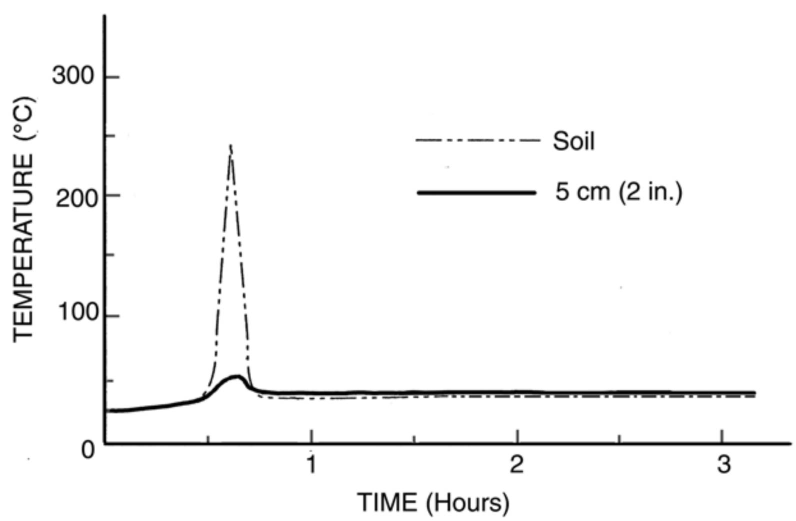

Figure 3. Surface and soil temperatures recorded under a cool-burning prescribed fire in mixed conifer forest (modified from Agee 1973).

Results from the May 1998 Boggs Mt. DSF broadcast burn can be compared with those from experiments conducted at Eldorado National Forest (Eldorado NF) in central Sierran Ponderosa pine-black oak vegetation types (Deal 1997; Deal and McLemore this volume). The Eldorado NF experiments involved two burns, one in fall 1996 and another in spring 1997, in which obsidian specimens were placed at soil surface and two inches below soil surface in the path of prescribed burns. As in the Boggs Mt. DSF May 1998 burn experiment, flame lengths did not exceed 3 feet. All three burns can thus be described as low intensity fires. The effects on hydration bands differed markedly in these three low intensity burns, however (Table 20). This variation suggests that fire intensity may not be a useful measurement for evaluating the potential for a given prescribed burn to cause obsidian hydration bands to become damaged and unmeasurable.

Table 20. Comparison of fuels conditions, fire behavior and obsidian hydration analysis results in the May 1998 Boggs Mt. DSF and Fall 1996 and Spring 1997 Eldorado NF broadcast burns (Deal 1997).

Characteristic	**May 1998** **Boggs Mt. DSF burn**	**Fall 1996** **Eldorado NF burn**	**Spring 1997** **Eldorado NF burn**
Site conditions			
Fuel loading	3.6 tons/acre	16.0-31.0 tons/acre	< 4.0 tons/acre
Soil moisture	47%	26%	n/a
Fire behavior			
Flame length	< 2 feet	1-3 feet	0.25-1 foot
Maximum temperature	<101°C (214°F)	571°C (971°F)	n/a
Duration of raised temp.	*ca*. 2 hours ?	> 48 hours	*ca*. 4 hours
Fire effects			
Site characteristics	Blackened ground surface, intact duff layer and incomplete fuels consumption.	Thick ash layer covering site, and duff layer and fuels <1 inch diameter mostly completely consumed.	n/a
Hydration analysis (no. specimens)	NC: 50%; CH: 50% DH/NVB: 0% (10)	NC: 33%; CH: 0%; DH/NVB: 67% (27)	NC: 67%; CH: 0%; DH/NVB: 33% (27)

Key: NC = no change. CH = changed hydration band measurement. DH = diffuse hydration band. NVB = no visible hydration band.

In contrast to fire intensity, which describes the amount of energy released by the flaming front of a fire and can be calculated directly from flame length, fire severity describes the quantitative and qualitative effects of a fire based on post-fire site characteristics (Skinner and Chang 1996; DeBano et al. 1998). While fire severity is often quantified in terms of percent tree mortality, severity can also be described in terms of post-fire fuels, duff and ash conditions (Table 21; Lentz et al. 1996). Comparing post-fire site characteristics for the May 1998 Boggs Mt. DSF and Fall 1996 Eldorado NF broadcast burns indicate while both were low intensity fires, the former had light fire severity and the latter moderate to heavy severity (Table 21). The effects on hydration bands are correspondingly distinct:

none of the specimens analyzed after the May 1998 DSF burn had damaged, unmeasurable bands while 67% of those from the Fall 1996 Eldorado NF burn did. Fire severity may be a more useful measurement for evaluating the potential for a prescribed burn to damage hydration bands.

Table 21. Fire severity classification based on post-fire site characteristics (Lentz et al. 1996).

Fire severity	Post-fire characteristics
Light	• Some degree of intact duff layer.
	• Blackened surface immediately after the fire.
	• Some small twigs and much branch wood remaining unburned.
	• Light ground char.
Moderate	• Full consumption of leaf and needle litter.
	• Deeply charred duff but unaltered mineral soil.
	• Light colored ash covering the surface immediately after the fire.
	• Largely consumed branch wood with no foliage or twigs remaining.
Heavy	• Complete consumption of duff and litter.
	• Visible alteration of top layer of mineral soil, e.g., subsurface blackening.
	• Few large branches remaining; those and all remaining sound logs deeply charred.
	• Deep ground char occurring in scattered patches.

Projected fire severity for a prescribed burn is described (albeit sometimes indirectly) in the specific prescription under which each burn occurs. Assessing descriptors such as total fuel loading, total anticipated fuel consumption and desired post-burn duff layer can provide insight into the likely fire severity for a burn. For example, the Boggs Mt. DSF prescription notes low fuel loads and planned fuel consumption (3.46 and 2.25 tons/acre respectively) and specifies that at least an 0.25 inch duff layer should remain after a prescribed burn. In contrast, complete fine fuels and duff layer consumption was a goal of the Fall 1996 Eldorado National Forest prescribed burn (Deal 1997)

Fuel loads and duration of raised temperature for the Spring 1997 Eldorado NF burn are similar to those from the May 1998 Boggs DSF burn. Fuels and duff layer consumption figures and time/temperature charts for the Spring 1997 Eldorado NF burn are not available (Deal 1997). One can note, however, that none of the specimens placed at two inches below the soil surface under that fire had damaged, unmeasurable bands in the post-fire obsidian hydration analysis. This finding lends additional support to the above-mentioned hypothesis that relatively cool-burning prescribed fires in mixed conifer forest vegetation types will not cause hydration bands of obsidian specimens located at least two inches below soil surface to become damaged and unmeasurable.

The laboratory experiment results reported above suggest that while maximum temperature is the most important factor in determining whether exposure to elevated temperatures will damage hydration bands, the duration of exposure is also an influential variable (see also Deal 1997; Deal and McLemore this volume). Specimens heated at 200°C for 12 hours showed a far greater proportion of damaged, unmeasurable hydration bands (65%) than did those heated at the same temperature for only two hours (20%) (Table 22). A similar pattern can be observed in comparing results for specimens heated at 300°C for 12 and 1.3 hours. Previous research has suggested that hydration band diffusion precedes loss of a visible band (Skinner et al. 1996).

Table 22. Comparison of obsidian hydration results for specimens heated in the laboratory at 200°C and 300°C for short (2 hour or less) and long (12 hour) durations.

Temperature	Duration in hours	Results (number of specimens analyzed)	
200°C	2	NC: 80%; CH: 0%; DH: 20%; NVB: 0%	(5)
200°C	12	NC: 25%; CH: 10%; DH: 60%; NVB: 5%	(20)
300°C	1.3	NC: 0%; CH: 0%; DH: 100%; NVB: 0%	(5)
300°C	12	NC: 0%; CH: 0%; DH: 20%; NVB: 80%	(5)

Key: NC = no change. CH = changed hydration band measurement.

DH = diffuse hydration band. NVB = no visible hydration band.

Sample placement also appears to affect the laboratory results. In experiments in which temperature and duration were held constant while sample placement was varied, specimens placed in and on sand showed more consistent and more severe effects, while specimens placed in crucibles showed more variable and less severe effects (Table 23). During a fire obsidian specimens may be exposed to a complex mixture of radiant, convective and conductive heat. Specimens placed in and on sand may have received different proportions of these heat types than did specimens placed in crucibles. Matrix geochemistry may have also influenced the results, as silica is a major component of both sand and obsidian.

Laboratory results suggest several time/temperature thresholds. Exposure to temperatures under 125°C (257°F) for up to 24 hours may not cause hydration bands to become unmeasurable. Damage to the bands begins to appear at exposure to temperatures around 200°C (392°F). Diffuse hydration bands may develop after exposure for two hours or less. Longer exposure may lead to a greater incidence of damaged, unmeasurable bands. Exposure to temperatures of 300°C (572°F) and above for periods of at least 1.3 hours will likely damage hydration bands, rendering them diffuse or not visible at all.

Table 23. Comparison of obsidian hydration results for specimens heated in the laboratory at 200°C for 12 hours in crucibles, in sand and on sand.

Temp.	Duration	Placement	Results (number of specimens analyzed)
200°C	12 hours	In crucibles	NC: 50%; CH: 20%; DH: 20%; NVB:10% (10)
200°C	12 hours	In sand	NC: 0%; CH: 0%; DH: 100%; NVB: 0% (5)
200°C	12 hours	On sand	NC: 0%; CH: 0%; DH: 100%; NVB: 0% (5)

Key: NC = no change. CH = changed hydration band measurement. DH = diffuse hydration band. NVB = no visible hydration band.

These results are consistent with results from the May 1998 field experiments at Boggs Mt. DSF and with previous field and laboratory research. After field experiments in which a total of 90 obsidian specimens was placed in the path of a prescribed burn conducted in sagebrush vegetation at Modoc National Forest Green et al. (1997) suggest that hydration bands may become diffused at temperatures above 204°C (400°F) and that bands are certainly affected by temperatures above 343°C (649°F). When inducing hydration in freshly exposed obsidian surfaces by immersing them in heated solutions under pressure Tremaine (1989) found that processing obsidian at temperatures above 200°C (392ºF) produced significant proportions of poorly defined, diffuse and difficult to measure hydration bands. This problem did not occur so long as maximum temperatures remained below 200°C. In assessing laboratory experiments in which single obsidian specimens were placed in crucibles and heated at various temperatures for one hour Skinner et al. (1996) found that changes to the hydration bands first occurred at 200-300°C (392-572ºF).

Conclusions and Research Needs

Assessing the effects of prescribed burning on obsidian hydration bands is a challenging and complex task. Prescribed burns involve landscape fire, and landscape fire is an inherently variable phenomenon. Fires in different vegetation types with different fuels, soil and weather conditions produce different soil surface and sub-surface maximum temperatures and time/temperature profiles (DeBano et al. 1998). Taking accurate temperature measurements of fires is difficult because of "the ephemeral nature of the fire, the high temperatures involved, the steep temperature gradients and the high spatial heterogeneity" (Martin 1984: 141). These qualities also suggest that precisely replicating fire behavior and effects under field conditions is difficult, if not impossible. Laboratory experiments allow for the control of a number of specific variables, e.g., temperature, duration of increased heat, sample placement and sedimentary matrix, chemistry and moisture, and can be replicated to confirm results or test effects of additional variables.

Laboratory experiments assessing the effects of heat on hydration bands are a potentially valuable adjunct to prescribed fire and obsidian studies. Ultimately, however, the laboratory experiments are only relevant insofar as the laboratory conditions can be directly correlated with actual prescribed burn conditions. Fires generate three different types of heat (radiant, convective and conductive) in varying proportions, and it is not clear whether the heat created in a laboratory oven or muffle furnace creates similar conditions. Other uncertainties remain as well. An obsidian specimen in the path of a fire may be exposed to various momentary physical and chemical conditions that are difficult to replicate in the laboratory, and fires can alter physical and chemical properties of the surrounding soil or matrix.

A practical approach to this problem is to determine whether results from field experiments can be replicated in the laboratory. If field results can be replicated in laboratory experiments, then the myriad differences between exposure to fire and to laboratory heating regimes are not significant factors in the effects of prescribed burning on obsidian hydration bands. The maximum temperature data generated in the 1998 Boggs Mt. DSF field experiments are not sufficient for conducting laboratory replication experiments, however. Accurate time/temperature curves from experiments in which obsidian specimens with previously measured hydration bands have been placed in the path of prescribed burns are required (e.g., Deal 1997; Deal and McLemore this volume). Field experiments that generate such data are rare, as specialized equipment and trained personnel are needed to measure the changing temperatures at each sampling site accurately.

Analysis of the results from the field and laboratory experiments conducted in this study has suggested a preliminary hypothesis – that relatively cool-burning prescribed fires in mixed conifer forest vegetation types will not cause hydration bands of obsidian specimens located at least two inches below soil surface to become damaged and unmeasurable. This proposal is supported not only by the experimental results but also by the theoretical consideration that sub-surface soil temperatures will not rise above 100°C (212ºF) so long as any moisture remains in the soil and the practical knowledge that prescribed fires that are intended to be cool-burning are conducted under conditions of relatively high atmospheric humidity and fuels and soil moisture (Biswell 1989). This hypothesis remains an educated guess based on research and logic; it is not a finding based on direct experimentation.

The data presented above can be used to address the research questions identified at the outset of this study, so long as the limitations of the data set are made explicit. The small sample sizes used in this study limit the robustness of the data. Additionally, selecting obsidian specimens with hydration bands that had been measured several years previously in archaeological studies created uncertainty about whether the changed post-experiment hydration band measurements are a direct result of exposure to experimental conditions or other factors. This study has, however, suggested the following tentative conclusions:

Exposure to broadcast burns in a Ponderosa pine-mixed conifer forest with fuel loads under four tons/acre conducted when relative humidity is above 35%, wind speeds are 0-2 mph, 100 hour fuels moisture content is above 28% and soil moisture is above 45% is unlikely to cause obsidian hydration bands of specimens located at soil surface to become damaged and unmeasurable. Exposure to slash pile burn conditions under the same weather, fuels and soil conditions is likely to damage some bands of specimens located at soil surface.

Both maximum temperature and duration of exposure to elevated temperature are important factors. Further research is necessary to determine whether exposure to temperatures below 100°C (212°F) for less than 24 hours does not damage hydration bands. Fire severity may be a more useful measurement than fire intensity in determining thresholds beyond which hydration bands are consistently altered or damaged.

Maximum temperature and duration of exposure to elevated temperatures appear to be the most influential factors in affecting hydration bands. Soil moisture is linked to temperature and duration, as soil temperatures will remain below 100°C as long as moisture remains in the soil. The effects of soil chemistry remain uncertain. Obsidian source was not an influential factor in this study, but only four geochemical sources from a restricted geographical area are represented in the samples. Neither hydration band width nor specimen weight appeared to affect the results.

Further research is necessary to determine whether field results can be replicated in laboratory experiments. The maximum temperature data generated in this study are insufficient for such research; time/temperature curve data are required.

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MEADOW CANYON PRESCRIBED BURN: EFFECTS OF FIRE ON OBSIDIAN HYDRATION BANDS

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Introduction

Upon manufacture, the freshly exposed surface of an obsidian artifact begins absorbing water and a visible hydration band gradually forms. By measuring the width of this band at high magnification, archaeologists can determine how long the obsidian has been absorbing water as well as the relative age of the artifact. Measurements from a large sample of obsidian artifacts and flakes can provide a relative chronology of cultural horizons and under certain conditions direct dates can be obtained (Origer personal communication, 1999). Moreover, Deal (1997:15-17, 1999:2, 14-15), Origer (personal communication, 1999), and Gates (personal communication, 1999) propose that hydration band analysis can provide information about prehistoric fire patterns not possible through tree ring dating or other analytical tools.

Fire affects obsidian by reducing or increasing hydration band width, by diffusing bands so they can no longer be accurately measured, or by eliminating bands entirely, thereby destroying valuable archaeological data. It is therefore easy to understand why scientists are concerned about the potential loss of data during wildfires and prescribed burns.

Forest Service fire management and line officers have argued that since natural wildfires must have taken place repeatedly on archaeological sites in the past, prescribed fires should pose no more threat than natural fires. Yet archaeologists are reluctant to allow prescribed burns on sites with obsidian artifacts until more is understood about the hydration process and its reactions to fire. Furthermore, archaeologists suggest that repeated burning by Native Americans around archaeological sites may have prevented sites from burning prior to white contact, or kept fuel loads low enough to keep wildfires from damaging hydration bands (Anderson 1993:25).

However, most scientists still consider obsidian hydration analysis a reliable and relatively inexpensive dating tool (Ericson 1978; Origer 1996; Deal 1997, 1999). Unless proven otherwise, hydration band analysis must be considered a chronological tool of value to scientists and fire management personnel.

Previous Obsidian Studies

Previous studies have shown that fire affects a variety of archaeological resources (Burgh 1960; Switzer 1974; Pilles 1982, 1984; Lentz 1996; Origer 1996; Trembour 1990; Picha et al. 1991; Rowlett 1991a, 1991b; Wettstaed 1993; Swan and Francis 1988; and Cavaioli n.d). Origer (1996) and (Lentz) 1966 have discussed the effects of fire on obsidian hydration bands. However, relatively few studies have looked at hydration bands both before and after exposure to fires (Linderman 1991; Deal 1997; Green et al. 1998; Benson 1999). Previous studies by Linderman (1991), Deal (1997), and Green et al. (1997) suggest that fuel load, maximum temperature, and duration of heat probably are the major factors involved in damage to obsidian artifacts during fires.

1989 Regional Forester's Challenge Grant Study, Willamette National Forest. In 1989, an experimental prescribed burn was conducted on the McKenzie Ranger District of the Willamette National Forest (Linderman 1991). The burn was designed to refine our understanding of the effects of temperature on obsidian artifacts. Phase I of the study was a prescribed burn in Bunchgrass Meadow, which was selected because of the well documented history of Native American burning in high Cascade meadows. It should be noted that this was a low intensity (light fuel load) prescription burn in a grassland meadow. Before the burn, 20 obsidian artifacts were sent to an obsidian lab, where the hydration bands were measured. After the burn, the bands were once again measured and no detrimental effect was observed.

Phase II involved moderate fuel loads in six slash disposal units. Sixty obsidian specimens with measured hydration rinds were placed in preselected burn plots centered with metal stakes. Temperature sensitive dots and liquid paints with temperature thresholds ranging from 325° to 1400°F were used to determine temperatures. Half the obsidian specimens were placed on the surface; the other half were placed approximately 3.5 cm below surface (duff). Fifty-four of the 60 specimens were retrieved after the burn. Results from this part of the study were dramatically different:

> Of fifty-four flakes that were submitted, only six flakes were not effected [*sic*] by the temperatures of the slash burning.... All of the surface flakes and most subsurface flakes were affected by the temperature generated by the fire; there were no measurable hydration rinds (Linderman 1991:8).

Linderman (1991:8-9) notes that unaffected flakes were in high BTU units, where "flames traveled across the five-meter field test plots in 48-60 seconds, with a flame height of approximately three feet." Linderman (1991:9) was unable to explain why three of the six samples that were treated to temperatures in excess of 1400°F were not affected, and speculates that because they were in high surface BTU units "the heat was enough to alter the subsurface artifact's paint but not of sufficient duration to remove the hydration rind." Linderman recommends further studies to understand these ambiguous results.

Eldorado National Forest Obsidian Hydration Study. Deal (1997, 1999), Eldorado National Forest, conducted obsidian hydration studies before and after two prescribed burns in areas of commercial timber, measuring temperature and duration of heat. The first burn took place in an area that had no history of fire for the past 68 years; the second study took place in an area with a history of repeated prescribed burns.

Although results of thermocouple readings from this study are not yet available, preliminary results from this study indicate that damage to obsidian hydration rinds was significantly greater after the fire in the area with no recent fire history, although damage also occurred in the area with a history of repeated prescribed burns (Deal 1997).

Warner Range Study. Green et al. (1997), Modoc National Forest, studied the effects of a prescribed fire on obsidian hydration rinds. The prescribed fire was ignited in a high altitude sagebrush flat, with varying densities of sagebrush, forbs, and grasses. Tom Origer, Sonoma State University Obsidian Laboratory, measured hydration bands of 90 specimens measured before and after the prescribed burn. The obsidian specimens were treated to three fuel conditions: light, moderate, and heavy.

Temperatures were measured with temperature sensitive tablets, crayons, and paint, which do not yield exact temperatures, but a range. Red tablets melted at 300°F, green at 400°F, yellow at 650°F, and blue at 932°F. Four tablets (red, green, yellow, and blue) were placed under each obsidian specimen. (Green et al. 1997:7-8)

Thirty of the specimens were placed in the low fuel area, where they were originally found. The remaining 60 specimens were placed in areas where the desired fuel loads existed (moderate and heavy fuel areas). (Green et al. 1997:5).

Twenty-five specimens in the light fuel load area were unaffected by the fire and five lost definition of the obsidian rind. Moderate and heavy fuel loads, with higher temperatures, affected a larger number of hydration bands. The number of specimens affected in the high fuel plot was almost identical to that for medium fuels (Green et al. 1997:13-14).

Green concludes that fires in areas of low fuel loadings--where temperature are kept below 400 degrees--will have no significant effect on hydration bands. "Somewhere above 500 degrees and perhaps above 500 or even 550 degrees the hydration rind is affected, causing it to become diffuse and unreadable" Green et al. (1997:14-15). Results from the Meadow Canyon study demonstrate that hydration rinds are damaged at much lower temperatures than suggested by Green's study.

Meadow Canyon Study

In order to restore the health and integrity of plant communities in the Meadow Canyon area of the Toquima Range in central Nevada, the Tonopah Ranger District plans to restore fire as a natural ecosystem recycling process in the sagebrush-grass-forb plant community. However, a dilemma in using prescribed fire as a vegetation management tool emerged in the context of archaeological resources protection. An obsidian hydration study was proposed to determine effects of prescribed fire on the integrity of prehistoric resources in the Meadow Canyon area. Information from this study will help us design ecosystem restoration plans compatible with the protection of our archaeological heritage. (Brack 1996)

Research Design

The purpose of the Meadow Canyon study was to determine the effects of different intensity fires on obsidian hydration bands as well as the effects of fire on chert artifacts. Based on results from previous studies, the Tonopah Ranger District proposed an experiment to study the effects of fire associated with light, moderate, and heavy fuel loads on obsidian hydration bands and determine a relatively "safe" temperature range for obsidian.

The research design called for a large, statistically valid sample with minimal variables. Ninety obsidian specimens were treated to light, moderate, and heavy fuel loads, with two replicate plots for each condition. Ten specimens were set aside for control. All obsidian specimens were placed on the surface. Maximum temperature and duration of exposure were recorded by thermocouples and recorded on data loggers outside the fire line.

Research Hypotheses:

H0: Prescribed fire does not affect obsidian hydration bands, and there is no difference in the effect by fire intensity.

H1: Prescribed fire does affect obsidian hydration bands, and the effect varies by fire intensity.

Because there was insufficient time to gather enough obsidian artifacts and measure their hydration bands before the scheduled burn, 100 obsidian artifacts with hydration bands that had been measured previously at different hydration labs were borrowed from the Modoc National Forest. All specimens were measured after the burn by Tom Origer, Obsidian Laboratory, Sonoma State University.

Since chert is an ubiquitous tool material found at sites in central Nevada, 90 specimens of chert also were included in the experiment. The chert specimens consisted of crude flakes manufactured for the experiment from raw chert collected from a prehistoric chert quarry in the Shoshone Range, about 40 miles west of Meadow Canyon. The flakes varied in size from about 0.5 centimeters to more than 5 centimeters in length. Most of the flakes manufactured for the study were about 1-1.5 centimeter in length. No archaeological artifacts were included. The experiment took place on the morning of September 23, 1997, in Meadow Canyon, Nye County, Nevada.

Research Environment. Meadow Canyon, located on the east slope of Mount Jefferson at an altitude of 8,400 feet, contains large stands of decadent sagebrush, individual plants often reaching more than eight feet high. The study area is a bowl-shaped geological feature approximately 1 x 2 miles in diameter, cut by a vigorous perennial stream. Bordering the stream are low ridges containing moderately dense lithic scatters of chert and obsidian tools and waste flakes, and groundstone. Nearly every ridgeline contains a site. Presence of groundstone indicates that the Native Americans who populated this region prior to the arrival of Europeans processed grasses, roots, and/or medicinal plants at these locations.

Native American Burning Practices. Ethnographers Julian Steward and Omer Stewart both refer to the burning practices of the Paiute and Shoshone peoples who occupy the Great Basin.

> The brush in "basins" in the hills near the winter [Paiute] villages was burned and *Mentzelia* and *Chenopodium* seeds were broadcast. There is no question that this practice was native, for it was described *in all parts of north central Nevada* [emphasis mine]. (Steward 1938:104).

Stewart repeatedly commented on Native American burning practices specific to central Nevada, as well as the Great Basin as a whole. Fire as a land management tool clearly has a long history in the Great Basin and in Meadow Canyon specifically.

With the arrival of white settlers and mineral prospectors in the 1860s, and subsequent large scale mining, the Western Shoshone were left with little choice but to adopt wage labor as their primarily mode of subsistence, and to a large extent abandoned traditional practices of gathering native plants. Change in subsistence modes and, finally, fire abatement practices established by government agencies effectively stopped widespread burning of native plants and grasses. This is the probable scenario for what happened in Meadow Canyon. The Tonopah District hopes to reintroduce fire into the ecosystem and bring back native grasses.

The Meadow Canyon Prescribed Burn. September 22, 1997, the day before the burn, nine subplots were selected in a rectangular area 132 x 174 feet (about 0.53 acre). Three test plots with sparse ground cover of forbs, grasses, and light sagebrush were designated for light fuel loads, three with forbs, grasses and moderately dense sagebrush were designated for moderate fuel loads, and three with very dense sagebrush were designated for heavy fuel loads. Fuel and soil moisture content were measured prior to ignition.

Stephen Sackett, Sally Haase, and Gloria Burke, scientists from the Pacific Southwest Research Station in Riverside, California, positioned thermocouples in the test plot to provide accurate measurements of maximum temperatures and duration of heat. Once the thermocouples were in place, 90 obsidian artifacts and 90 chert flakes were distributed equally among the nine test plots. Two pieces of chert and two pieces of obsidian were placed as close as possible (about 1-2 centimeters) to each thermocouple. All specimens were placed on the ground surface; however, some thermocouple readings were taken below surface.

The morning of September 23, 1997, the fire crew ignited the burn on the upslope side of the test plot. Fifteen-foot flames quickly shot up and the fire rapidly spread across the test. The fire was over within 10 minutes. (Sackett and Haase 1998). The following morning, 89 of the 90 obsidian specimens were recovered. All of the chert flakes were severely damaged and many had shattered beyond recognition. Total recovery of the chert was therefore impossible. The 89 recovered obsidian specimens were sent along with the control specimens to the Obsidian Laboratory, Sonoma State University, where the hydration bands were measured by Tom Origer.

Results

Table 1 shows maximum temperature and change in hydration rind thickness. Table 2 contains data for the 10 control specimens. Table 3 lists maximum temperature and duration of time exposed to temperatures above 80, 100, and 140°F. Table 4 shows temperatures below and above 500°F as related to unaffected and affected hydration data. Although the flames died down after only 10 minutes, temperatures above 140°F persisted over 12 hours after ignition at one location.

Heavy Fuel Subplots. Only one specimen in heavy fuel subplots (No. 1370-20a) was not affected. Although the hydration band of this specimen was diffuse, Origer was able to measure the hydration band thickness at 4.0 microns, a change of only 0.2 microns. The (subsurface) thermocouple probe recorded a maximum temperature of 96°F; no surface temperature was recorded for this specimen.

Hydration bands of all other specimens were either diffuse or not visible after the fire. Maximum surface temperatures ranged from 169 to 1324°F. A combination of high temperatures, long exposure durations (5.6 to 25.7 hours), and heavy fuel loads proved detrimental to obsidian hydration rinds, fully supporting the hypothesis (H1). (Table 1, page 3 and Table 3, page 3)

Moderate Fuel Subplots. Results in moderate fuel subplots were slightly different. Only three specimens were unaffected. Two of these were exposed to a maximum temperature of 183°F and one specimen to 1033°F. Surface temperatures of affected specimens ranged from 177°F to 1033°F. (Table 3, page 2)

Fifteen specimens exposed to temperatures below 500°F were affected; nine specimens treated to higher temperatures (above 500°F) were affected (Table 4). Specimen No. 1307-1b was exposed to a high temperatures of 1033°F, but to temperatures above 100°F for only 1.0 hour (Table 3, page 2). As in Linderman's study, duration of exposure may explain why this hydration band was not affected. Note that the Meadow Canyon results refute Green's (1997) statement that temperatures under 400°F probably do not damage hydration rinds. Temperatures at which damage occurred were much lower in the Meadow Canyon study.

Overall, duration of exposure was a factor, particularly when compared with specimens from light fuel and heavy fuel plots; yet some results are puzzling. Why, for example were hydration bands of two specimens affected when treated to maximum temperatures of only 165°F and temperatures over 100°F for less than 0.4 hour?

Light Fuel Subplots. Hydration bands on 12 specimens in low fuel plots were not affected, while 16 were affected. The band of one specimen that was reported as diffuse before the fire was measurable after the fire.[1] Thermocouple readings are not available for this anomalous specimen. Surface temperatures in low fuel plots ranged from 98°F to 820°F, lower overall than temperatures in moderate and heavy fuel plots.

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[1]This anomalous result may be due to different lab technicians before and after the fire.

Several results are quite surprising. Five of 12 hydration bands not affected were exposed to maximum temperatures of 530°F and higher, while only four of the affected specimens were treated to 530°F or higher. Furthermore, eight affected hydration bands were exposed to low temperatures ranging from 98 to 499°F (See Table 4). Duration of exposure was not always a factor, as evidenced by specimen Nos. 407-1511f and 407-1621b, which were treated to a relatively high temperature of 549°F and to temperatures above 100°F for 6.0 hours (Table 3, page 1). Looking at the same table, the above may be contrasted with those for specimen No. 407-1499q, exposed to 161°F and above 100°F for only 1.3 hours.

Chert Results. All chert specimens in this study were severely damaged; those that survived were covered with a thick coat of soot. Many pieces shattered into so many fragments, it was impossible to collect all the pieces. All of the large and many of the medium size flakes shattered into tiny fragments. Many of the smaller flakes were structurally unchanged, but altered in other ways. Although analysis of the chert specimens was limited to visual observation, this study demonstrates that fire is highly detrimental to chert artifacts. Since 90% of tool stone on the Tonopah Ranger District is chert, sites should be protected from all fires. It would be interesting to know whether heat-treated chert artifacts withstand the effects of fire better than the raw chert used in this study.

Control Sample. Hydration band measurements for the ten control specimens also changed (Table 2), but all were measurable. Three measurements deviated from the original reading by 0.2 microns or less, which is not significant. Technicians normally take six separate measurements of each sample, using the mean of all six measurements. Typically, individual measurements by the same technician often fluctuate as much as 0.2 microns. Measurements taken by different technicians also deviate, and some technicians tend to obtain consistently higher or lower measurements than the mean (Stevenson, Dinsmore, and Scheetz 1989), which may in part explain the deviations observed within the control samples. Further comments are reserved until further study.

Summary of Results

Results from the Meadow Canyon study confirm that fire affects obsidian hydration bands and that there is a direct relationship between fuel load (and temperature) and effect. Obsidian samples in heavy and moderate fuel plots were more likely to be affected than those treated to light fuel loads, confirming the H1 hypothesis. The null hypothesis (H0) was rejected.

We also learned that some obsidian specimens treated to high temperatures are not affected. Overall, more affected specimens were treated to temperatures below 500°F than above, which was not expected.

This study suggests that a more realistic "safe temperature range" probably falls between 250-300°F, or lower. At present, fire management manuals place this safe range at 500°F. Clearly, the safe temperature range should be lowered. A few hydration bands will be damaged regardless of temperature and a few will be unaffected by extremely high temperatures.

Implications and Recommendations

Although test results demonstrated that heavier fuel loads are more detrimental to obsidian hydration bands, the present study showed that most hydration bands treated to temperatures above 300°F will be affected. This is significantly lower than the temperatures currently recommended in fire management handbooks.

Until we have a better understanding of the effects of fire on hydration bands, we should try to prescribe burns below 300°F when obsidian is present. Even this will not guarantee protection of all obsidian hydration bands. Archaeologists and fire management personnel should take active steps to protect sites before prescribed fires. Sagebrush and other undergrowth can be cut and removed from sites before the burn. One National Park Service archaeologist provides his survey crew with pruning shears. Exposed obsidian artifacts and flakes identified prior to a fire can be removed or buried, and locations mapped and recorded. With low fuel loads, depths of 3-4 centimeter probably are acceptable, but higher temperatures will require greater depths.

Further research may explain why so many artifacts exposed to low temperatures were damaged during the Meadow Canyon fire and, conversely, why some hydration bands endured high temperatures.

Future temperature related studies should probably take place in the lab. Origer (see Loyd, this volume) and Sackett both have proposed heating obsidian samples in ovens, where temperatures can be controlled. This procedure is also much less expensive than a prescribed burn. In the lab it should be possible to concentrate on temperature without other factors interfering, but length of exposure should also be tested. It should be possible to determine what combinations of temperature and exposure time will avoid damaging obsidian rinds.

In the Meadow Canyon study, different obsidian lab technicians measured hydration bands on many of the specimens before and after the prescribed burn. Ideally, all specimens should be measured by the same technician before and after the fire. This does not appear to be a major problem in the present study, since most of the hydration bands disappeared or were diffused; however, it could be a problem in future studies, especially with low fuels.

Based on the results of the Meadow Canyon study, another study is recommended to validate or reject the results. As in the Meadow Canyon study, a large sample is recommended, but the study should concentrate on obsidian exposed to low temperatures and light fuel loads. Hydration rinds should be measured before and after the prescribed fire by the same lab technician. Obsidian sources also should be taken into consideration in order to determine whether obsidian from certain sources withstands higher temperatures than obsidian from other sources. Some samples should be placed under the ground surface in an attempt to determine depth at which obsidian is no longer affected.

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Stephen S. Sackett, Sally M. Haase, and Gloria Burke set up the thermocouples in the field and prepared the final report on temperatures and duration of exposure. I am particularly grateful for their expertise.

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Fire Management Officer Dave Haney and his crew prepared the burn plot and implemented the burn with the assistance of Mike Dondero, Fire Management Officer from the Carson Ranger District. I was impressed with the skill of the fire crew in managing the burn.

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Librarians and graduate students at the University of Nevada, Reno campus helped locate government publications with pertinent data. Diane Hartsock, Tonopah Public Library, obtained copies of many referenced publications.

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Table 1. Maximum Temperatures and Hydration Band Measurements Before and After Prescribed Fire.

LOW FUEL LOAD

	Before (mµ)	After (mµ)	Difference (mµ)	Maximum Temperatures Surface (°F)	Below Surface (°F)
Unaffected					
1390-12	4.0	3.6	-0.4	531	80
1390-32	5.7	5.8	+0.1	787	
1166-10b	5.2	7.2	+2.0		86
407-1618w	3.3	3.5	+0.2	530	130
407-1511f	3.7	3.2	-0.5	549	
407-1621b	1.8	1.5	-0.3	549	
407-1499y	4.3	~3.0	-1.3	161	
407-1679j	3.6	3.5	-0.1	98	108
407-1680i	3.1	3.0	-0.1	259	
407-1671f	3.0	~3.0	0.0	227	
407-1499h	1.8	1.2	-0.6	*	
407-1499w	3.7	DH (~4.0)	+0.3	322	
Affected					
1390-35	4.2	DH	NA	531	80
1342-2a	4.3	DH	NA	787	
1369-3b	3.8	DH	NA		86
1369-11a	3.2	DH	NA	379	
1166-6a	4.0	DH	NA	379	
1342-21a	3.2	DH	NA	499	
1369-7a	3.6	DH	NA	499	
407-1499ee	1.8	DH	NA	530	130
407-1618aa	3.6	DH	NA	322	
407-1499q	3.2	NVB	NA	161	
407-1706d	2.7	DH	NA	98	108
407-1697i	3.2	DH	NA	820	
407-1678h	3.5	NVB	NA	820	
407-1681l	3.2	DH	NA		141
407-1684f	NVB	DH	NA		141
1339-51b	3.8	*			
407-1682c	1.3	NVB	NA	227	
Anomalous Result					
407-1618v**	DH	3.7	NA	*	

* No data.

** Diffused band before fire; visible band after fire.

Table 1 (continued). Maximum temperatures and Hydration Band Measurements Before and After Prescribed Fire.

MODERATE FUEL LOAD

	Before (mµ)	After (mµ)	Difference (mµ)	Maximum Temperatures Surface (°F)	Below Surface (°F)
Unaffected					
1337-55b	4.5	3.5	-1.0	183	
1339-25a	3.6	DH (ca.3.5)	-0.1	183	
1307-1b	5.7	DH (ca.3.5)	-0.2	1033	
Affected					
1339-51a	4.3	NVB	NA	466	96
1339-55d	4.4	NVB	NA	307	
1307-6a	5.2	DH	NA	466	96
1344-68c	5.2	DH	NA	307	
1339-22a	48	DH	NA	1033	
1307-20a	4.4	DH	NA		98
407-1678a	2.6	DH	NA		98
1339-9b	4.9	NVB	NA	463	83
1260-3	1.6	NVB	NA	463	83
1260-5	1.5	NVB	NA	165	
1260-4a	3.0	DH	NA	165	
1337-53a	1.7	NVB	NA	373	
1336-58a	5.7	DH	NA	373	
1336-12b	4.3	DH	NA	572	
1260-12	2.7	DH	NA	572	
1336-48a	5.2	DH	NA	551	
1337-98a	1.8	NVB	NA	551	
407-1702b	2.6 + 3.8*	DH	NA	338	92
407-1702g	3.4	DH	NA	338	92
407-1699a	1.6	DH	NA	531	
407-1713a	1.6	DH	NA	531	
407-1709d	3.2	DH	NA	409	
407-1713h	2.9	DH	NA	409	
1336-12a	4.1	DH	NA	952	
407-1710i	2.0	DH	NA	952	
407-1711j	2.9	DH	NA	177	
407-1709b	4.8	NVB	NA	177	

* Two bands.

Table 1 (continued). Maximum Temperatures and Hydration Band Measurements Before and After Prescribed Fire.

HEAVY FUEL LOAD

	Before (mµ)	After (mµ)	Difference (mµ)	Maximum Temperatures Surface (°F)	Below Surface (°F)
Unaffected					
1370-20a	3.8	DH (c.4.0)	+.02		96
Affected					
407-1675a	2.1	NVB	NA	672	125
407-1684e	4.0	NVB	NA	672	125
407-1709k	4.1	DH	NA	424	
407-1684i	2.7	NVB	NA	424	
407-1684a	3.6	NVB	NA	815	
407-1684m	3.0	NVB	NA	815	
407-1723b	2.1	DH	NA	1324	
407-1676b	3.7	DH	NA	1324	
407-1719k	4.4	DH	NA	169	
1370-43b	4.3	DH	NA	596	102
1370-58a	3.6	DH	NA	596	102
1370-92a	4.3	DH	NA	799	
1370-57b	2.5	DH	NA	799	
1370-18b	3.8	DH	NA		96
1370-60c	1.5	DH	NA	501	
1370-55a	3.0	DH	NA	501	
1370-55c	3.1	DH	NA		546
1370-57a	3.4	NVB	NA		546
1344-68a	5.5	DH	NA	802	136
1344-81a	4.4	DH	NA	802	136
1370-18a	3.7	DH	NA		142
1344-7c	4.9	NVB	NA		142
1370-8a	3.7	NVB	NA	373	
1344-30a	5.4	NVB	NA	373	
1370-55b	1.6	NVB	NA	647	
1344-68b	4.7	NVB	NA	647	
1370-57c	3.6	NVB	NA	697	
1344-26a	4.5	NVB	NA	697	

Table 2. Control Sample Results.

	Before (mμ)	After (mμ)	Difference (mμ)
Control			
1344-3a	5.7	6.2	+0.5
1344-3b	5.8	5.7	-0.1
1344-7a	3.4	2.9	-0.5
1344-7b	3.6	3.2	-0.4
1344-26d	7.5	7.2	-0.3
1344-43a	4.3	DH (~4.4)	+0.1
1344-43c	4.0	3.4	-0.6
1344-81c	4.2	3.2	-1.0
1307-2b	5.0	3.4	-1.6
1307-3a	2.4	1.4	-1.0

Table 3. Temperature and Duration of Exposure

LOW FUEL LOADS

FSMA No.	**Temperature (°F)**		**>80°F (hours)**	**>100°F (hours)**	**>140°F (hours)**
	Surface	**Below Surface**			
Unaffected					
1390-12	531		4.2	1.8	0.6
“		80	0.1	0.0	0.0
1390-32	787		7.8	2.0	1.1
1166-10b	4.0	86	1.1	0.0	0.0
407-1618w	530		9.8	4.1	2.7
“		130	8.4	4.2	0.0
407-1511f	549		11.0	6.0	1.3
407-1621b	549		11.0	6.0	1.3
407-1499y	161		8.2	1.3	0.3
407-1679j	98		2.3	0.0	0.0
407-1680i	259		9.9	3.3	0.2
407-1671f	227		4.4	1.2	0.6
407-1499h	*				
407-1499w	322		10.1	4.0	0.7
Affected (DH/NVB)					
1390-35	531		4.2	1.8	0.6
“		80	0.1	0.0	0.0
1342-2a	787		7.8	2.0	1.1
1369-3b		86	1.1	0.0	0.0
1369-11a	379		6.9	2.4	0.9
1166-6a	379		6.9	2.4	0.9
1342-21a	499		7.3	2.5	1.0
1369-7a	499		7.3	2.5	1.0
407-1499ee	530		9.8	4.1	2.7
“		130	84	4.2	0.0
407-1618aa	322		10.1	4.0	0.7
407-1499q	161		8.2	1.3	0.3
407-1706d	98**		2.3	0.0	0.0
“		108**	4.3	0.6	0.0
407-1697i	820		9.2	4.3	1.6
407-1684f		141	2.9	1.0	0.0
407-1678h	820		9.2	4.3	1.6
407-1681l		141	2.9	1.0	0.0
1339-51b	259		9.9	3.3	0.2
407-1682c	227		4.4	1.2	0.6
Anomalous Result					
407-1618v***	*		*	*	*

* No data.

** Below ground temperature higher than surface temperature.

*** Diffuse band before fire; visible band after fire.

Table 3 (continued). Temperature and Duration of Exposure.

MODERATE FUEL LOADS

FSMA No.	Temperature (°F) Surface	Below Surface	>80°F (hours)	>100°F (hours)	>140°F (hours)
Unaffected					
1337-55b	183		3.9	1.0	0.3
1339-25a	183		3.9	1.0	0.3
1307-1b	1033		7.8	1.0	0.6
Affected (DH/NVB)					
1307-6a	466		13.4	7.9	5.6
"		96	4.0	0.0	0.0
1399-51a	466		13.4	7.9	5.6
"		96	4.0	0.0	0.0
1337-55d	307		8.6	4.3	2.7
1344-68c	307		8.6	4.3	2.7
1339-22a	1033		7.8	1.0	0.6
1307-20a		98	1.0	0.0	0.0
407-1678a		98	1.0	0.0	0.0
1399-9b	463		7.3	1.8	0.8
"		83	0.8	0.0	0.0
1260-3	463		7.3	1.8	0.8
"		83	0.8	0.0	0.0
1260-5	165		1.3	0.4	0.0
1260-4a	165		1.3	0.4	0.0
1337-53a	373		7.5	2.0	1.1
1336-58a	373		7.5	2.0	1.1
1336-12b	572		8.3	2.0	0.9
2160-12	572		8.3	2.0	0.9
1336-48a	551		4.0	1.6	0.5
1337-98a	551		4.0	1.6	0.5
407-1702b	338		8.4	3.9	2.5
"		92	3.3	0.0	0.0
407-1702g	338		8.4	3.9	2.5
"		92	3.3	0.0	0.0
407-1699a	531		17.1	8.3	3.6
407-1713a	531		17.1	8.3	3.6
407-1709-d	409		8.4	4.1	2.8
407-1713h	409		8.4	4.1	2.8
1336-12a	952		15.6	8.3	4.1
407-1710i	952		15.6	8.3	4.1
407-1711j	177		3.4	0.8	0.2
407-1709b	177		3.4	0.8	0.2

Table 3 (continued). Temperature and Duration of Exposure.

HEAVY FUEL LOADS

FSMA No.	Temperature (°F) Surface	Below Surface	>80°F (hours)	>100°F (hours)	>140°F (hours)
Unaffected					
1370-20a		96	1.6	0.0	0.0
Affected (DH/NVB)					
407-1675a	672		11.3	6.9	4.1
"		125	10.1	3.7	0.0
407-1684e	672		11.3	6.9	4.1
"		125	10.1	3.7	0.0
407-1709k	424		16.4	13.3	8.1
407-1684i	424		16.4	13.3	8.1
407-1684a	815		14.3	7.6	4.4
407-1684m	815		14.3	7.6	4.4
407-1723b	1324		11.9	7.1	3.8
407-1676b	1324		11.9	7.1	3.8
407-1719k	169		5.6	2.6	0.7
1370-43b	596		12.3	6.3	4.8
"		102	8.8	0.8	0.0
1370-58a	596		12.3	6.3	4.8
"		102	8.8	0.8	0.0
1370-92a	799		12.7	9.6	9.4
1370-57b	799		12.7	9.6	9.4
1370-18b		96	1.6	0.0	0.0
1370-60c	501		14.3	8.3	2.5
1370-55a	501		14.3	8.3	2.5
1370-55c		546	17.5	7.6	3.8
1370-57a		546	17.5	7.6	3.8
1344-68a	802		14.4	9.9	7.1
"		136	14.9	8.0	0.0
1344-81a	802		14.4	9.9	7.1
"		136	14.9	8.0	0.0
1370-18a		142	10.9	5.3	0.4
1344-7c		142	10.9	5.3	0.4
1370-8a	373		9.6	4.7	2.6
1344-30a	373		9.6	4.7	2.6
1370-55b	647		21.0	12.9	9.4
1344-68b	647		21.0	12.9	9.4
1370-57c	697		25.7	16.4	12.4
1344-26a	697		25.7	16.4	12.4

Table 4. Temperatures Above and Below 500° F.

(Note: Only surface temperatures included.)

	Light Fuel (° F)	**Moderate Fuel (° F)**	**Heavy Fuel (° F)**
UNAFFACTED SPECIMENS (Measurable hydration band)	98	183	none
	161	183	
	227	1033	
	259		
	322		
	*		
	530		
	531		
	549		
	549		
	787		
AFFECTED SPECIMENS (No visible band or diffused band)	98	177	169
	161	177	373
	227	165	373
	322	165	424
	379	307	424
	379	307	501
	499	338	501
	499	338	596
	530	373	596
	531	373	647
	787	409	647
	820	409	672
	820	424	672
		424	697
		466	697
		466	799
		501	799
		531	802
		551	802
		551	815
		572	815
		572	1324
		952	1324
		952	
		1033	

* No data

The Effect of Heat on Obsidian Density

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Introduction

When archaeologists first discovered that fire could alter the hydration rims of obsidian artifacts, some saw it as the final argument against obsidian hydration dating as a reliable method for site dating. Every site has been exposed to fire at some time during its formation process. Can any point or flake be known to have been untouched by fire during its entire history? Other papers in this volume address the effect of heat on hydration bands under various temperature and fuel conditions. Under many conditions fire-affected obsidian cannot be distinguished from non-fire-affected samples unless pre-fire hydration rim measurements are known. This study examines the change in another dimension, density, in obsidian samples exposed to heat for relatively short duration.

Previous studies demonstrated that obsidian could be dehydrated in a muffle furnace. A. Jambon of the Laboratoire MAGIE, Université Pierre et Marie Curie, Paris, and Y. Zhang, and E. M. Stolper of California Institute of Technology measured weight loss in obsidian as a result of high temperatures in a muffle furnace over periods of three weeks to three months and at temperatures ranging from 510 to 980^{o}C. Following the technical discussions of these geo-chemists highlights the difficulty of anthropologists wading into the physical sciences, but their basic findings are clear and directly related to our work. They interpreted the weight loss as loss of water, or dehydration, and observed it progressing as a function of the square root of time – similar to the commonly accepted obsidian hydration diffusion curve (Jambon et al., 1992:2931). Of course, weight loss without loss of volume is density loss. Our objective was to determine whether density loss could be observed after much shorter exposures to heat.

Understanding the change in obsidian density is important. Density has been proposed as a means to source obsidian by some. Michael Jablonowski and others at the Obsidian Laboratory at Sonoma State University's Anthropological Studies Center have conducted experiments to see if obsidian sources could be distinguished by relative density. He floated obsidian from Central California's four predominant sources (Napa Valley, Annadel, Borax Lake, and Mt. Konocti) in zinc bromide solution and established that specimens did separate into four source-determined groups. The extension of this technique to more obsidian sources was less effective due to overlapping density signatures.

Understanding the change in obsidian density may also be critical in understanding developing theories regarding hydration rates. Christopher Stevenson believes that obsidian source is inadequate for determining hydration rate and argues that percent intrinsic water (%OH) is the defining factor. Because, he reasons, %OH may not be uniform even in a single rock, rate must be calculated artifact by artifact. In the course of their work, he and Wallace Ambrose have developed a calibration curve expressing the correlation between obsidian density and structural water content (Stevenson et al., 1996:233). They observed that "high density obsidians will have low quantities of structural water and hydrate slowly while low density glasses will have higher OH concentrations and faster hydration rates" (Ibid., 235.)

Possibly the most promising application of obsidian density, from the prospective of readers of this volume, is the potential for it to reveal the extent to which obsidian artifacts have been fire-affected. Although this study only introduces the subject, we hope that further attention to the effect of fire on obsidian density will lead to a better understanding of the vagaries of obsidian hydration dating which have made its general acceptance so elusive.

The Study

Jablonowski's study not only demonstrated that zinc bromide flotation was an effective way to compare obsidian density, but his documented procedures and preserved materials made the start of our research very convenient. Our study was restricted to Napa Valley obsidian. First because it is a source about which we know the most and second because it is relatively clear of inclusions. Zinc bromide is water-soluble and was diluted until it was slightly more dense than Napa obsidian so that minor temperature increases could be used to subtly reduce the density of the heavy liquid. The lower the temperature when the obsidian sinks, the more dense the obsidian. Although the change in density is too slight to measure with a simple weight divided by volume method, we can estimate the effect of a degree of temperature change on the density of the zinc bromide by reference to the International Critical Tables.

Although we were confident that one hour in the furnace was adequate to erase the visible hydration band (see Loyd, this volume), we were unsure that the density loss would be significant enough to measure with our flotation methods. We chose obsidian samples with a very high surface area to volume ratio and significant hydration bands in an attempt to address this issue. We selected five thin Napa Valley obsidian flakes with between 3.9 and 4.8 microns of hydration and cut them in half. Each initial flake was given a letter code from A to E and the halves were noted as 1 and 2 so that there were 10 samples identified as A1 though E2. All samples were less than 0.1 gram in weight and between 0.8 and 1.6 mm in thickness at the thickest point.

A 100-milliliter beaker was filled with 60 milliliters of the prepared zinc bromide solution. At 20°C the solution had a weight of 134.4 grams indicating a starting density of about 2.24 grams/cc^2. It should be noted that this density is significantly below the range of densities included in Stevenson's density/%OH chart that spans from 2.32 to 2.40 grams/cc^2 (Stevenson et al. 1996:236). Taken at face value this would indicate a very high %OH for Napa obsidian.[2]

Extrapolation of the International Critical Tables indicates that this density corresponds to approximately a 73% zinc bromide solution (Washburn 1928:64.) At room temperature all flakes floated upon the solution. The solution was warmed slowly with a 1500-watt hair dryer while being agitated with a glass thermometer to distribute the heat. The solution was allowed to settle approximately every minute to observe the behavior of the flakes and to note the temperature. As flakes began to drop the temperature was recorded, and at a point when all flakes were distributed throughout the solution their relative positions were recorded. This was continued until all flakes settled to the bottom. The top of Exhibit 1, titled "Flotation Run #1 – Before Burn", shows the distribution of flakes in the zinc bromide solution at two points. The U-shaped object represents the zinc bromide filled beaker. At 24°C both halves of flake A are floating on top and E1 is sitting on the bottom. The adjoining "beaker" shows that at 27°C all flakes are resting on the bottom and therefore are denser than the zinc bromide at that temperature.

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[2] The "hockey stick" nature of Stevenson's curve presents some problems for extrapolation. The horizontal high density end of the curve indicate near identical %OH for densities ranging from 2.35 to 2.40 grams/cc^2, while the more vertical low density end indicates steeply falling %OH from 0.95% to 0.20% as density changes from 2.32 to 2.34 grams/cc^2.

On the following day a member of our team fired one half of each flake in a muffle furnace for one hour at 700°C. The other half was preserved as a control. One week after the initial flotation the experiment was repeated. The results are shown on the bottom half of Exhibit 1 (Flotation Run #2 – After Burn). Positions were measured at four temperature stages. The clearest comparison can be made between the 27°C beakers. All flakes had settled to the bottom of the beaker at 27°C before the burn but all "1" halves were suspended at that temperature after the burn. The final beaker shows that C1 was still floating at 29°C. The "1" halves, then, were less dense, that is they floated at temperatures a couple of degrees higher than they had fallen through the week before. Only after the experiment did we check to see that the less dense flakes (the "1" halves) were the flakes that had been exposed to the high heat.

Conclusion

So what did we learn? The same process that made the hydration band disappear had made the obsidian less dense. To accept Jambon et al.'s (1992) explanation, our flakes had been dehydrated. But what was not clear was whether it was the hydration rim that had been dehydrated or the core obsidian. We therefore repeated the experiment with similar flakes with no measurable hydration rim. Exhibit 2 shows the results of this second run. Eight similar, thin flakes with no hydration were labeled A through H. Before the burn all were denser than the solution at 24°C.[3] After the burn flakes A, B, D, and E continued to float even at 32°C. We confirmed that the less dense flakes were those subjected to the muffle furnace. This was a more dramatic change than had occurred with the hydrated flakes and indicated that it is the core obsidian and not only the hydration rim that is being effected by the heat.

Because of this, we reasoned that surface area to volume ratio should not be an issue and conducted a third run using two larger "chunks" of obsidian with no hydration rims. These specimens, labeled EL and ER, were 2.4 and 3.2 grams in weight and 6.2 and 6.5 millimeters in thickness respectively. The results of this run are shown on Exhibit 3. The larger flakes occupied more of the beaker volume and it was not possible to make fine distinctions in position. Rather we noted when they touched the bottom of the beaker and were therefore denser than the solution. Before the burn ER was denser than EL and sat at the bottom of the beaker at 24°C. After the burn ER was less dense and continued to float after EL had touched down and did not sink to the bottom until the temperature was raised to 35°C. According to the International Critical Tables this represents about 0.02 grams per cubic centimeter or close to 1% loss in density.

Relative density studies offer us an additional means of understanding obsidian hydration. Zinc bromide flotation has been adequate to open the discussion, but further analysis will require more a precise pycnometer. Before we go much further we will want to get a more thorough understanding of the base line – that is what is the range of densities for the subject obsidian when it is not effected by heat and what is the effect of hydration on that density. This will give us a context within which to evaluate the heat effect on density and, hopefully, maintain this promising and inexpensive technique of site dating.

[3] Although we need to float the same obsidian flakes before and after induced hydration to confirm this, the higher density of these flakes before burn than the flakes in Run 1 appears to confirm our hypothesis that non-hydrated obsidian is more dense than hydrated obsidian independent of the burning.

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Thermal and Environmental Effects on Obsidian Geochemistry: Experimental and Archaeological Evidence

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Abstract

Recent EDXRF compositional studies of thermally altered archaeological obsidian from a number of late period sites in New Mexico and Arizona suggested that extreme thermal alteration may have been responsible for the depletion of elemental concentrations in the mid-Z x-ray region; a region where the most sensitive incompatible elements for the discrimination of archaeological obsidians reside. A stepped heating experiment subjecting samples of peraluminous to mildly peralkaline artifact quality obsidian to temperatures between 500°C and 1080°C indicated that at temperatures over 1000°C extreme mechanical changes occur, but the elemental composition in the mid-Z region does not vary greatly beyond that expected in typical instrumental error. It appears that the apparent depletion of elemental concentrations in the archaeological specimens is due to EDXRF analysis of surface regions where melted sands in the depositional matrix become bonded to the surface glass and subsequently incorporated into the results. If accurate analyses of burned obsidian artifacts are desired, the layer of melted sand from the depositional contexts must be removed before analysis.

Introduction

Recently, a number of obsidian studies in pre-Classic Salado and Hohokam, as well as northern Rio Grande contexts have focused on the potential effects of pre-depositional and post-depositional burning on the trace element chemistry of archaeological obsidian (Shackley 1998a; Steffen 1999a, 1999b). These studies, while informative, were not conducted in controlled laboratory conditions focused on thermal threshold rates to determine at which temperature, if any, trace element composition may change significantly (Skinner et al. 1997; Trembour 1990). Our purpose here is to discuss the results of a controlled laboratory experiment focused specifically on the thermal effects on archaeological obsidian within a background of archaeological applications in the American Southwest, and an understanding of thermal gradients in silicic melts. The results presented here, of course, are likely applicable anywhere.

Archaeological Background

In the past few years, large scale archaeological projects in Arizona and New Mexico have, as part of problem domain generation, integrated archaeological obsidian studies into analytical research (see Bayman and Shackley 1999; Peterson et al. 1997; Shackley 1995, 1999, 2000; Simon et al. 1994). Evident for over 60 years is the periodic and often culturally produced pre-depositional and post-depositional burning of obsidian artifacts (Gladwin et al. 1938; Shackley 1988, 1990). Cremation, common in pre-Classic Hohokam and Mogollon contexts, is the most obvious vector for the pre-depositional effects, but post-occupational burning of rooms and entire sites is also responsible for surface modification of obsidian artifacts (Foster 1994). Gladwin and Haury's excavations at Snaketown in predominately pre-Classic contexts, are the best known studies where cremations were common and artifacts burned to varying degrees (Doyel 1996; Gladwin et al. 1938; Hoffman 1997; Haury 1976; Figure 1 here). Recent analyses of pre-Classic and Classic period burned obsidian artifacts, often projectile points from these contexts, have indicated significant variability in the source element chemistry inconsistent with typical rhyolite glass composition (Cann 1983; Peterson et al. 1997; Shackley 1998a). Analysis of artifacts from burned contexts in Rooms 15 and 16 of the Upper Ruin at Tonto National Monument indicated partial to nearly complete depletion of trace elements in 3 of 19 specimens (Shackley 1998a). All of these Tonto Ruin specimens, like the Snaketown artifacts, exhibited a thin layer of melted material, likely from the surrounding matrix. As we shall see, this latter attribute is the operative issue hampering reliable trace element compositional studies, not necessarily direct high temperature effects.

The Nature of Silicic Magma Cooling Behavior and Chemistry

As a background to understanding both the modal trace element composition of silicic glasses and temperature properties, a slight digressive discussion of melt temperatures will be useful. Magmas erupted on the earth's surface are quite hot and dangerously explosive, particularly silicic magmas, so there have been few direct studies (Carmichael et al. 1974). Macdonald and Gibson's (1969) measurement of the peralkaline obsidian at the Chabbi eruption in Ethiopia in 1968 and Carmichael's (1967) estimates are the most appropriate here (see also Buddington and Lindsley 1964; Table 2 here). These measurements are made with mineral geothermometers using two minerals (usually titanomagnetite and ilmenite) to estimate the liquidus temperature of the silicic lava; by theory, the equilibration temperature of the mineral pair closely approximates the liquidus temperature (Buddington and Lindsley 1964; Carmichael et al. 1974:6; Hildreth 1979). Those shown in Table 2 are considered upper limits, and for this exercise the temperature that we would expect to see physical and possibly chemical changes. Given these data, our initial firing began at 500°C. The process of volatilization and subsequent removal of some compounds, such as water and silica, is apparently not an intervening variable (Hildreth 1979, 1981).

High Temperature Experimental Procedures

Sample Description. Thirteen samples from five different obsidian sources in the greater American Southwest and northwest Mexico were heated and analyzed. All samples were megascopically aphyric; no megascopically observable phenocrysts. For each obsidian source, at least two nodules were sampled in order to establish a source differentiation baseline beyond that previously reported (see Shackley 1995).

Thirteen nodules from five known obsidian sources in the Arizona, New Mexico and northern Chihuahua were split to obtain fresh surfaces and avoid contamination during analysis (Table 1, Figure 2).

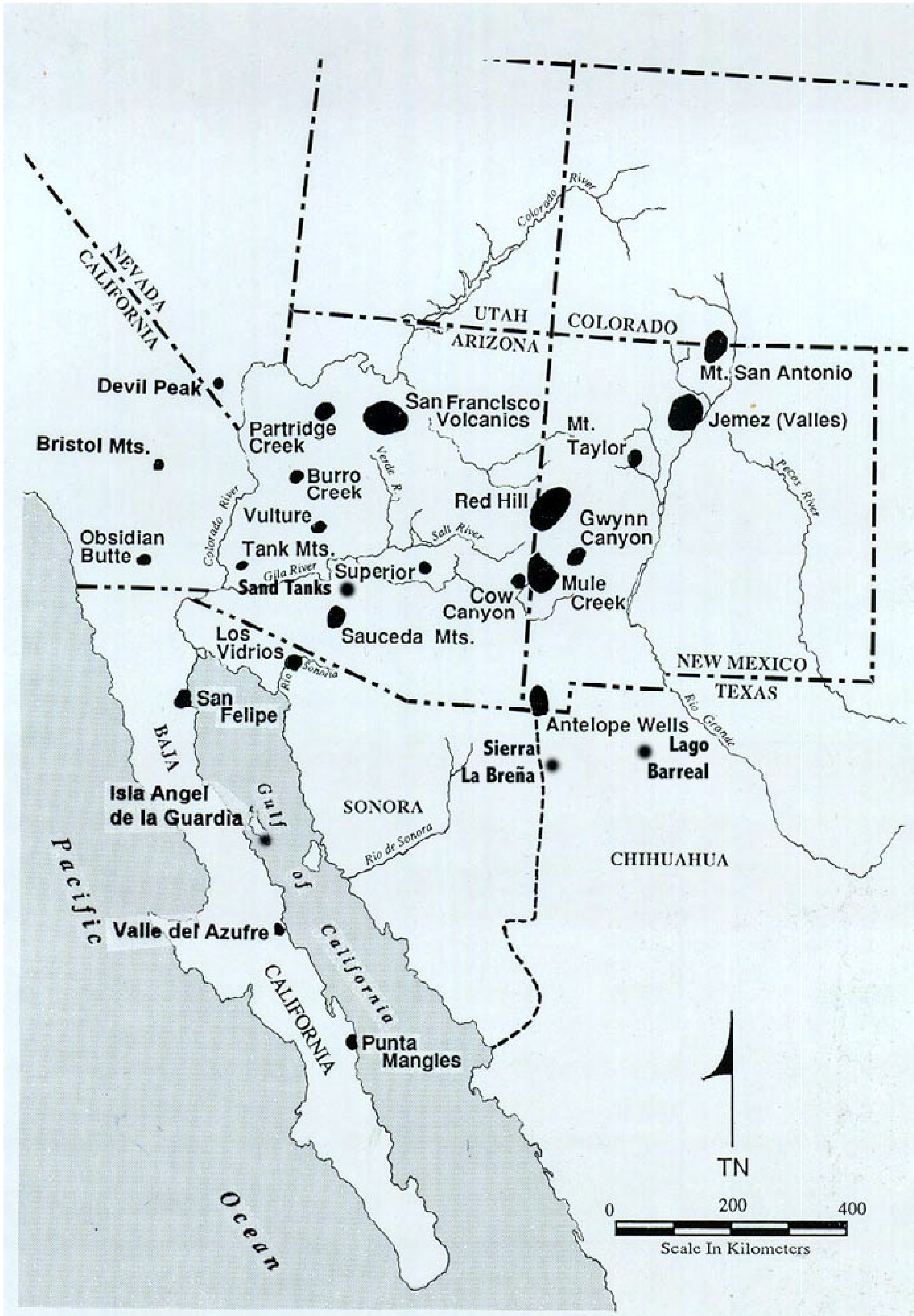

Figure 1. Sources of archaeological obsidian in the greater North American Southwest.

The five sources include both peraluminous and mildly peralkaline lavas in order to attempt to cover the spectrum of trace element variability typical of silicic glasses (see Cann 1983; Mahood and Hildreth 1983; Hildreth 1981; Shackley 1988). Each flake was weighed, measured, optically scanned and analyzed using EDXRF prior to any heating for baseline comparative data (Table 1). Additionally, for each flake, the analyzed surface was recorded, and all future XRF analyses were performed on the same surface. The Spectrace 400 instrument used in the Department of Geology and Geophysics is well reported, and instrumental settings and laboratory standards are reported elsewhere (see Davis et al. 1998; Shackley 1995, 1998b; http://obsidian.pahma.berkeley.edu/tontobs/anlysis.htm).

Figure 2. Experimental samples before heating.

Table 1. Physical data for the experimental obsidian samples.

Obsidian Source	Specimen #	Max. Length	Max. Width	Max. Thick-ness	Pre-heated weight	Weight 500°C	Weight 700°C	Weight 800°C	Weight 940°C	Weight 1080°C
Vulture, AZ	2	1.85	1.7	1.1	2.9	2.9	2.9	2.9	2.9	additional material[1]
Vulture, AZ	3	1.8	1.7	0.3	1	1	1	1	1	1
Burro Creek, AZ	1	2.8	2.1	0.85	3.8	3.8	3.8	3.8	3.8	additional material
Burro Creek, AZ	2	2.7	2.2	0.5	3.1	3.1	3.1	3.1	3.1	broken
Burro Creek, AZ	3	1.7	1.5	0.35	1	0.9	0.9	0.9	0.9	broken
Antelope Wells, NM	1(7-B-8)[2]	3.2	2.5	0.8	5.9	5.9	5.9	5.9	5.9	ceramic fused
Antelope Wells, NM	2(13-B-1)	1.9	1.35	0.6	1.3	1.3	1.3	1.3	1.3	ceramic fused
Cow Canyon, AZ	1	2.7	1.5	0.5	1.3	1.3	1.3	1.3	1.3	additional material
Cow Canyon, AZ	2	3	1.9	1	5.6	5.6	5.6	5.6	5.6	broken
Cow Canyon, AZ	3	3	1.4	0.6	1.4	1.4	1.4	1.4	1.4	broken
Government Mt., AZ	1	4.7	3.1	1.05	10.9	10.9	10.9	10.9	10.9	10.9
Government Mt., AZ	2	3.8	2.05	0.5	2	2	2	2	2	broken
Government Mt., AZ	3	2.6	3.15	0.8	6.3	6.3	6.3	6.3	6.3	broken

[1] At some point during heating to 1080°C, the ceramic sample base in the kiln shattered and some of this material was incorporated into the melted glass.
[2] Designation for Antelope Wells sample splits also reported in Shackley (1995).

Heating. Obsidian samples were heated using a Blue Electric Furnace in the Petrography Lab, Department of Geology and Geophysics, University of California, Berkeley. The kiln was lined with ceramic plating and linked to a digital thermometer to accurately monitor temperature. To maintain a constant heating temperature, the kiln thermostat was checked and adjusted manually throughout each heating session. The same obsidian samples were heated during each session, and each was weighed and examined for physical changes following heating. After every heating session, flakes were submitted to EDXRF analysis. The samples were subjected to five heating sessions (Step 1 through Step 5) of increasingly higher temperatures.

Table 2. Estimated melt extrusion temperatures for various lavas (from Carmichael et al. 1974). Rhyolite temperature underlined.

Kilauea, Hawaii	Tholeiitic basalt	1150–1225°C	T. L. Wright et al. (1968)
Parícutin, Mexico	Basaltic andesite	1020–1110°C	Zies (1946)
Nyiragongo, Congo	Nephelinite	980°C	Sahama and Meyer (1958)
Nyamuragira, Congo	Leucite basalt	1095°C	Verhoogen (1948)
Taupo, New Zealand	Pyroxene rhyolite: pumice flows	860–890°C	Ewart et al. (1971)
	Amphibole rhyolites: lavas, ignimbrites, pumice flows	735–780°C	
Mono Craters, California	Rhyolite lavas	790–820°C	Carmichael (1967*a*)
Iceland	Rhyodacite obsidians	900–925°C	
New Britain, Southwest Pacific	Andesite pumice	940–990°C	Heming and Carmichael (1973); Lowder (1970)
	Dacite lava, pumice	925°C	
	Rhyodacite pumice	880°C	

Step 1: 500°C. The kiln was pre-heated to 500°C and samples placed loosely on the ceramic plate inside the kiln. The kiln was closed and monitored until the temperature again reached 500°C. It took 30 minutes for the temperature to return to 500°C. Samples were heated at 500°C for one hour. After one hour, the kiln was turned off and the kiln door opened. Samples cooled inside the kiln for 30 minutes.

The obsidian samples were then weighed and analyzed using EDXRF. No weight or chemical changes were detected. Samples were also visually inspected for physical changes. No physical changes were apparent after heating at 500°C.

Step 2: 700°C. The kiln was pre-heated to 700°C and samples placed loosely on the ceramic plate inside the kiln. The kiln was then closed and monitored until the temperature reached 700°C. It took 15 minutes for the interior kiln temperature to return to 700°C. Samples heated inside the closed kiln at 700°C for one hour. After one hour, the kiln was turned off and the door opened. Samples cooled completely inside the kiln.

After cooling, samples were again weighed and analyzed using ED-XRF. No weight or chemical changes were detected. Minor physical changes were noted in one sample: Vulture #2. This sample exhibited a band of white discoloration and minor vesiculation on a small section of the flake's cortical surface. No other changes were noted.

Step 3: 800°C. The procedure for step 3 was identical to that of steps 1 and 2. Samples were placed loosely on the ceramic plate in the pre-heated kiln. It took 30 minutes for the internal kiln temperature to return to 800°C. One sample, burro creek #2, cracked from heat stress when placed on the heated ceramic plate. Samples were heated at 800°C for one hour and then allowed to cool completely inside the kiln with the door open.

After cooling, samples were again weighed and analyzed using EDXRF. No weight or chemical changes were detected. Minor physical changes were noted in three samples. Vulture #3 exhibited minor vesiculation and a white discoloration along one edge of the flake. Cow Canyon #1 showed a reddening of residual cortical material on the dorsal surface of the flake. The dorsal surface was not analyzed using EDXRF. Antelope Wells #2 exhibited melting and vesiculation of cortical material along the flake edge. Again, the cortical surface was not analyzed using EDXRF.

Step 4: 940°C. Due to thermal cracking of the one sample during step 3, minor procedural changes were enacted during step 4. In step 4, the kiln was pre-heated to 350°C, and samples were then placed on the ceramic plate inside the kiln and the door closed. The internal temperature was then raised to 940°C. It took one hour for the internal kiln temperature to reach 940°C. The samples remained inside the kiln at 940°C for an additional hour. After heating, the kiln was turned off and samples were allowed to cool inside the kiln with the door closed until the temperature reached 600°C, at which point the kiln door was opened and the samples cooled completely.

Again, samples were weighed and analyzed using EDXRF. No weight or chemical changes were noted after heating at 940°C. Upon visual inspection, no additional physical changes were noted.

Step 5: 1080°C. In step 5, samples were placed in a cold kiln to avoid thermal fractures. It took 90 minutes for the internal kiln temperature to reach 1080°C. Samples were heated at 1080°C for one hour and then allowed to cool in the kiln with the door closed for 45 minutes until the temperature reached 600°C. The kiln door was then opened and samples cooled completely.

Figure 3. Samples after heating to 1080ºC. Off-white material is the broken ceramic base plate incorporated into glass while heating to this temperature (see text).

For the two samples that were not fused with the ceramic plate, Vulture #3 and Government Mountain #1, no weight changes were apparent. Given this, it seems reasonable to conclude that no heavy compounds came out of solution due to heating. Chemical changes, as shown through EDXRF, will be discussed below.

Summary of Physical Changes

Only minor physical changes, limited to thin edges and cortical surfaces, were apparent from heating prior to Step 5 at 1080°C. Heating to 1080°C caused severe physical changes to the obsidian samples, quite expectable given the predictive data on silicic magma extrusion temperatures. Minor physical changes began after 700°C in the range of extrusion temperatures predicted by Carmichael (1967) and others. Due to melting and fusion of the obsidian samples inside the kiln at some temperature over 940°C, weight measurements were not available for most of the samples. However for the two samples that were not fused, no weight changes were apparent.

Changes in Elemental Chemistry

While physical changes in the glass samples were abrupt and extraordinary, more importantly, the elemental chemistry exhibited no significant changes with a few important exceptions. For most of the samples, there was no statistically significant changes in trace element chemistry between ambient and the temperature beyond the melting point of silicic lava (about 1000°C), above that expected and typical in the instrumental variability of EDXRF (see Davis et al. 1998).

Table 3 exhibits the measured elemental chemistry at ambient through all heating steps to 1080°C (see also Figure 4). Those elemental changes over 10% are shown in bold and underline. These changes are not necessarily related to the most obvious physical changes and do not correlate with modal chemistry (peraluminous versus peralkaline) or other samples analyzed here from the same source. Most intriguing is the complete depletion of titanium in the Government Mountain 2 sample, while the other two from this source showed no significant change. This is not immediately explicable, nor necessarily important archaeologically as we will argue. The Vulture 3 specimen gained over 30 ppm (about a 19% change) in rubidium, although this may be related to analysis of a small amount of ceramic material incorporated into the obsidian at the last step as discussed earlier (Figure 4). The only significant shift in elemental composition was in one of the mildly peralkaline glasses from Antelope Wells (Table 3). Both rubidium and zirconium were depleted; 20% for rubidium and 17% for zirconium. The three-dimensional and biplots of the data graphically indicate this change.

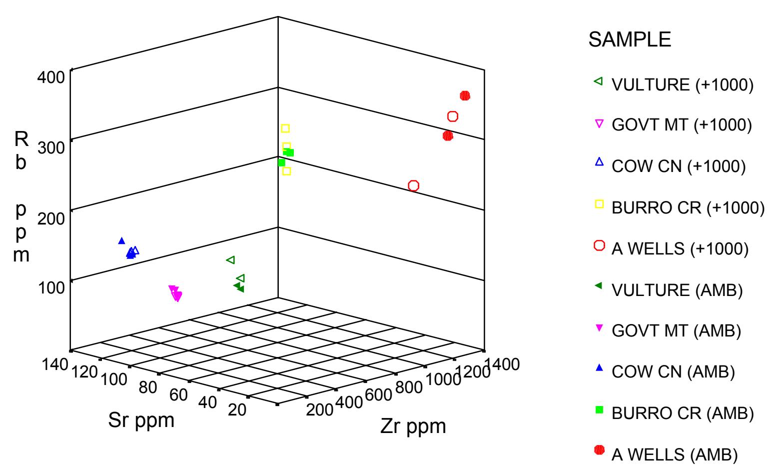

Figure 4. Rb, Sr, Zr ambient and 1080ºC concentrations for experimental samples. AMB=ambient measurements; +1000=1080ºC measurements.

Table 3. Elemental concentrations for the analysis of the five source standards at ambient through 1080°C. Bold and underlined concentrations are those Ti, Mn, Fe, and Rb – Nb that exhibited more that 10% change. All measurements in parts per million (ppm).

TEMP	SPEC.	Ti	Mn	Fe	Zn	Ga	Pb	Th	Rb	Sr	Y	Zr	Nb
Amb-ient	V2	1115.1	336.8	8412.5	36.4	17.9	26.8	15.6	136.0	37.0	19.2	128.2	18.9
	V3	945.4	317.5	8229.7	43.8	20.8	27.8	32.2	140.9	39.2	19.5	121.7	18.4
	BC1	569.5	466.6	9088.7	44.1	23.7	40.6	37.3	350.8	1.2	70.9	99.6	41.6
	BC2	563.6	462.8	9188.9	42.2	19.6	39.8	37.4	351.6	3.4	69.6	96.2	43.7
	BC3	476.0	446.0	8882.9	50.2	20.2	37.1	33.5	334.4	6.5	66.7	91.4	47.5
	AW1	1661.7	1044.1	23944.0	191.7	24.6	49.6	41.5	365.6	3.8	136.8	1308.5	97.8
	AW2	2009.2	971.1	21450.1	161.0	25.5	42.0	33.8	314.9	3.6	119.3	1190.6	96.7
	CC1	1243.1	589.8	10096.4	61.4	18.8	27.9	14.4	157.3	120.2	24.3	144.1	20.5
	CC2	1143.2	502.0	9421.6	44.0	16.7	22.5	17.1	141.5	113.5	25.7	133.0	20.3
	CC3	1090.8	492.4	9091.3	46.1	13.6	23.9	18.5	143.6	111.3	24.4	130.7	18.5
	GM1	510.7	550.7	9513.7	57.9	22.3	35.9	18.2	116.1	77.5	19.5	82.8	57.0
	GM2	559.7	578.1	10355.7	57.5	25.0	37.6	17.1	117.9	79.7	19.2	79.5	58.8
	GM3	526.7	551.0	9512.1	55.3	22.8	35.7	16.7	111.7	75.1	20.7	79.2	52.4
500°C	V2	1318.4	348.1	8777.3	38.7	14.9	23.9	21.1	143.4	39.1	17.9	124.6	25.4
	V3	1024.5	317.0	8177.0	32.3	18.7	26.9	26.4	141.2	34.5	23.8	131.0	21.6
	BC1	620.5	484.1	9091.5	43.0	20.9	37.3	38.6	357.1	4.2	70.4	96.6	45.8
	BC2	642.9	496.6	9403.0	44.5	21.7	41.8	36.1	355.7	3.3	69.2	97.2	44.1
	BC3	536.9	446.2	9040.0	44.1	17.8	41.4	39.5	337.2	3.6	69.9	91.7	43.4
	AW1	1681.0	999.6	23473.0	174.5	23.2	45.3	40.6	360.4	4.2	134.5	1298.6	105.0
	AW2	1769.4	954.4	22128.2	187.6	24.2	42.6	38.9	312.5	4.6	118.9	1153.1	93.7
	CC1	1119.3	549.5	9969.1	98.9	26.9	30.4	18.8	148.9	111.5	29.8	136.9	17.8
	CC2	1143.9	425.1	8895.4	47.4	16.4	22.0	17.0	137.3	107.5	25.2	129.9	21.1
	CC3	1193.4	536.4	9970.7	54.1	20.6	29.3	18.4	157.7	119.0	24.9	138.8	23.3
	GM1	622.8	532.4	9400.1	60.4	21.6	38.1	15.5	113.3	78.6	21.4	84.1	51.8
	GM2	479.4	628.3	10398.8	59.1	26.2	35.2	0.0	124.1	82.2	23.4	84.8	55.1
	GM3	533.5	500.8	9176.7	54.5	21.4	33.1	15.9	112.4	76.1	19.5	75.0	49.1
700°C	V2	1055.8	323.4	8158.4	34.8	19.4	32.6	13.4	130.9	36.3	16.8	123.8	16.1
	V3	994.1	341.3	8527.3	34.3	16.7	23.2	15.9	139.4	37.1	18.2	129.0	23.7
	BC1	675.3	457.9	9064.8	42.6	19.5	41.8	28.9	344.4	4.8	69.5	96.4	43.6
	BC2	581.2	466.5	9395.5	54.7	23.9	41.3	40.8	348.1	2.9	69.6	96.7	48.6
	BC3	618.9	455.2	9004.2	46.8	20.0	42.7	41.1	333.1	3.3	66.6	90.0	42.2
	AW1	1714.0	946.5	22531.4	173.9	25.4	41.6	34.8	354.8	5.6	136.5	1287.2	95.0
	AW2	1974.0	942.1	22596.9	188.2	22.6	50.0	49.3	313.4	2.5	118.8	1152.8	89.8
	CC1	1315.9	530.4	9672.4	46.9	19.4	25.4	18.4	143.1	117.9	25.2	137.4	19.3
	CC2	1124.1	486.2	9312.5	49.0	16.3	23.9	21.0	143.4	111.2	24.1	133.6	17.2
	CC3	1354.0	594.4	10286.6	51.6	20.1	23.6	15.0	156.5	122.7	30.2	139.7	19.7
	GM1	542.3	535.0	9455.3	55.3	21.6	36.3	18.7	117.8	77.8	16.7	81.8	57.6
	GM2	485.6	628.5	10367.6	61.4	25.0	40.8	22.9	122.7	84.0	20.9	81.1	50.8
	GM3	495.2	561.6	9711.8	54.7	22.8	37.1	20.4	117.3	78.1	23.5	82.9	54.4
800°C	V2	1168.2	350.1	8541.3	47.2	23.5	27.7	20.5	140.0	37.8	16.8	125.3	15.6
	V3	1010.4	329.2	8365.2	38.6	19.8	28.4	19.8	144.1	33.2	20.0	129.8	20.7
	BC1	542.0	498.7	9245.9	53.3	22.4	43.0	38.5	364.1	4.1	69.6	98.7	45.4
	BC2	628.1	465.8	9004.4	49.3	23.0	41.0	38.2	345.4	3.0	66.9	93.6	44.4
	BC3	551.9	452.0	8922.2	36.4	18.2	38.8	40.1	343.4	2.6	69.7	92.4	40.9
	AW1	1807.1	1032.4	24632.8	183.6	24.1	45.9	46.1	379.1	4.8	137.3	1333.3	101.2
	AW2	1794.8	864.5	20596.9	151.3	24.6	44.6	43.3	308.5	5.0	117.5	1149.8	95.2
	CC1	1097.8	439.9	8930.8	48.2	14.9	21.2	17.3	141.0	109.6	24.6	128.2	22.1
	CC2	1177.3	495.5	9517.7	72.1	22.8	28.4	20.0	151.6	110.6	22.6	134.5	17.6

Table 3 (continued).

TEMP	SPEC.	Ti	Mn	Fe	Zn	Ga	Pb	Th	Rb	Sr	Y	Zr	Nb
	CC3	965.8	464.4	9140.8	44.9	19.9	22.6	21.0	145.2	108.7	24.9	129.5	18.6
	GM1	532.1	568.3	9636.0	53.9	23.0	34.1	20.5	119.9	81.2	22.9	84.5	53.9
	GM2	582.2	671.5	10551.8	70.6	22.8	39.7	20.6	123.5	85.0	23.6	82.7	59.8
	GM3	524.4	570.3	9599.6	56.6	21.3	34.1	21.3	118.7	77.9	21.1	81.3	54.0
940°C	V2	1069.2	295.0	8476.0	40.3	17.5	31.7	23.8	140.8	37.5	18.4	130.1	13.8
	V3	1074.0	342.6	8508.8	37.2	17.7	28.2	14.2	142.4	36.9	19.5	127.7	20.7
	BC1	636.5	495.3	9160.5	48.0	22.3	42.8	40.1	350.3	3.1	70.5	101.7	48.6
	BC2	573.9	487.2	9113.8	40.9	21.3	38.1	35.4	348.3	2.3	71.0	98.6	42.5
	BC3	580.7	467.6	9155.9	53.4	21.7	38.8	29.4	352.0	2.1	66.8	98.5	41.4
	AW1	1652.6	1034.0	23297.7	177.7	24.7	47.8	52.9	367.3	4.2	136.5	1306.2	99.1
	AW2	2201.9	1046.4	22446.3	165.4	24.3	42.5	36.5	317.2	4.9	120.5	1192.3	97.6
	CC1	1303.9	640.9	10596.6	57.9	21.6	29.4	19.9	164.5	121.8	23.6	143.3	19.9
	CC2	1151.9	542.5	9470.2	46.6	17.9	25.4	12.9	146.1	114.5	28.1	136.1	22.0
	CC3	1282.4	541.0	9972.7	53.9	20.1	22.2	19.7	158.1	121.3	28.1	141.2	18.1
	GM1	563.3	526.0	9333.0	59.6	22.4	35.3	20.0	114.6	81.9	20.0	77.5	58.2
	GM2	**0.0**	613.2	10645.7	66.5	24.9	38.5	19.2	123.3	85.5	24.2	83.8	57.9
	GM3	529.1	553.4	9583.4	60.8	19.2	36.8	17.7	115.8	75.6	21.0	79.9	51.9
1010°C	V2?	1014.3	344.6	8415.0	34.6	18.0	59.8	31.6	150.8	37.9	19.4	135.9	22.0
	V3	**1639.3**	476.2	10662.4	62.5	27.2	57.0	23.3	**172.9**	45.7	23.5	146.4	25.1
	BC1?	550.1	515.6	9673.5	44.3	24.5	59.9	39.1	358.0	3.5	72.1	97.1	43.7
	BC2?	511.2	400.0	9006.5	49.1	22.3	43.5	29.9	324.7	3.0	65.6	96.1	42.8
	BC3	624.4	571.4	10325.9	56.6	23.7	60.1	39.4	383.7	5.2	74.8	102.7	41.7
	AW1	1654.8	1006.4	22707.6	173.3	26.7	43.8	40.6	339.5	5.1	125.8	1240.9	95.7
	AW2	1735.5	651.1	17325.5	136.8	14.9	39.0	24.0	**253.1**	6.5	105.8	**986.7**	80.4
	CC1	1165.3	520.9	9620.3	96.8	23.8	43.7	15.0	147.3	111.8	25.2	131.8	16.6
	CC2?	1191.6	502.3	9528.1	46.2	18.1	41.8	21.0	144.9	113.4	28.0	138.1	19.3
	CC3?	1142.5	506.4	9597.7	51.4	18.0	32.3	23.6	151.3	108.5	25.8	123.6	21.0
	GM1	496.3	537.4	9397.2	54.3	20.5	50.9	14.2	109.6	75.7	21.8	82.8	51.5
	GM2?	**0.0**	478.1	9163.5	56.0	20.7	40.8	16.1	108.8	74.7	23.3	75.7	46.2
	GM3	473.7	491.7	9204.2	56.9	20.9	52.2	15.9	109.3	76.8	20.2	79.4	52.8

[1] Those samples marked with a "?" are samples that deformed too much to determine which sample of the source group that particular sample belonged.

Figure 5 graphically displays the conundrum presented by the Antelope Wells data. One of the samples was affected such that source assignment *could* be a problem; however, given that only rubidium and zirconium were affected, source assignment could be confident in a typical assemblage of archaeological obsidian in the southern Southwest. What is more of a concern is the effect on only one of the samples. Sample AW-1 is well within the range of variability on these two elements for Antelope Wells. While Antelope Wells is distinctive in the Southwest north of the border, recent research in the Basin and Range region of northern Chihuahua indicates a number of peralkaline obsidians used in prehistory that have similarly high proportions of iron and zirconium (see Shackley 1995, 1999). This could cause a problem in this region, particularly since surveys and geoprospection are in their infancy in the Basin and Range region of northern Chihuahua unlike the portion of the Southwest north of the border (Shackley 1995, 1999). As we will argue, however, pragmatic considerations make this apparent problem less of an issue.

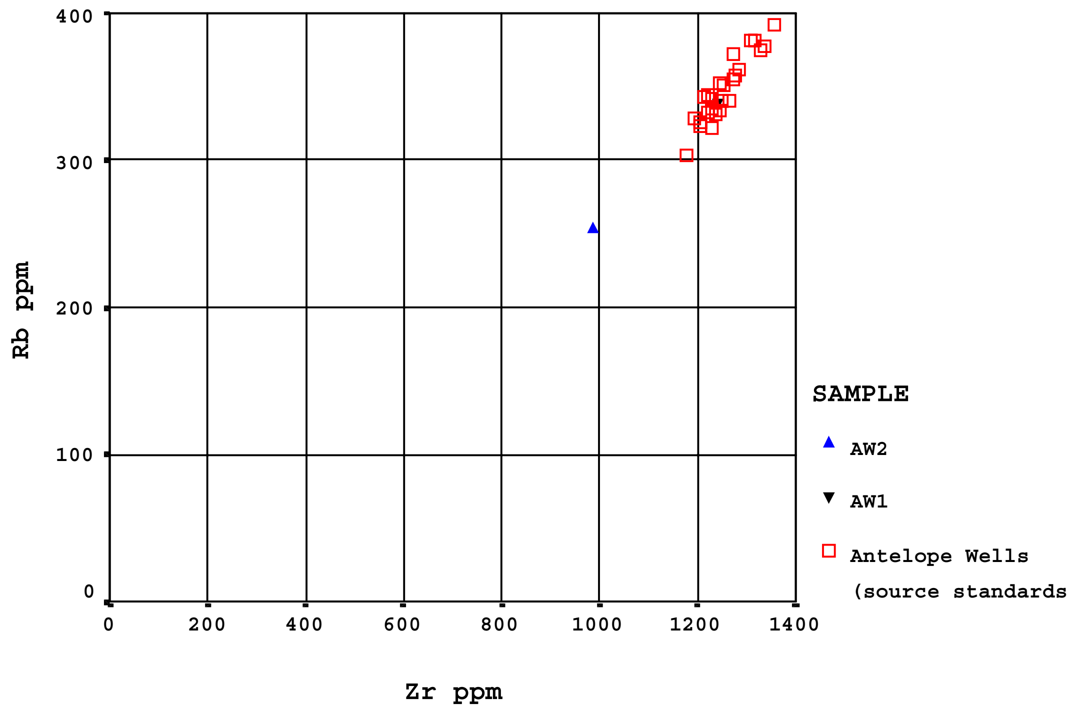

Figure 5. Rb versus Zr biplot of elemental concentrations for Antelope Wells samples and source standards after heating to 1080ºC.

Site Depositional Issues and High Temperature Incorporation of Surrounding Matrix

Not surprisingly, the high temperature experiments suggested that material incorporated into the glass can modify expected trace element composition. And while we are arguing that high temperature modification of artifact quality obsidian will not necessarily inhibit confident assignment to source, another physical change will cause problems.

As mentioned earlier, artifacts subjected to high temperatures are relatively common in the Southwest, particularly in pre-Classic and Classic contexts in central Arizona due to inclusion in cremation, domestic trash burning, or deliberate or accidental domestic house fires. The most well known examples are those from cremation contexts such as the obsidian points recovered during excavations at Snaketown (Figure 6). Based on the experiments discussed above, some of these artifacts must have been subjected to temperatures near or over melting point. Most importantly here are the examples that while not exhibiting physical evidence of melting, are coated with material incorporated into the surface at near melting temperatures (Figure 6).

However, we recently analyzed an obsidian assemblage from two rooms of the Upper Ruin at Tonto National Monument in Tonto Basin, central Arizona (Shackley 1998a). Both rooms were subjected to what appears to be a high temperature fire, probably sometime during occupation. Three of the 22 samples analyzed were pieces of debitage that exhibited various degrees of surface accumulation from the surrounding matrix, one completely covered. As you can see in Table 4, two of the samples could be assigned to the Superior (Picketpost Mountain) source with reservation due to partial depletion of trace element concentrations, and one appeared nearly completely depleted in trace elements even though a small break indicated that it was indeed obsidian (Figures 7 and 8).

What is apparent here is that while we were initially concerned that high temperatures were exclusively responsible for the depletion of trace element concentrations, the depletion is *only* apparent and due to the limitations of EDXRF. Energy Dispersive XRF, at the 30kV tube voltage used in these analyses, penetrates the surface only approximately 4-5 microns (µm). Therefore, any significant surface accumulations will be analyzed rather than the glass itself. Either the surface must be cleaned, the artifact broken to present an unobstructed surface, or not analyzed at all. Newer EDXRF technology, such as Kevex's Omicron™ instrument that can analyze very small areas, may ameliorate this problem in some artifacts.

Summary and Recommendations: The Pragmatic Approach

At least two conclusions can be derived from these experiments relevant to archaeological applications of EDXRF analysis of archaeological obsidian. First, there appears to be no significant change in elemental composition up to temperatures above 1000°C, particularly for peraluminous silicic glasses. This is predictable given recent theory and practical experiments in the understanding of silicic melt temperatures. Second, the real problem lies in the interaction between those artifacts that were subjected to high temperatures and accumulated surrounding matrix on the surface combined with the analytical limitations of EDXRF. But are these issues really causing significant problems in the use of obsidian compositional data in addressing archaeological problems? In this experimental analysis of 13 samples, only one exhibited significant changes in the trace element composition such that source assignment became hazardous. Indeed, this Antelope Wells sample could still be assigned to source with some degree of confidence using up to five or six of the other EDXRF measured elements that were not affected. In the case of the Upper Ruin assemblage from Tonto National Monument, only three artifacts were affected by surface accumulation and only one could not be assigned to source.

What we conclude is that melting temperatures have no significant effect on the elemental composition of obsidian (at least those elements of interest here), but the surface accumulation of surrounding matrix on some artifacts can affect our ability to assign artifacts to source. Using more advanced technology, removing the coating in some manner or eliminating that artifact from the analysis can ameliorate this latter issue. So, the physical changes that occur due to extreme heat do not necessarily present a problem in assigning source provenance.

Acknowledgments

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Figure 6. Top: Selected Snaketown Serrated points from Snaketown. Approximately 40% are burned to some degree. All could be assigned to source (from Shackley 2000). Severely burned and physically modified projectile points from Snaketown. Note incorporation of matrix on center and right specimens (from Gladwin et al. 1938, plate XXXVII bottom).

Table 4a. X-ray fluorescence concentrations for archaeological samples from Rooms 15 and 16, Upper Ruin, Tonto National Monument (from Shackley 1998a). All measurements in parts per million (ppm).

Sample	Ti	Mn	Fe	Rb	Sr	Y	Zr	Nb	Source[1]
140	1243.5	208.3	8365.7	101.7	30.0	17.9	100.6	1.2	Superior*
156	771.3	301.4	6285.3	75.8	12.9	16.5	54.0	16.1	Superior*
294	597.8	26.8	4116.1	4.8	14.2	0.0	7.0	4.1	burned*

[1] These are source probabilities based on best linear fit of the calibration utility (Shackley 1995). Those samples marked with "*" can only tentatively be assigned to source due to a less than adequate fit with the available source standards. These samples appear to be burned and/or chemically weathered such that the elemental chemistry may be altered.

Table 4b. Superior (Picketpost Mountain), Arizona source standard mean and central tendency data (Shackley 1995).

Element	Mean	Std Dev	Minimum	Maximum	N
Ti	831.84	148.94	708.9	1298.1	13
Mn	489.01	19.63	455.8	536.6	13
Fe	7873.22	163.89	7518.1	8175.4	13
Rb	130.23	2.74	125.7	136.3	13
Sr	19.09	2.03	15.9	21.7	13
Y	25.26	2.13	20.5	28.7	13
Zr	99.83	2.64	94.5	104.9	13
Nb	32.51	1.79	29.3	35.4	13
Ba	243.7	5.57	237.0	254.6	13

Figure 7. Burned obsidian sample with surface accumulation of matrix (Sample 294, Room 16, Upper Ruin; courtesy WACC/NPS).

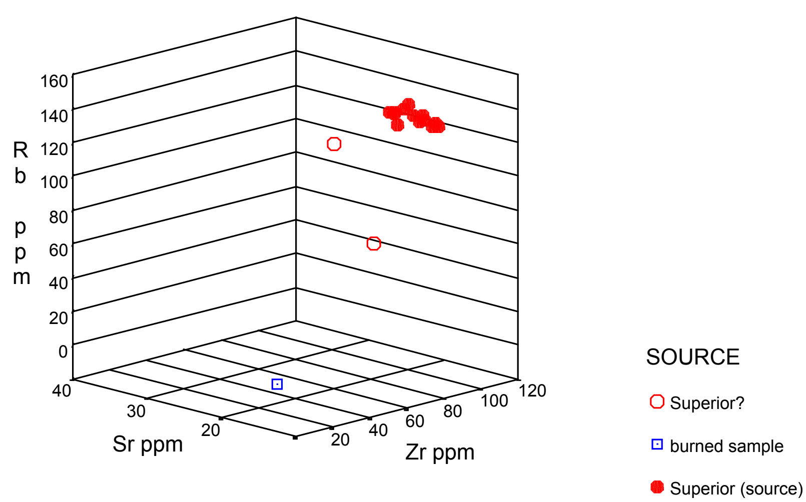

Figure 8. Rb, Sr, Zr three-dimensional plot of three artifacts from the Upper Ruin, Tonto National Monument, and Superior (Picketpost Mtn) source standards.

REHYDRATION OF BURNED OBSIDIAN

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Introduction

Throughout this volume are various observations on the direct effects of fire on obsidian, from macroscopic vesiculation to microscopic crazing. This paper is aimed at questions regarding less direct effects of burning obsidian; does fire effect how hydration progresses after the obsidian has been burned? I will be presenting information from a series of experiments that are in progress at Sonoma State University designed to address these questions.

Over the years at Sonoma State we have been aware of fire studies being done by various folks. Some have submitted samples to the Sonoma State Laboratory for hydration measurements. We took an active interest in this issue after the Salt Point Fire in 1993, which burned over many archaeological sites. At the time, our questions were focused on what effect exposure to the fire had on existing hydration on archaeological specimens. This study included specimens that had been collected from a site in the area of the burn before the fire, which were compared to samples collected after the fire had over the site. It was observed that of 23 specimens collected before the fire, between the surface and a depth of ten centimeters, 100% had measurable hydration. Of 21 specimens collected from the surface of the site during the 1994 post-fire survey, only three or 14% had measurable hydration (Anderson and Origer 1994). These results reinforced the body of data showing that exposure to fire/heat removes visible hydration from obsidian specimens.

Not content to accept the data provided by natural fire, we set out to see if we could create the same effect under more controlled conditions; could we burn off existing hydration? We designed a trial. We dug two small holes, put some obsidian with measurable hydration in the holes and piled charcoal briquettes on top. Obsidian was exposed to the fire for a maximum of one hour. To measure the temperature of our fire, we used ceramics firing cones. We were successful in removing the hydration from the specimens that we cooked, and Anderson and Origer reported the results of that experiment in 1997. In this case, our temperature control was limited, in that the cones expanded like marshmallows rather than melting over. At the time we hypothesized that this was due to the cones coming into direct contact with the briquettes. We believe that the maximum temperature of the fire was 1000-1200ºF

We completed a second experiment to verify our preliminary results; however, we used a different source of fire. In our first trial, we used charcoal briquettes; in our second, we used a wood-burning fireplace insert. Again the obsidian specimens were cooked for one hour. We believe that the second experimental fire was hotter than the first. While temperature control was recognized as ultimately being important, we were initially focused on replicating the effect we had observed from the natural fire.

In 1997 we had the opportunity to look at how obsidian that had the hydration burned out of it would rehydrate under laboratory conditions. We used nine samples from our first dehydration experiment and ten freshly flaked, unburned specimens for the test. The samples were cooked in a Parr pressure reactor at 150°C, for two sessions of ten days each. All specimens hydrated in the reactor. However, the fresh flakes got off to a slow start, having substantially smaller hydration rims after the initial ten days than the dehydrated archaeological specimens. After 20 days the measurements ranged from 3.9 to 4.7 microns, with the range in the fresh specimens being 0.1 microns lower than the burned specimens at both ends of the total range (Table 1).

Table 1. Briquette Burn/Rehydration Study Results.

Specimen #	10 Days	20 Days	
55A	3.4	4.1	CA-SON-1182 Burned
55B	3.3	4.2	
74E	3.4	4.5	
76G	3.4	4.5	
76H	3.8	4.1	
78H	---	4.7	
80E-1	3.9	4.6	
80E-2	3.7	4.7	
82B	3.5	4.0	
11	2.4	3.9	Fresh Unburned
12	2.5	4.4	
13	2.5	4.6	
14	2.5	4.2	
15	2.6	4.3	
16	2.7	4.5	
17	2.7	4.3	
18	2.5	DH	
19	2.5	4.6	
20	2.6	4.5	

Next we rehydrated specimens from our second dehydration experiment along with ten freshly flaked specimens. In an effort to see how the early stage of the rehydration process progressed, and to account for the disparity in early measurements in our first experiment, we cooked these specimens in the reactor for four runs of 3, 2, 5, and 10 days sequentially. The total time in the reactor was the same as in the previous experiment. Again all specimens hydrated in the reactor. In this case all the specimens rehydrated at the same pace (Table 2).

Table 2. Burn/Rehydration Study Results.

Specimen	3 Days	2 Days	5 Days	10 Days	
1	1.4	2.0	3.2	4.1	CA-SON-2098 0-20 cm
2	1.6	2.2	3.2	---	
3	1.6	2.2	3.3	---	
4	NVB	2.2	DH	~3.8	
5	1.6	2.2	3.2	4.3	
6	1.6	2.2	3.3	4.1	CA-NAP-159 Surface
7	1.6	2.0	3.1	3.9	
8	1.5	2.0	3.1	4.4	
9	1.6	2.0	3.2	4.0	
10	1.6	2.1	3.3	4.2	
11	1.5	2.2	3.3	4.3	Fresh
12	1.6	---	3.3	4.1	
13	1.5	2.3	3.4	4.0	
14	NVB	---	3.3	---	
15	1.6	2.1	3.2	4.2	
16	1.5	2.4	3.1	---	Fresh Unburned
17	1.6	2.2	3.2	4.2	
18	1.6	2.1	3.2	---	
19	1.6	2.1	3.1	4.2	
20	1.6	2.4	3.4	4.1	

This raised the question of whether the temperature of the fire that burned the obsidian effected the rate of rehydration. We realized that our ability to control or measure temperature in our open flame experiments was poor. We concluded that to effectively address the questions that were being raised, we needed to design an experimental procedure that allowed for precise control of the variables we were encountering.

Basic Premises

For this paper three basic questions were asked.

- Does fire effect existing hydration on obsidian?
- Does hydration occur (or reoccur) after a fire?

- Does the temperature of the fire effect the rehydration?

While the answer to the first question seems apparent, there are some issues that we need to address. Assuming that fire does affect hydration, how hot of a fire do you need, for how long before hydration disappears?

To address this question we heated three pieces of obsidian at each of three temperatures in a muffle furnace. The muffle furnace allowed control of the temperature within a couple of degrees of the set point. Temperatures selected for this experiment were 225, 300, and 500°C. Each group of flakes was baked for one hour at the selected temperature. For our purposes, success is total removal of visible hydration. The set cooked at 225°C retained their hydration. Flakes cooked at 300°C had highly diffuse bands after one hour. Specimens cooked at 500°C had no visible hydration.

A second batch of nine flakes was cooked in the furnace. Three flakes each at 325, 350, and 375°C degrees for one hour. Only the flakes cooked at 375°C lost all visible hydration.

From these two experiments we established a low temperature for our subsequent work at 375°C. We selected 700° for our high temperature. Our control group remained at ambient temperature.

Experiment

For our experiment we used three temperature sets, ambient, 375°C and 700°C. Temperature control for dehydration was provided by using a muffle furnace.

Eight obsidian flakes were exposed to each temperature regime; four archaeological specimens with existing, measurable hydration, and four freshly made flakes, with no measurable hydration. Flakes that were baked in the muffle furnace were cooked for one hour at their respective temperatures. After baking in the muffle furnace, a thin section was removed from each flake, and measured for hydration.

Rehydration was achieved by using a pressure reactor or 'bomb' with a controlled temperature of 150°C, and a solution of silica gel saturated deionized water. Flakes were rehydrated for one, three, six, and ten days sequentially, with a thin section removed and hydration measured after each round in the bomb. This provided a total of 23 days of rehydration for comparison with previous work. Table 3 shows the mean hydration on specimens after each round in the pressure reactor.

Results

Flakes that started out with no hydration at all, and were not baked in the muffle furnace, rehydrated most like the flakes that were baked at 700°C. The implication is that very high temperatures truly reset the obsidian to a zero point, from which hydration begins as if the piece were freshly flaked. The flakes baked at 375°C reacted erratically to the rehydration process. Hydration of fresh flakes baked at 375°C proceeded "normally", as compared to fresh unbaked flakes. However, the flakes that had hydration that was baked away at 375°C rehydrated poorly, with the hydration becoming diffuse on some specimens.

Table 3. Muffle Furnace/Rehydration Study Results.

Specimen	1 Day	3 Days	6 Days	10 Days	
1	0.8	1.8	---	4.5	Ambient
2	0.9	1.9	3.1	4.6	
3	---	1.7	3.3	4.7	
4	0.8	---	3.2	4.3	
375-1	0.9	1.8	3.3	4.4	375° Centigrade
375-2	---	1.7	3.4	4.4	
375-3	0.8	---	3.2	4.4	
375-4	0.8	1.7	3.1	4.5	
U	0.8	DH	3.4	DH;W	
V	---	1.8	DH;W	4.3	
W	0.8	2.0	3.0	DH;W	
X	0.9	1.7	DH	DH	
700-1	0.9	1.7	3.3	4.6	700° Centigrade
700-2	0.9	1.7	3.1	4.5	
700-3	---	2.0	3.1	4.5	
700-4	0.8	1.9	3.3	4.4	
Z	0.9	2.0	3.4	4.4	
AA	0.8	1.9	3.3	4.8	
BB	0.9	1.9	3.0	4.7	
DD	0.8	1.9	3.0	4.5	

Conclusions

The answer to our first question, does fire effect existing hydration on obsidian, is clearly yes it does. All the specimens baked in the muffle furnace lost their visible hydration. This was expected based on previous research. Our second question, does obsidian rehydrate after it has been burned, is also a yes. All the specimens that had been baked in the muffle furnace rehydrated in the pressure reactor. Our third question, does the temperature of the fire effect the hydration results, is a substantially less resounding yes.

Clearly further work needs to be done to establish what effect fires with low to mid-range temperatures have on obsidian hydration and rehydration. Also the relationship of temperature and duration of burning needs to be further explored. Our burns were all for one hour at various temperatures. When viewed from the perspective of wild fires or controlled burns that may smolder for extended periods, it is clear that more research is necessary.

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Fire Regimes and Fire History: Implications for Obsidian Hydration Dating

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Abstract

That fire can alter the hydration bands of obsidian specimens and thus affect the accuracy of dating is well known. It is also well known that before the 20th Century, fires were generally frequent (intervals of 5-20 years were common) in most forest, woodland, grassland, and shrub ecosystems of the western United States and especially California. Thus, it is likely that obsidian material that has been unprotected for more than a few decades on or near the soil surface has been exposed to fire. Only material that was buried and remained so after it was no longer used is likely to have escaped being influenced by fire. Fire intensity and duration of burning are highly variable and dependent upon the nature of the available fuels and weather. Thus, high variability in dates inferred from hydration rinds should be expected from artifacts that have been exposed to the effects of past fires.

Introduction

Dating of hydration bands in obsidian artifacts has become an important tool used to help determine dates of archaeological sites, artifacts, and especially intra- site stratigraphy (Friedman and Trembour 1983; Byram 1995). Yet, there are several environmental factors that can confound interpretations of dates due to their effects on the hydration rind development. These factors include (but are not limited to) ambient air temperature, patterns of humidity, exposure to the sun, soil temperature and moisture regime, and fire (the focus of this paper) (Byram 1995).

The ability of fire to alter the hydration bands of obsidian specimens and thus affect the accuracy of dating is well known (Byram 1995). Paleoecological data indicate fire has been interacting with vegetative ecosystems for 350 million years (Clark and Robinson 1993). It is well established that fire has been an important ecosystem process in much of the area that is now California throughout the Holocene. Before the last 100 years, fires were generally frequent (intervals of 5-20 years were common) in most forest, woodland, grassland, and shrub ecosystems (Martin and Sapsis 1992; Agee 1993; Skinner and Chang 1996). Nevertheless, during the 20th Century, fire suppression has been successful in generally minimizing the acres burned by all but the occasional high-severity fires (Skinner and Chang 1996). The success of the fire suppression policy has contributed to a cultural view that fire is unusual or an anomaly in the ecosystem. This view of fire leads to a tendency to ignore the potential long-term influences of fire not only on ecosystems, but also on past cultures and cultural materials.

Fires were frequent before the 20th Century for several reasons. Most important, the Mediterranean climate of California, with warm, dry summers and cool, moist winters, ensures that conditions for fire occurrences are experienced annually in most locations (McCutchan 1977). Thunderstorms cause many fires annually, particularly throughout the mountainous regions (Schroeder and Buck 1970). The occurrence of fire has often been augmented by human cultures. Ethnographic accounts reveal that Native Americans commonly used fire in many areas of California as a tool to help manage the production of food and necessary materials (Blackburn and Anderson 1993).

Fire intensity and duration are highly variable and dependent upon the condition of available fuels and weather (Rothermel 1983; Agee 1993). The effects of fire on hydration rinds of exposed obsidian are related to the magnitude (and probably duration) of temperatures reached. Thus, investigators should expect high variability in dates inferred from hydration rinds of artifacts that have been exposed to past fires (Byram 1995).

In this paper, we have three objectives: (a) summarize what is currently known about long-term patterns of fire occurrence; (b) summarize what is known about the nature of fire (characteristic behavior and temperatures) for broad vegetation types; and (c) discuss the implications of this information for obsidian hydration dating.

California Fire Regimes

The Mediterranean climate of California, with its annual warm/dry season, has helped induce vegetative ecosystems where fire has been an important, and often frequent, ecological force for millennia. Some notable exceptions would be extremely dry areas of the deserts, alpine areas above treeline and other areas where fuel accumulates at very slow rates. Several review articles have summarized research on frequency and importance of fire in the more common of California's vegetative ecosystems (e.g., Kilgore 1973; Biswell 1974; Barro and Conard 1991; Martin and Sapsis 1992; Weatherspoon et al. 1992; Agee 1993; Skinner and Chang 1996). Even studies in the moist coastal forests of northwestern California have documented the relatively frequent occurrence of past fires (Stuart 1987; Finney and Martin 1989, 1992; Brown and Swetnam 1994).

Generally, grass dominated ecosystems (including woodlands with fairly continuous understories of grass and herbs) are thought to have had the most frequent fires. These areas are able to carry fires often with annual fires not uncommon. Shrub fields and closed-cone conifer stands are not well studied in California in terms of fire frequencies. This is because most fires in these types are severe and remove evidence of previous fires. These types appear to have quite variable fire return intervals ranging from ~10 years in coastal sage scrub to more than 100 years in some areas. The conifer forests of the ponderosa pine, mixed conifer, and upper montane areas generally have median fire return intervals of approximately 5 to 40 years with considerable variation possible. Subalpine environments are little studied in California. Nonetheless, these areas have a high incidence of lightning. The characteristic fire regime appears to be of frequent, small, smoldering fires that usually do not spread well because of the compactness of the fuelbed and the slow accumulation of fuel.

Martin and Sapsis (1992) provide a California-wide perspective of what our knowledge of historical fire frequency implies in terms of annual area burned. They estimate that, of the 30 million hectares of flammable vegetation in California, between 2.3 (7.7%) and 5.3 (17.8%) million hectares burned annually under historical fire regimes. Of this total, tree dominated ecosystems (9.7 million ha.) accounted for between 0.5 and 1.0 million ha., shrub ecosystems (7.7 million ha.) accounted for 0.3 to 0.9 million ha., and grass/herb ecosystems (12.7 million ha.) accounted for 1.6 to 3.5 million ha.

Clearly, fire was historically a major ecosystem process that frequently affected vast areas. With few exceptions, it was rare for areas to escape the influence of fire for long periods of time.

Fire Characteristics in Various Fuel Types

Potential fire behavior expressed as magnitude and duration of heating is of interest. Most experiments that have studied the effects of fire on obsidian hydration rinds have found that high temperatures are more likely to cause alterations than are low temperatures (Friedman and Trembour 1983; Green et al. 1997). One study showed that temperatures above 200°C for short periods affected the hydration rinds (Green et al. 1997). Thus, the potential for fire affecting the ability to use hydration rinds for accurate dating is related to both the frequency of and the temperatures reached by the many fires that have occurred over years past.

Fire behavior, even within a relatively homogeneous landscape, can be quite variable. The rate of spread and intensity changes with variation in humidity, air temperature, wind speed, fuel moisture, fuel arrangement and fuel quantity (Rothermel 1983). Fires in grasslands will have very different characteristics than fires in shrub or forest environments.

All temperatures given in the following discussion are those recorded at the soil surface. Temperatures within a fire vary greatly from those at the soil surface depending upon the position of measurement in relation to the burning fuel (Woodmansee and Wallach 1981).

Grass and Herb Dominated Fuel Types

Surface temperatures in grasslands have been found to vary from 100°C to over 680°C depending upon fuel loading. The highest surface temperatures are probably associated with local accumulations of loosely compacted litter (Wright and Bailey 1982). Fires usually move rapidly through grasslands and the heating is of short duration. Surface temperatures recorded in fires in annual grasslands range from 80°C to 160°C. Slow moving fires recorded lower peak temperatures than did faster moving fires (Woodmansee and Wallach 1981). However, others have found backing fires to reach higher temperatures than forward spreading fires (Wright and Bailey 1982).

Shrub/Chaparral Dominated Fuel Types

The surface temperatures recorded for chaparral and shrub fires show extremes of over 700°C with temperatures over 500°C remaining for more than 10 minutes (DeBano et al. 1979). DeBano et al. (1979) characterized temperatures in fire described as light intensity, moderate intensity, and high intensity to average 260, 430, and 685°C respectively. Average soil surface temperatures in shrublands were reported to run 350 to 370°C by Woodmansee and Wallach (1981) .

Tree Dominated Fuel Types

Fires in forested environments vary considerably depending upon the nature of the fuelbeds. Where fires run through regularly there is little fuel and lower temperatures are reached. Where fires are infrequent, considerable duff and litter can build up, generating much higher temperatures. The highest temperatures, ranging from 620 to 1000°C, are usually associated with burning of heavy logging debris as in clearcuts (Wright and Bailey 1982). Stark (1977) found in Douglas-fir/larch stands that soil surface temperatures ranged from less than 180°C where little duff and litter were consumed to over 300°C where most duff and litter were consumed. Weatherspoon (unpublished data on file PSW Redding, California), in mixed-conifer stands of northern California, found surface temperatures ranging generally from 90°C to over 250°C. Temperatures exceeded 150°C about 50% of the time.

Implications for Obsidian Hydration Rind Dating

Obsidian exposed to fires with peak temperatures of more than 200°C for short duration may have significant alterations of their hydration rinds (Green et al. 1997). It is clear from the above discussion that many different fuel conditions can produce surface temperatures exceeding this critical level. The existence of conditions necessary to exceed the critical temperature is especially true for shrub fields and forests where fire is less frequent and in productive perennial grasslands where greater amounts of fuel accumulate. Areas of lighter fuels - annual grasslands and herb dominated understories of woodlands - are probably less likely to reach the critical temperatures as often as areas with heavy fuel concentrations. It is also clear from studies of fire history that obsidian material that has been unprotected for more than a few decades on or near the soil surface has likely been exposed to fire. Indeed, considering the frequency of fire in most California environments, it is likely that exposed material has been affected by fire several times. Only material that was buried and remained so after it was no longer in use is likely to have escaped the influence of fire.

Fire intensity and duration of burning are highly variable and dependent upon the nature of the available fuels and weather conditions. The variable nature of fire across the landscape and from ecosystem to ecosystem is well known. It has been found that the degree that hydration rinds have been altered by fire varies from place to place, even within a local site (Green et al. 1997). This variation appears to be related to the nature of the fire as it is affected by fuel and weather conditions. Thus, high variability in dates inferred from hydration rinds should be expected from artifacts that have been exposed to the effects of past fires.

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PROTECTING ARCHEOLOGICAL SITES WITH PRESCRIBED FIRE

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Abstract

Past fire studies have shown that fire has a measurable effect on the hydration rind that forms on obsidian artifacts. Ecosystem management requires the reintroduction of fire through either prescribed fires or to allow wildfires to burn unabated. Wildfires are happenstance and when occurring in areas where significant archaeological resources are located, damage to sites can occur not only through suppression actions but from the unnatural fire intensities generated from accumulated fuel loading attributed to successful fire management practices. Wildfires therefore, do not afford the opportunity for archaeologists to successfully protect known and newly discovered sites. Prescribed fire, through proper planning and site surveys can protect archaeological resources and allow the reintroduction of fires as a natural process in fire dependent ecosystems.

Prescribed Burning is A Multi-Disciplinary Process

A single prescribed burn can achieve multiple benefits. Fire in resource management can achieve specific results for hazardous fuel reduction, prepare sites for seeding and planting, dispose of logging debris, improve wildfire habitat, manage competing vegetation, control disease, improve forage, enhance appearance, improve access, perpetuate fire dependent species, cycle nutrients, manage endangered species, and improve air quality. Since the early 1960's resource managers from all disciplines have been taking a constructive view of fire in North America. Prescribed fire is a reasonable way to reinforce fire into many ecosystems. Prescribed fire is defined as fire applied in a skillful manner, under exacting weather conditions, in a definite place to achieve specific objectives

In the hands of confident prescribed burners, fire is a versatile process that can achieve many objectives simultaneously in many plant communities. It is natural and frequently the only management method available to achieve particular objectives. Resource managers often speak of "tools" that can be used to manipulate the ecosystem. Tools can consist of hand clearing, ball and chaining, use of herbicides, logging, disking, chipping and mulching, fertilizing, and other mechanical methods. These are tools, but fire is not a tool, fire is a process that cannot be replaced or mimicked by any other means. Fire has been and is an essential component of our ecosystems.

Historic and Prehistoric Fire Severity

We often overlook the importance of aboriginal burning (Lewis 1973). Often we think of fire and fire ecology as originating from natural causes like lightning. Equally important and even more profoundly dominate; fire is a cultural phenomenon. It is among man's oldest tools, one of the first products of the natural world that was domesticated. Anthropological burning is the primary source of ignition in the world and mankind is the most significant modifier of the fire environment, most notably its fuels. Today, it is nearly impossible to discriminate between the influences of climatic change, biotic migrations, natural fire, and aboriginal firing of the landscape. Fire has been applied and reapplied for new as well as old purposes resulting in profound cultural and environmental changes. One would think then, that if man alone can create fire, he alone can extinguish it, and he can alter the landscape as much by excluding fire as by introducing it.

Prior to the 1930's large-scale fire suppression actions were not common. Fires continued to burn across the landscape and often were quite large in size. When the limited resources of personnel would gather to extinguish a fire threatening a town or a ranch, they would use burning out techniques by lighting backfires from existing roads, creeks, rivers, or other natural barriers. Even while such suppression actions were being taken on one fire, many more fires continued to burn until the fall rains or natural barriers extinguished them. Visualize the type of fire that was being experienced prior to 1930. The fires were often large in size covering thousands of acres. The fires were variable in intensity, but were most often of low intensity. The fires would spread with the changing wind conditions sometimes moving rapidly through the fuels and sometimes moving slowly. The fires would move rapidly upslope and back slowly downslope and into creeks and drainages. Fires burning in forested landscapes would often be ground fires preserving the canopy. In chaparral fires were often moderate intensities leaving a mosaic of uneven age classes. For the most part we can visualize that fire burned known and unknown archaeological sites, historical sites, and in many cases several times.

Following the introduction of large scale and effective fire suppression methods in the 1930's, large-scale fires would become less common. Agencies trusted with the protection of our natural resources found decades of success in their fire suppression efforts. Unknowingly to most of our public land managers, each successful year began the eventual buildup of fuels far beyond what would ever have been seen in previous centuries. Finally, in the early 1960's the catastrophic results of this unnatural fuel buildup began and continue today. Think now of the fires of today, where in the past, fires that burned unknowingly through archaeological and historic sites were of low intensities resulting in insignificant changes to artifacts, fires of recent history have far exceeded these intensities and result in significant and dynamic changes to artifacts.

Prescribed Fire Project Planning

How then, can we use prescribed fire to protect prehistoric and historic sites? Balancing all the environmental concerns for re-applying fire to the landscape is the responsibility of the Prescribed Fire Project Manager. Project development often has to balance protection of watercourses, rare and endangered plant habitats, wildlife corridors, smoke management considerations, aesthetics, and prehistoric and historic sites. What often is first proposed as a five hundred acres project can become less than a fifty acre project if all the resource managers consider their specialties to be mutual exclusive. Integrated resource management is the key to returning the project to its maximum intended size and yet achieves the results desired for all resource managers.

The California Department of Forestry and Fire Protection (CDF) uses a Programmatic Environmental Checklist with its Vegetation Management Program (VMP) to evaluate the protection measures needed to minimize impacts to archaeological sites.

In order to complete this checklist, the project manager and the associate archaeologist have the opportunity to review the project on the ground and search for potential sites. The use of CDF's VMP has allowed the legal access to thousands of acres of private lands and has led to the locations of numerous new archaeological sites. This opportunity to locate these sites has yielded significant information to add to the ethnology of California.

Once located, archaeological sites need to be protected from undesirable fire and site preparation effects. The prescribed fire project manager and the cultural resource manager should then evaluate three parameters. First, has the site experienced a wildfire in the past 75 years? If so, most of the perishable artifacts have already been destroyed. Second, the placement of fire lines must be considered to avoid impacts to the site. Third, what effects will the fire have on the remaining artifacts and what significance are they to future scientific study.

The easiest protection to provide is from mechanized equipment by excluding the area from encroachment of the equipment. In most cases this can easily be developed into the burn plan.

The difficult decision then needs to be given to excluding the site from fire. This decision may sound simple but can lead to disastrous results. Leaving the site untouched by fire during the prescribed burn may seem like the correct choice, but what will be the long-term implications?

Consider the results of a prescribed fire project where it was required to leave vegetation buffer along all ephemeral streams. Five years later a wildfire burned through the area, resulting in high intensity runs through the buffers left along the streams. All of the previously burned areas of the project received only light fire intensity levels and adequate surface material was left to protect the soil. Winter rainfall resulted in intense scouring of the stream courses where the vegetation was completely removed. Had the biologist understood fire behavior and allowed the prescribed fire project manager to let the fire slowly back into the stream course, the resulting wildfire and rainfall event would have been less catastrophic.

So now lets revisit the simple recommendation to exclude an archeological site from a prescribed fire. Considerations must be given to:

1. Will the site stand out so as to be readily identifiable to unauthorized persons? and

2. Would a resultant wildfire cause extreme spalling, cause artifacts to be exploded, exposed to disintegration, or prevent further research and dating of artifacts?

Rather than a simple statement to exclude from the burn project a better course of action may be to evaluate the fire effect to the site and incorporate appropriate mitigation methods.

The first step is to consider the significance of the site. If the site doesn't appear to contain any artifacts out of the ordinary or would not make a dramatic change to ethnology then allowing fire onto the site may be appropriate. The next step would then be to mitigate the intensity of the fire. The project manager can provide an analysis of the intensity of the fire that would be applied, the duration of the fire, and the firing technique used on the site.

For example, if we chose to allow fire to burn over a site that contained a grass and woody debris ground cover we would look first at allowing a heading fire (burning with the wind) to cross the site. The fire behavior prediction run shows that fire line intensity would be 394 Btu/Ft/S. This is the amount of heat that would be generated at the flaming front. We must also keep in mind that 70 percent of the heat is transferred to convective lift. Note that flame lengths would be nearly seven feet and this would appear to the untrained observer as a very intense fire!

Rate of Spread, CH/H	44.0
Heat per Unit Area, Btu/SqFt	490.0
Fireline Intensity, Btu/Ft/S	384.0
Flame Length, Ft	7.0
Effective Wind Speed, MI/H	5.0

The same project would then consider the use of a backing fire (burning against the wind). The fire behavior analysis shows us that by using a backing fire on 22 Btu/Ft/S would be generated at the flaming front almost 70% would be transferred through convective lift.

Rate of Spread, CH/H ---------------------------------- 2.0

Heat per Unit Area, Btu/SqFt ---------------------- 490.0

Fire Line Intensity, Btu/Ft/S -------------------------22.0

Flame Length, Ft -- 1.9

Effective Wind Speed, MI/H -------------------------- 0.0

The simple solution would appear to use a backing fire on the site, however we must now consider the duration the fire would remain on the site. Head-firing shows that the fire would spread across the site at 44 chains per hour, or travel at about 48 feet per minute, thus the exposure of heat to the site would be short lived. The backing fire would spread across the site in two chains per hour, which is approximately two feet per minute. Exposure of the fire to the site is significantly longer is we use a backing fire. This implication would lead us to consider heat penetration through the duff and it's effect on artifacts below the surface. Laboratory tests on stone and ceramic artifacts found that the threshold temperature below which most objects are not changed sufficiently to alter their diagnostic values to be 800ºF. Above this temperature water loss, increased friability, discoloration, and change in form could occur. In both firing methods above the fire intensity is well below this threshold. To protect this site a firing technique using a head fire would be the best course of action for long-term protection.

In planning such a course of action, other mitigation could be incorporated. These could include, hand-clearing of excessive fuel buildup prior to burning, application of water to following the fire passage to immediately cool the site, and pre-burning the site prior to the main prescribed fire under even cooler prescriptions than called for in the burn plan. Most prescribed fires burned at a temperature under 80ºF and relative humidity above 20 percent will keep the surface temperature below 800ºF and soil temperature under 100ºF up to two inches below the surface. Large logs and woody debris should be hand cleared form the site, if possible, to avoid long-term residency.

If the site contains significant features like rock art, special measures can be taken. Use of aluminum fire blankets to shield the art from the affects of smoke and heat may be needed.

If absolutely required to exclude the site from prescribed fire activities, than the archeologist should work with the prescribed fire project manager to design a burn pattern that blends the site into the surrounding unburned vegetation. It is never preferred to leave the site as an unburned island within the project perimeter. Constructing handlines around the site to exclude is not as preferred as the use of Class A foams. The foams can be applied prior to burning and are very effective by preventing ignitions yet leaving vegetation undisturbed.

Conclusion

There are few if any sites within California that have not been burned at one time or another. Most cultural sites have been subject to low-intensity fires many times in the past and whatever damage is possible under these conditions has already occurred. The least impact to sites has been to those that have been burned prior to 1930. Archaeological sites that have not been exposed to fire in the last 60 to 100 years are in peril. Significant changes to surface and below ground artifacts will occur if they are burned by high intensity wildfires.

Prescribed fire projects afford the opportunity for the archeologist and the prescribed fire manager to work together and provide long term protection to our cultural resources. The archeologist should welcome the opportunity for prescribed fire projects as a chance to document sites on private lands, to evaluate the effects of low intensity fires on cultural sites, and to mitigate the long term impacts that could be caused by high intensity wildfires.

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Manual Fuel Load Reduction as a Means of Reducing the Effects of Fire on Obsidian Hydration: Examples from Lassen Volcanic National Park and Lava Beds National Monument

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Introduction

Recent research indicates that medium to high intensity prescribed fires and wildfires can have an adverse effect on obsidian hydration. This is problematic for Federal and state cultural resource managers in the western United States, where obsidian is ubiquitous and years of fire suppression have necessitated the use of fire to reduce fuel loads and to return fire to fire-dependent ecosystems. At the forefront of this effort is the National Park Service (NPS), where the use of fire as a management tool has been growing steadily since the 1960s.

Each of the four units in the Northern California Subcluster–Lassen Volcanic National Park, Lava Beds National Monument, Redwood National Park, and Whiskeytown National Recreation area–have active and expanding fire management programs. All four units contain archeological obsidian in varying quantities and configurations. However, the fuel types in each unit differ, as do the assumptions regarding the effects of fire on obsidian hydration and archeological survey strategies. Until recently and for a variety of reasons, cultural resource managers have had to consider the immediately tangible effects (e.g., cutting hand line through an obsidian scatter) over the more "invisible" effects of fire on obsidian hydration. Central to this rationale has been the notion that such areas have burned many times in the past, and that all obsidian has been previously subjected to the effects of fire, or that sites contain subsurface components that are protected from the effects of fire. In the absence of obsidian and other studies, however, these are nothing more than untested hypotheses, and included some potentially untenable assumptions. For example, is it correct to assume that the intensity of today's post-suppression fires is the equivalent of those that burned in pre-suppression times? Or, is it safe to conclude that subsurface obsidian (by its mere presence below surface) has not been exposed to the effects of fire in the distant or recent past?

Presuming obsidian hydration data are considered a resource value worthy of protection, attempts should be made to evaluate the integrity of those data (through obsidian studies) and/or implement protective measures to preserve those extant data that may be present. Up to this point, a lack of funding and other issues (e.g., Native American concerns, adequate sample sizes) have weighed against an empirical evaluation of the former. Drawing from the results of obsidian studies within or peripheral to each Northern California Subcluster unit, it is very likely that hydration data are preserved in many contexts. At this juncture, implementing a variety of protective measures seems most logical.

Experimental studies identify fire temperature and duration as the key variables when evaluating the effects on obsidian hydration (e.g., Green et al. 1997). In simplest terms, both relate most directly to fuel conditions; the heavier the fuels, the hotter and longer the fire will burn in a particular locale. The keys for protecting obsidian data are to either exclude from burning those sites that contain fuels that will burn at or above the expected threshold of effect or burn on site under conditions when the threshold will not be exceeded or fuels have been previously reduced below hazardous levels. A number of techniques have been used to accomplish these goals in the Northern California Subcluster units including line construction, foaming, sprinkler systems, covering with fire shelters, collection, and manual fuel reduction. Each has its strengths and weaknesses, depending on the type of resource and local conditions.

While unquestionably effective, techniques involving total exclusion of fire (e.g., handlines, sprinklers, foaming) essentially leave “islands” of unburned fuel on archeological sites. Like it or not, these places will eventually burn, and probably not under conditions (e.g., temperatures, suppression techniques) that will be friendly to the resources present. Further, unburned spots within burn areas could be magnets for increasingly sophisticated resource violators. Two individuals recently arrested in Lassen Volcanic for illegally collecting mushrooms had been tracking NPS fire activities over the Internet.

As for non-exclusionary methods, burning over sites with obsidian at times when fire will be of low intensity may not be possible or desirable if the burn is not sufficient to achieve other stated resource objectives. As such, in certain circumstances, manual fuel load reduction may provide a viable means of protecting obsidian from the effects of fire. Examples of applications of the technique at Lassen Volcanic National Park and Lava Beds National Monument are presented.

Lassen Volcanic National Park

CA-PLU-98/140/148 is a large obsidian scatter located near the south-central margin of Lassen Volcanic National Park. The site sits on a conifer-covered ridge between two ephemeral drainages. Most of the obsidian on the site can be visually attributed to the nearby Kelly Mountain source. It is one of the largest lithic scatters in the area and probably represents a temporary base camp. It is unknown if the site contains a subsurface component.

The site is crosscut by the Pacific Crest Trail and another trail, and is located at the boundary of two prescribed burn units. Given its location, the site area would be critical for ensuring that either one of the two prescribed burns did not escape its boundaries and become a wildfire. Ideally, the site area would be burned over to create a safe buffer zone. However, a number of dead and down conifer trees were located in that portion of the site previously identified as containing the most obsidian artifacts, and simply putting fire into the site area was judged infeasible given the presence of the obsidian. A number of alternative protection plans was discussed during an on-site visit by Walter Herzog (Lassen Volcanic Prescribed Fire Specialist) and me in August 1998. Exclusionary techniques were deemed infeasible due to the size of the site, access problems, and proximity to heavily used trails. It was decided that the best method would involve manual fuel load reduction using a 16 person California Department of Forestry and Fire Protection (CDF) Convict Crew. Specifically, all fallen trees would be cut into rounds, moved off site into designated areas, and burned.

In October 1998, four NPS sawyers and a CDF Convict Crew removed nearly 300 m^3 of fuel from the site in about three hours. Four piles were created, and these were burned after the first snow in the Fall of 1998. One white fir snag on the eastern margin of the site was felled; although at least 160 years old, no fire scars were found on the specimen.

Today, the surface of the cleared area consists largely of a shallow duff layer. While ground fires under such conditions can result in hot, long duration fires, the localized severity of such fires would be much greater if the logs were present. Although it is not yet certain whether fire will be intentionally put within the boundaries of CA-PLU-98/140/148 (it probably will not), the manual reduction of fuels will act to reduce the intensity and duration of those fires (when or if it does burn).

These actions also accomplished Fire Management's goal of lowering fuel loads at the interface of the prescribed burn units.

As an aside, following fuel removal, it was noted that the cleared area suddenly looked quite attractive for camping. Such factors should be taken into account when assessing which protective measures to implement for a given site.

Lava Beds National Monument

In 1991, the Lava Beds National Monument Archaeological District was listed on the National Register of Historic Places. All aboriginal archeological resources in the Monument with integrity are considered contributing elements of the District. Located near the Medicine Lake Highlands, the majority of aboriginal sites within the Monument contain obsidian, some in considerable quantities. Aboriginal sites are seen as significant for their information potential and importance to contemporary Native Americans. While no obsidian studies have been conducted in the Monument proper, obsidian hydration is an important component of information potential, and studies in peripheral areas suggest that obsidian data will be present on Lava Beds specimens (past burning notwithstanding). Thus far, determinations of integrity for Lava Beds archeological sites have relied primarily on content and spatial characteristics.

Away from the former shore of Tule Lake and two dozen or so ice caves, the archeological record at Lava Beds is characterized by small (<10-20 meters in diameter), sometimes dense, obsidian scatters. These have been termed "Event Scatters," and presumably relate to one or very few reduction episodes. The discrete nature of these scatters attests to their high spatial integrity. Obsidian hydration data from these sites would provide much information on land use patterns within Lava Beds.

Depending on local fuel conditions, fire intensity on these sites could be high enough to affect obsidian hydration. As such, an experimental method of fuel reduction will be implemented while conducting archeological survey for prescribed burns in the Spring of 1999. In addition to the usual field equipment, surveyors will carry hand clippers and bow saws. When a site is found, it will be formally recorded and then cleared of flammable vegetation. My small-scale clearing experiments in low to medium density sagebrush suggest that a 50 to 100 m^2 area can be cleared by two people in 10 to 15 minutes. The extent of the clearing (relative to the site boundary) will depend on the nature of nearby fuels and projected fire behavior models. For example, studies have shown that the amount of heat damage sustained by resources not directly within the flame zone is related to the severity of the burn; in the case of moderate burns this distance is about one meter., and about four meters in severe burns (see Ryan and Noste 1985). What constitutes a "safe" clearing (i.e., how much flammable material is left behind) will be determined through consultation with NPS Fire Management personnel. Hopefully, information on temperatures in and around the cleared area can be obtained during fire situations.

Provided it works, this technique is attractive because it allows for sites with obsidian to be mitigated for the effects of fire "on the fly," thus cutting down on factors such as return travel time. A site recorded and cleared in the spring or early summer should be in good shape for a burn in the fall of the same year. However, as those of us who work around fire know, the prescribed fire schedule is anything but predictable. As such, it would be worthwhile to assess how much new growth might return to a cleared area within a year or more. For larger sites, fire crews could be brought in to assist with vegetation clearing.

An archeologist at Bandelier National Monument in New Mexico reported that crews are taking similar measures to protect sites there from prescribed fires (Mike Elliot, personal communication

1998). In addition to training in hydrology, some crewmembers are chainsaw certified and will remove snags and fallen logs from the site area.

Final Thoughts

Until recently, cultural resources managers in the NPS have come into the loop of fire planning at about midstream. As more data become available and more attention has been paid to cultural resources and fire, the playing field has begun to level. It is now possible for cultural resource management to come in at the planning stages, including input at the Fire Management Plan level. Indeed, cultural resources managers should have as much say on how, when, and if a fire will be implemented as other resource managers.

In the case of effects on obsidian, we need to identify those areas and conditions where burning is likely to have an effect on hydration. Initially, sensitive areas can be highlighted through the use of predictive modeling programs such as BEHAVE, FOFEM, and CONSUME. From the results, the appropriate field strategies can be implemented. It is important to note, however, that these programs provide only general, normalized information. For example, while the BEHAVE runs for a prairie might indicate a cool and fast moving fire (and thus little or no effect on obsidian hydration), it cannot be foretold that some obsidian scatters in the prairie have fallen trees within their boundaries, and will burn significantly hotter and longer than predicted. Further, even under relatively homogeneous fuel conditions (e.g., sagebrush), burning will often occur in a mosaic fashion. That said, there is no substitute for field survey, although the amount will depend on a variety of factors including the nature of the fuels, resource density, and the amount risk the cultural resource manager is willing endure.

It should be emphasized that this planning is not restricted to prescribed fire situations. For example, many NPS units maintain zones where the ironically named “Wildland Fires for Resource Benefit” are allowed to burn under the right circumstances. In such zones known or suspected to contain sites with obsidian, proactive inventory and periodic vegetation clearing could be implemented. The same could be done in areas prone to wildfire.

Finally, manual fuel load reduction is only one of a number of techniques that can be used to protect obsidian in archeological sites. Its overall and long term effectiveness will need to be evaluated through applications in a wide variety of fuel types and fire behaviors.

Note

1. A follow-up presentation to this paper was delivered at the Northern California Data Sharing Meeting of the Society for California Archaeology (Siefkin and Brunmeier 1999). This presentation described the implementation of the “on-the-fly” mitigation tactics proposed above for Lava Beds National Monument during the Summer of 1999. More than 60 obsidian scatters in a large burn unit were cleared of vegetation during the course of survey and site recording. Post-burn spot checks revealed the technique to have been extremely effective at eliminating or greatly reducing fire intensity within and around the sites.

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THE DOME FIRE PILOT PROJECT: EXTREME OBSIDIAN FIRE EFFECTS IN THE JEMEZ MOUNTAINS

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Introduction

The Dome Fire began on April 25, 1996, in the Jemez District of the Santa Fe National Forest (SFNF) in the Jemez Mountains of northern New Mexico. Due to high winds and serious drought conditions, the wildfire spread rapidly and burned hot. By the time the fire was contained ten days later, over 16,000 acres had been burned on the Jemez District and in the adjacent Bandelier National Monument. During post-fire survey for road closures, SFNF archaeologists discovered a startling fire effect: obsidian in a large quarry site had been burned into frothy puffs of bubbled glass. Once it was recognized that the fire had caused this remarkable transformation of the volcanic glass, further examination at the quarry revealed several clusters of the "vesiculated" obsidian (Trembour 1990), as well as a wide range of other fire effects to obsidian artifacts and natural nodules at the site.

This article reports on a pilot project funded by the Heritage Resource Program of the Santa Fe National Forest. The Dome Fire Effects Study seeks to address several basic questions about the unusual fire effects observed at Capulin Quarry (LA 23961). What caused the obsidian to vesiculate at this site? How hot had the fire burned to produce such an extreme heat response? Were the burning conditions at this location somehow unusual, or was the Dome Fire an unusually hot forest fire overall? If the fire was not unusually hot at this site, why did we not see vesiculated obsidian at all the quarry sites that burned? Is there compositional variation in the obsidian at different quarry sites, or even variation in the glass within a single quarry? Could x-ray fluorescence (XRF) analysis of trace elements identify geochemical variation that may have played a role in the extreme heat effects observed? Or, could such an apparently hot fire affect trace element values as measured with x-ray florescence? In addition to these questions, we wanted to know what effect there had been to obsidian hydration (OH) bands at the site given the more obvious macroscopic fire damage. Were hydration bands obliterated by this hot fire, would diffuse hydration bands be visible on burned artifacts, and did such microscopically observable effects vary depending on the severity of burning on the site? The goal of this pilot project was to conduct analyses that would build a foundation for answering these questions, beginning with a description of the range of obsidian fire effects observed at Capulin Quarry.

The Jemez Mountains have an excellent history of research on the effects of forest fires on archaeological resources. The La Mesa Fire, which occurred adjacent to the current project area in 1977, was the first forest fire to incorporate archaeologists into the process of fire suppression, and provided the first comprehensive post-fire archaeological analyses (Traylor et al. 1979, 1990). Included in the La Mesa Fire research was Trembour's (1979, 1990) seminal work on fire effects to obsidian. The second major contribution from the Jemez Mountains resulted from the 1991 Henry Fire (Lentz et al. 1996), a study that also included a significant analysis of obsidian fire effects (Origer 1996). In response to the 1996 Dome Fire, several studies have been conducted at Bandelier National Monument including survey, testing, and excavation (Elliott 1999; Elliott et al. 1998; Ruscavage-Barz 1999; Schub and Elliott 1998). Most recently, the 2000 Cerro Grande Fire burned over 42,000 acres to the north of the current project area; post-fire archaeology projects are being conducted for this major forest fire by the Los Alamos National Laboratory and the Santa Fe National Forest.

Dome Fire Effects at Capulin Quarry

The Dome Fire was named for the St. Peter's Dome area, a portion of the San Miguel Mountains located on the southeast side of the Valles Caldera in north-central New Mexico west of Los Alamos and northwest of Santa Fe (Figure 1). Topography in the Dome area is characterized by rugged and incised landscapes with flat sloping mesas created by numerous uplifted sedimentary blocks, volcanic domes, and large pyroclastic deposits associated with the Valles and earlier caldera eruptions. Capulin Quarry (LA 23961; also known by the SFNF site number AR 03-10-03-1691) is an area of obsidian procurement and reduction located atop a large exposure (800 by 400 m) of obsidian-bearing pumice and rhyolite-tuff deposits. The site is defined largely as a surface deposit, although subsurface testing has been conducted at the site (Larson et al. 1988). An interesting aspect of the quarry sites in the Dome area is that due to the shallow forest soils and their location in primarily erosional settings along ridgetops, these quarries occur on "the surface" as defined from a variety of perspectives--including geological, archaeological, pedogenic, and topographic surfaces as well as the contemporary landscape surface. Elevations at the quarry range from 8300 to 8500 feet above mean sea level. Overstory vegetation in the area is dominated by Ponderosa pine with some spruce and fir. Understory vegetation includes grasses, Gambels oak, and New Mexico locust. Average annual precipitation is 18 inches, with most coming in summer months during the July-August "monsoon" rains.

Burning at Capulin Quarry was variable in severity. Most of the ridgetop and sideslopes where the dense source exposures of natural obsidian and obsidian artifacts occur experienced burning of mostly high and moderate severity, but there are some patches of light burning. Areas of light burning can be found especially around the perimeter of the quarry, along the western edge of the ridge (where a wide road--Forest Road 289--served as a firebreak), and on the eastern end (the tip of the main northwest-southeast trending ridge along which the obsidian-bearing geological deposit outcrops). There are few kinds of archaeological materials at the quarry other than obsidian, but some hammerstones observed within the burn area had fire-blackening and sooting, and several of the few chert artifacts seen at the site exhibit the classic fire-crazing and potlidding well-known for this material type.

It was the clusters of vesiculated obsidian that first drew our attention to archaeological fire effects at the site (Figures 2 and 3). These clusters are areas up to 2 m in diameter with concentrations of whitened and "puffy" obsidian that, at the time they were first discovered (in mid-July, five weeks after the Dome Fire started), stood out as loci of light-colored material in conspicuous contrast to the blackened soil background. Several clusters occur around burned-out stumps, and most of the twelve clusters mapped for this project are relatively evenly spaced within one severely burned area of the site. Chances are good that additional unrecorded clusters occur at the site, as their visibility is surprisingly low where the soils were not charred black. Further, our success in locating the vesiculated materials decreased significantly with the successful generation of grasses seeded into the Dome Fire burn areas as part of post-fire rehabilitation.

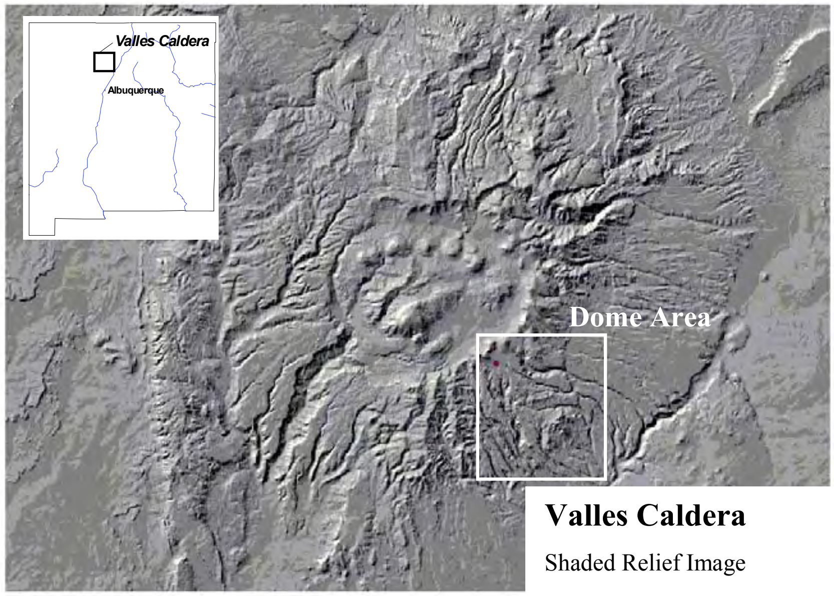


Figure 1. Project location map.

Figure 2. Cluster of vesiculated obsidian at Capulin Quarry following the Dome Fire.

In the 100-x-100-m area of the site where the largest concentration of vesiculated obsidian clusters occur, the burning was nearly uniformly severe: all surface organic materials were consumed to expose mineral soil, and standing trees suffered greater than 80 percent mortality with most exhibiting some degree of direct burning. There were numerous root burn-outs, and several examples of tuff boulders with heat spalling. The topographic location of this portion of the site makes it a good candidate for intense wildfire impact: it is a southwest-facing bowl below a narrow ridge that drops steeply to the north into the deeply incised upper reaches of Capulin Canyon. More dispersed occurrences of vesiculated obsidian were also found on the northwest-southeast trending ridge that bounds this bowl to the east, and in a southeast-facing draw between that ridge and the main ridge.

Figure 3. Closer view of a vesiculated obsidian cluster at Capulin Quarry; partially vesiculated flake near the center of the image is Specimen 1691-06; the pocketknife used for scale measures approximately 10 cm (Photo by John C. Phillips).

Fieldwork conducted for this study included site mapping and collection of obsidian artifacts and other samples from Capulin Quarry, and collection of geological samples from across the obsidian-bearing deposits exposed at various locations in the Dome area (both within and outside of the Dome Fire area). Geological sampling is described in further detail in the section below that discusses XRF analyses of these materials. At Capulin Quarry, Shawn Penman and the author mapped the site using a Sokkia total station. Both the topography and the distribution of the clusters of vesiculated obsidian in the burned portions of the site were mapped. The locations of several photo points were also documented. Photo-documentation of site erosion and the recovery of vegetation at the site was conducted from these points at regular intervals of at least every six months (and usually more often) through the first three years following the fire.

Artifacts were collected from burned and unburned parts of the site using both systematic and judgmental approaches. Systematic collections were conducted to recover burned artifacts from within clusters and to document their positioning on the burned surface as well as spatial relationships among macroscopically altered and unaltered pieces. Specimens were collected from within three vesiculation clusters (Clusters 2, 3, and 7) after recording their location in a 50-x-50-cm grid and photographing the burned materials in situ. One set of specimens (Unit 1) was collected from within a 50-x-50-cm grid placed to include an area of dispersed vesiculated materials (not dense enough to warrant the term cluster). In the analyses that follow, collection locations within the burned areas of the site are designated by proximity to the vesiculation clusters. The categories used here are:

- *in cluster*: within the maximum 1 meter diameter central core of vesiculation clusters;
- *near cluster*: within 2 meters of the center of a cluster;
- *burn area*: specimens were collected from throughout the burned portions of the site, without proximity to clusters;
- *unburned*: specimens were collected from within the quarry but in areas not burned during the Dome Fire.

To sample both burned and unburned materials more broadly across the site, specimens were collected judgmentally within two large collection areas (approximately 20 m^2). "Collect 1" was located within the burned area, and "Collect 2" was located outside of the burned area[i]. Judgmental sampling also included collecting individual specimens that were of particular interest (e.g., because they were especially good examples of certain fire effects or raw material visual appearance), or to increase the total sample of partially vesiculated flakes.

After collection, all specimens were closely examined to identify whether any macroscopic fire effects could be observed. This inspection was conducted using the naked eye, assisted in some cases with a 10x hand lens. As part of the process of learning to accurately identify fire effects, some artifacts were examined under a dissecting microscope at magnifications up to 50x. However, all fire effects described here as "macroscopic" are visible without magnification once the analyst is familiar with their appearance.

Decisions about how to collect and select artifacts for analysis were greatly aided by discussions with Fred Trembour, Richard Hughes, and Tom Origer. Before sending specimens for XRF and OH analysis, raw material appearance and observed fire effects were recorded and each specimen was photographed. Specimens were submitted for XRF and OH analyses along with these observations and accompanied by specimen photographs. When the XRF and OH analyses were conducted, Hughes and Origer marked on the photographs the exact locations sampled. This step was important for understanding possible relationships between the analytical results obtained and the nature and location of macroscopic fire effects. In several cases, multiple XRF readings or OH cuts were needed to better measure the potential role of variable fire effects on individual specimens; in these cases, the information recorded on specimen photographs proved to be especially useful.

Obsidian Fire Effects

I will describe in some detail the range of fire effects observed on artifacts at Capulin Quarry. In addition to the eye-catching vesiculation, other more subtle alterations were seen again and again on obsidian at the site. These include the familiar obsidian sheen and relatively well known fire fracture, as well as less commonly recognized attributes such as obsidian crazing and subsurface bubbling. There is a need for a standardized set of definitions of the characteristic attributes found on burned obsidian. Only two studies, by Trembour (1979, 1990) and Nakazawa (1998), provide this kind of systematic description based on field observations as well as heating experiments[ii]. Access to standardized descriptions would have several benefits. It would facilitate communication among researchers, aid archaeologists in recognizing fire effects when encountered in the field or lab, and increase documentation of the occurrence of fire alteration. Increased recognition and documentation of obsidian fire effects will expand our knowledge of variation in burned assemblages, and result in a better understanding of just how widespread is the occurrence of fire alteration of obsidian--both in contemporary fires and in prehistory. The descriptions provided here do not meet the criteria for an inclusive set of definitions, but may contribute toward that goal. The categories discussed below build on Trembour's (1990) descriptions, with reference to Nakazawa's (1998). It is important to note that the order of presentation of the categories in the list below is arbitrary and does not imply any sequential relationship among the fire effects or how they develop on obsidian during a fire.

- *Matte finish:* a dulling of one or more artifact surfaces. This may look like "weathering" or a lusterless patina. Depending on the nature of the source material, matte finish may be similar to the primary cortex. This probably is similar to Nakazawa's (1998) "decrease in vitreousness".
- *Surface sheen*: a metallic-like luster on obsidian surfaces. This is one of the most widely recognized obsidian fire effects but its cause has been unclear. Examination of the sheen under low and high power microscope (including a scanning electron microscope [SEM]) shows that

sheen is actually two different phenomena (Figure 4). One is caused by organic buildup (as indicated by extraordinarily high values of carbon when examined by qualitative energy-dispersive x-ray analysis under the SEM). This additive material causes the characteristic "gun-metal" sheen commonly observed on burned obsidian. The second kind of sheen is more silvery and reflective in appearance, and is caused by shallow (<10 microns) microscopic crazing (see below) and formation of very small bubbles. This appears to match Nakazawa's description of "tiny bubbles".

- *Fine crazing*: a delicate network of shallow cracks on fresh fractures or artifactual surfaces. This seems to occur across entire individual surfaces, but not necessarily on all of the specimen's surfaces. The crazing that I observed on burned obsidian at Capulin Quarry is quite unlike the kind of crazing that occurs on burned chert artifacts. This obsidian crazing is extremely shallow and is clearly a phenomenon that occurs only at the very surface (Figure 5). Chert crazing, on the other hand, is caused by *internal* fracturing (potlidding) expressed at the surface as cracking or crackling. The causes of fine crazing in obsidian are probably more similar to the surface crazing seen in silica glazes on high-fire ceramics, and as such may be a result of cooling processes and/or differential thermal expansion rather than the kind of material failure observed in chert crazing. Fine crazing in burned obsidian overlaps somewhat in appearance with radial fracture lines that develop during detachment from a core. However, obsidian crazing can be readily distinguished from radial lines because crazing forms a network of closed polygons and radial lines do not. In the specimens I have examined, crazing also can be expressed in ways that fracture associated with removal from a core could not --such as, for example, fine-line networks on ventral flake surfaces that are continuous across eraillure scars. Crazing can be easy to spot or very difficult to recognize--sometimes requiring a hand lens to identify. I have noticed that crazing more frequently is apparent on obsidian glasses that have smooth surface textures and/or that are clear rather than opaque. I suspect this is because it is easier to identify crazing on these surfaces, not because of actual variation in the occurrence of crazing among differing materials.
- *Deep surface cracking*: artifact surface is split by shallow crevices. This often occurs in conjunction with deformation of the artifact, such as by vesiculation. Most of the deep surface cracking that I observed can be understood as an effect subsequent to fine surface crazing, described above. Based on observations made during heating experiments and examination of specimens through SEM imaging, my impression is that deep cracking is not a separate phenomenon from fine surface crazing, but rather is caused by stretching of a finely-crazed surface when expansion of the glass occurs with bubbling, vesiculation, or other plastic deformation.
- *Vesiculation*: formation of abundant and interconnected bubbles throughout the interior and at the surface of the glass object as a result of heating that, in turn, causes deformation and increase in object volume or size. This "puffing" occurs without an actual appreciable decrease in total weight, although there is the definite illusion that the piece is much more lightweight than before it blew up (see Figure 3). "Vesiculation" is the term used by Trembour; Nakazawa's term for the phenomenon is "explosion" of the glass. These terms are similar to what is meant by the geological term "vesicularity", which is used to refer to the volume of bubbles in the glass that form in association with the pyroclastic processes that produced the deposit. As used here, "vesiculation" refers to vesicles in obsidian created as a response to heat exposure unrelated to the original formation of the clasts. Specimens can be either partially or completely vesiculated, and vesiculation may or may not alter the form of the artifact. One case I observed is a fully vesiculated flake that, while completely bloated, still retains all of the flake characteristics needed to determine the ventral and dorsal surfaces, orient the proximal and distal ends of the flake, and observe the location of cortex that existed on the flake before it was burned. In other cases, vesiculation renders an item unrecognizable. In particular, thin flakes

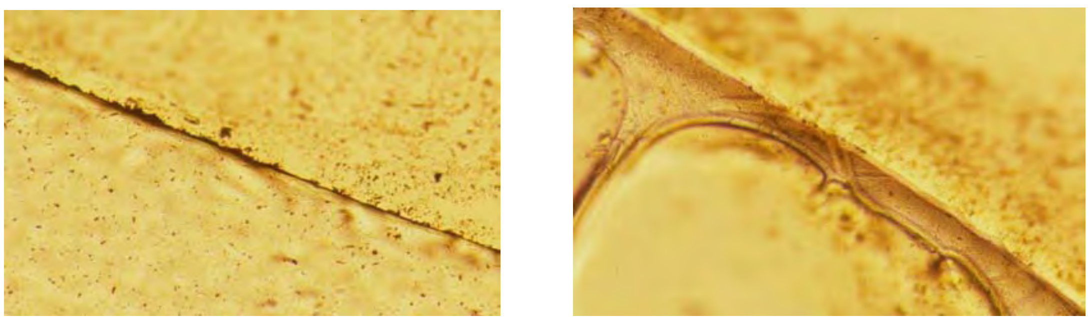
tend to curl upward and can end up looking just like pieces of packing foam. Despite lacking a shiny ("glassy") surface and having lost the ability to fracture conchoidally, vesiculated obsidian is still glass. This fact is demonstrated by the characteristic "clink" the deceptively soft-looking and pillowy pieces make when dropped on a hard surface.

- *Incipient bubbles*: individual bubbles developing subsurface, but without the abundance, density, and interconnectedness of vesiculation (Figure 6). These subsurface bubbles are more frequently observed in clear obsidian than in cloudy or opaque obsidian. One reason may be that subsurface bubbles are easier to see when the glass is more transparent. Another possibility is that cloudy glasses contain more precursors for bubble formation (e.g., internal inclusions such as phenocrysts or spherulites). In other words, if cloudy materials have more loci for bubble nucleation, the result would be more and smaller bubbles.
- *Fire fracture*: rapid fracture through the body of the artifact or nodule that can look similar to intentional lithic reduction but that initiates from within the item rather than from applied force at a margin or edge. As such, fire fracture is similar to potlidding, but at Capulin Quarry fracture rarely was expressed in the lens-shapes characteristic of potlidding. Fire fracture in the Dome Fire nearly always involved breakage of whole objects, and never occurred as potlids "popping-off" of the nodule or artifact. Distinguishing fire fracture from intentional lithic reduction can be difficult at first, but characteristic features emerge with continued examination. Because fire fracture occurs conchoidally, it has rings or waves of force but it is lacking a bulb of percussion--the attribute of applied-force fracture so characteristic of human-induced flaking. Because fire fracture initiates from within rather than at the edges of a nodule, all edges of a fire fractured piece are margins or terminations--there is no proximal end. Many fractures seem to initiate with an inclusion of some kind, such as a phenocryst, that can be seen near the center of the fracture surface. In many cases tiny "gullwings" point back to this center initiation. These faint v-shaped markings look like a minute disturbance in the fracture path akin to the pattern that a smooth current of water makes as it flows around a rock in a stream. For a lithic analyst at a quarry site, adding fire fracture to the complexity of reduction information already in abundance in such assemblages can be bewildering. The most disorienting aspect of fire fracture in these assemblages is that fire fractured materials do not conform to the most basic distinction made in lithic technology--the essential contrast of core vs. flake expressed by positive and negative flake/scar relationships. A fire fractured nodule breaks into many pieces--none of which are actual flakes or cores.

Discussion of Obsidian Fire effects

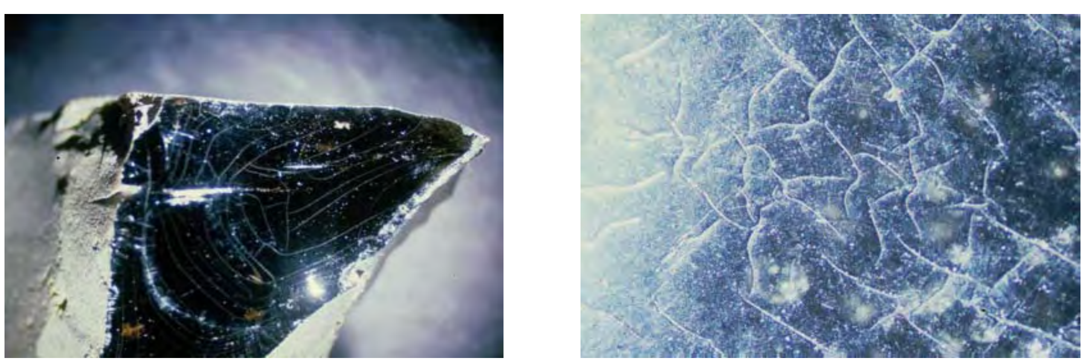
The macroscopic fire effects listed above are readily observed on obsidian artifacts and hand specimens. These attributes can be expected to preserve well in the archaeological record--except for full vesiculation (which renders the objects very fragile and susceptible to both mechanical and chemical weathering) and sheen caused by organic residue (which presumably will alter over time with exposure to the environment). Therefore, partial vesiculation, bubbling, and surface crazing all can be used as indicators not only of heat exposure during contemporary fires but also as evidence of past heat exposure. As observed many years ago (Friedman and Trembour 1983), crazing is particularly promising for use in recognizing past fire alteration. Crazing can be expected to preserve well on burned artifacts because the alteration is entirely surficial (i.e., it does not compromise the body of the specimen). Further, there is some experimental evidence that crazing does not occur until temperatures are reached that are higher than those expected to alter and obliterate pre-existing obsidian hydration bands (Friedman and Trembour 1983). The implication is that hydration bands measured on a crazed surface, or even on the crazing crack that extends into the surface, could be inferred as post-dating the fire exposure that caused the crazing (Trembour, personal communication 1997). Thus, crazed artifacts would provide ideal surfaces to explore the potential of obsidian hydration dating for estimating how long ago the fire exposure occurred. This possibility is only raised here, but is a consideration in my dissertation research that builds on this pilot project.

Understanding the relationships between macroscopic heat effects and microscopic alteration are central to the analyses reported here. In the following sections I present results obtained using the two microscopy techniques most commonly applied to obsidian--x-ray fluorescence analysis and obsidian hydration analysis--to examine obsidian burned during the Dome Fire. The first section examines chemical composition analyses in obsidian samples that are unburned compared to obsidian exposed to heat under experimental conditions and in the Dome Fire. That section begins with an XRF analysis of the obsidian source material to provide a geological baseline necessary to understand the results obtained for the burned obsidian. The second section investigates obsidian hydration bands at the burned quarry--assessing the impact of the fire for OH dating information in the burned assemblage, and examining the relationship between certain macroscopic fire effects and the expression of obsidian hydration bands on individual specimens.



(a) (b)

Figure 4. Comparison of surfaces with "sheen" in obsidian hydration cross-sections: (a) residue on surface--note that no hydration is present (Specimen 1691-01); (b) incipient vesicles in a shallow layer just below the surface (Specimen 1691-12). (Microphotographs by T. Origer)



(a) (b)

Figure 5. Examples of crazing: (a) fine crazing on a fire fracture surface (Specimen 1691-26B); (b) "network" of crazing lines (Specimen 1691-53). (Microphotographs by A. Steffen; Photomicroscopy facilities provided by Bio-Optics Lab, University of Oregon, Eugene)

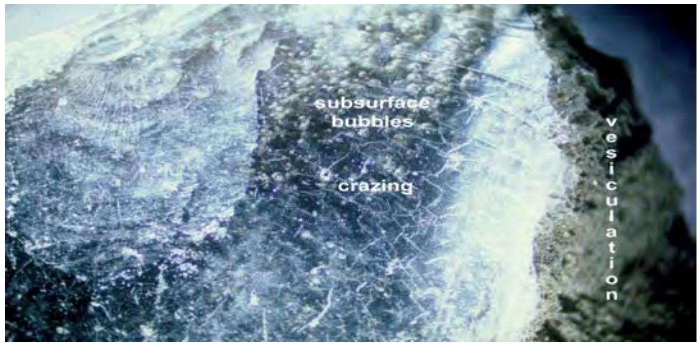


Figure 6. Artifact with several fire effects, including vesiculation, incipient bubbles, and crazing (Specimen 1691-53). (Microphotograph by A. Steffen; Photomicroscopy facilities provided by Bio-Optics Lab, University of Oregon, Eugene)

Chemical Composition Analyses

In this section I report on three x-ray fluorescence analyses. The first is a geological baseline analysis of obsidian in the "source" deposits that were exploited at the archaeological quarries in the Dome area. It was necessary first to obtain this kind of chemical composition background information before it would be possible to assess whether there is compositional variation in the obsidian found at burned sites. Without knowing what variation might occur within the source, it would be difficult to understand whether compositional variation may play a role in response of the obsidian to heat, or whether burning of the obsidian causes any changes in XRF measurement of trace elements. The second analysis presents XRF measurements on a set of obsidian samples heated to a variety of temperatures in a lab furnace. The goal was to determine whether any pronounced differences in XRF measures of trace elements and selected minor elements could be detected in materials heated in a setting more controlled than a forest fire. Finally, the third analysis applies XRF analysis to obsidian materials that were burned during the Dome Fire. XRF measures taken on these burned specimens were then examined 1) to see whether all materials are, in fact, from this obsidian source, 2) to compare XRF results among specimens collected from areas with varying degrees of burn severity, and 3) to assess whether burning in the fire resulted in any significant differences in the XRF measures of chemical composition.

Geological Sampling for Trace Element Analyses. Geological sampling was undertaken for two purposes: 1) to investigate the relative homogeneity of trace elements in obsidian from the Cerro Toledo rhyolite deposits, and 2) to provide an accurate geological baseline to compare with burned samples. Several dozen obsidian samples were collected from ten exposures of the geological unit (see Figure 7).

The "Obsidian Ridge" source in the Jemez Mountains is familiar to Southwestern archaeologists--both anecdotally and through geochemical characterization. Trace element analyses to define a geochemical "fingerprint" for this source are best known in the archaeological literature by the works of Newman and Nielsen (1985), Baugh and Nelson (1987), and, most recently, Glascock et al. (1999). However, the combined total of geological samples included in these analyses is less than 30, and the manner in which sampling locations are identified in these studies does not allow an assessment of whether they are drawn from numerous locations across the geological deposit or concentrate in only a few (or one). Adding somewhat to the confusion is the use of variable nomenclature: the source is known alternately as Obsidian Ridge, Rabbit Mountain, or as the obsidian contained within the Cerro Toledo Rhyolite. In this study, I will refer to the obsidian source deposits that I have sampled as "Rabbit Mountain/Obsidian Ridge", which occur within the larger geological unit known as Cerro

Toledo Rhyolite. Part of this departure from using the more traditional "Obsidian Ridge" name is that once the Dome area is explored extensively on the ground, it rapidly becomes clear that the Obsidian Ridge location is actually a relatively minor source outcrop. The ideal name for the source would be "Cerro Toledo" after the geological unit in which it is contained (see LeTourneau et al. 1997 for discussion). However, the actual locations sampled for this study do not represent all of the areas where obsidian can be found within the Cerro Toledo Rhyolite (for example, no sampling was conducted in the Sierra de Toledo area in the northeast part of the Valles Caldera). I use the "Rabbit Mountain/Obsidian Ridge" name in this study in part to identify that the deposits sampled for this analysis come only from within the Dome area.

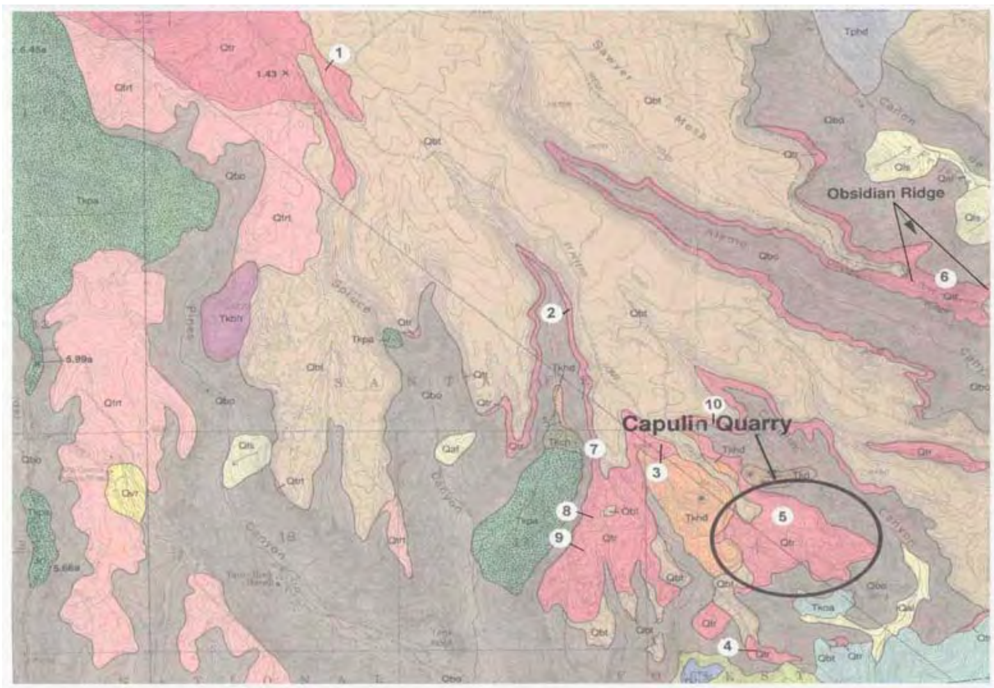


Figure 7. Map of geological sampling locations.

The current project benefits greatly from recent geological mapping in the Dome area (Goff et al. 1990). While obsidian-bearing geological deposits associated with the Rabbit Mountain/Obsidian Ridge outcrop locations are accurately mapped in the primary geological mapping resource for the Jemez Mountains (the excellent 125,000 scale map published by Smith, Bailey, and Ross in 1970), the more recent geological mapping published in 1990 by Goff, Gardner, and Valentine at 1:24,000 scale provides an increase in resolution that is better suited to archaeological understanding of the topographic distribution and geological relationships expressed in the outcrops associated with archaeological quarries. Examination of the portion of their map included in Figure 7 shows that the Qtr deposits (described below) are exposed in many more locations than at Obsidian Ridge, and that many of these locations are larger and have much broader surface expression than at that one well-known topographic location. The Rabbit Mountain dome is located to the northwest of the Goff et al. (1990) mapping area and only a small segment of that dome is included on their map (see Figure 7, upper left corner).

The Rabbit Mountain rhyolite of the Cerro Toledo Rhyolite is part of the Tewa Group, and is sandwiched between two of the largest Tewa Group units, the Upper (Otowi Member) and Lower

(Tshirege Member) Bandelier Tuffs. Goff et al. (1990) describe Rabbit Mountain rhyolite as black, very aphyric obsidian to white devitrified rhyolite, with an age of 1.43 million years as established by potassium-argon dating. There are two parts to the deposit, Qtr and Qtrt. The Qtr deposit forms domes, flows, and flow breccias that thin to the south and east, and have a maximum thickness of about 50 meters; Qtrt materials consist of mixed ash-fall and ash-flow deposits (Goff et al. 1990, also citing Heiken et al. 1986). The larger obsidian clasts are found in Qtr, while Qtrt obsidian pieces tend to be much smaller and of little value as a toolstone.

All ten sampling locations selected for the current study are in the Qtr deposits, as shown in Figure 7. Diverse topographic locations were chosen to include easily accessed mesa surfaces as well more inaccessible locations on side slopes. I did not obtain samples from the Rabbit Mountain dome (except from GS 1 at the base of the dome) because access to the area was limited due of private land ownership[iii]. Table 1 provides the UTM coordinates of each location, as checked using a GPS unit. Although part of the larger study, two of the ten locations (GS 5 and GS 9) were excluded from this geological baseline geochemical analysis because they represent locations with burned obsidian (GS 5 is the burned quarry where the abundant vesiculated obsidian was first observed, and GS 9 is a prescribed burn location where a single vesiculated obsidian artifact was recovered). Samples selected for XRF analysis included specimens representing a wide range of visual diversity--including clear black, clear brown-black, grey-and-black banded, opaque or cloudy light and darker greys and greenish greys (some with inclusions and some without), a grey-black material with a peculiar shimmering texture that looks like threads within the glass, and an opaque chocolate brown glass.[iv]

Trace element analysis was conducted on 30 specimens by Richard Hughes, Geochemical Research Laboratory. The methods and results discussed here were provided by Hughes in his 1998 letter report to the SFNF (Hughes 1998). The analyses were conducted using a Spectrace™ 5000 (Tracor X-ray) energy dispersive x-ray fluorescence spectrometer equipped with a rhodium (Rh) x-ray tube, a 50 kV x-ray generator, with microprocessor controlled pulse processor (amplifier) and bias/protection module, a 100 mHz analog to digital converter (ADC) with automated energy calibration, and a Si(Li) solid state detector with 160 eV resolution (FWHM) at 5.9 keV in a 30 mm^2 area. The tube was operated at 34.0 kV, 0.25 mA, using a 0.127 mm Rh primary beam filter in an airpath to generate x-ray intensity data for elements Zinc (Zn Kα), gallium (Ga Kα), rubidium (Rb Kα), strontium (Sr Kα), yttrium (Y Kα), zirconium (Zr Kα), and niobium (Nb Kα). Intensities for titanium (Ti Kα), manganese (Mn Kα), and total iron ($Fe_2O_3^T$) were generated by operating the x-ray tube at 15.0 kV, 0.28 mA with a 0.127 mm aluminum (Al) filter. Iron vs. manganese (Fe Kα/Mn Kα) ratios were computed from data generated by operating the x-ray tube at 15.0 kV, 0.30 mA, with a 0.127 mm aluminum (Al) filter. Barium (Ba Kα) intensities were measured for some specimens but are not included in this article. After matrix corrections algorithms were applied to specific regions of the x-ray energy spectrum to compensate for inter-element absorption and enhancement effects, intensities were converted to concentration estimates by employing a least-squares calibration line established for each element from analysis of up to 30 international rock standards certified by the U.S. Geological Survey, the U.S. National Institute of Standards and Technology, the Geological Survey of Japan, the Centre de Recherches Petrographiques (France), and the South African Bureau of Standards. Further details pertaining to x-ray tube operating conditions appear in Hughes (1988, 1994).

Trace element values generated for the 30 samples from eight geological sampling locations are listed in Table 2. Element values are expressed in quantitative units using parts per million (ppm) for all elements except total iron, which is indicated as weight percent composition. Data presented in the table is organized by element and provides the sample mean, standard deviation, and coefficient of variation for specimens from each sample location.

Table 1. Geological sampling locations.

Location ID	Easting	Northing	Associated Site	Location description
GS 1	369258	3965084	None	50m NW of FR 36; on south facing slope
GS 2	370793	3963445	None	300m down a steep mesa slope below W side of FR 289
GS 3	371392	3962341	AR 03-10-03-1488/1522 LA 24705	30m W of FR 289; in cleared "safety zone" (site disturbed by Dome Fire suppression)
GS 4	371941	3960741	None	20m W of FR 289; between road and mesa edge
GS 5	372050	3961840	AR 03-10-03-1691 LA 23961	Capulin Quarry; large ridge E of FR 289
GS 6	373247	3963352	AR 03-10-03-2360 LA 82485	Obsidian Ridge; in FR 287 atop narrow ridge
GS 7	371054	3962361	AR 03-10-03-1664 LA 55092	Along ridgetop, on or near an abandoned road
GS 8	371054	3961841	AR 03-10-03-1665 LA 55093	Along ridgetop, on or near an abandoned road
GS 9	370867	3961724	AR 03-10-03-1665 LA 55093	In saddle on abandoned road (an artifact within a 1992 prescribed fire)
GS 10	371888	3962450	AR 03-10-03-1401 LA 23922	At tip of ridge near head of Capulin Canyon

Hughes' (1998) analysis determined that these samples have the same trace element composition as Obsidian Ridge (a.k.a. Cerro Toledo Rhyolite [MacDonald et al. 1992, Appendix 1, p. 148]; cf. Baugh and Nelson 1987, Table 1). Trace element values also match well with neutron activation analysis and x-ray fluorescence data for Obsidian Ridge/Rabbit Mountain published recently by Glascock et al. (1999). Given that all of the current samples were collected from within the Cerro Toledo Rhyolite, these are the results expected. The relevance for the current study is that these results strongly indicate relative trace element homogeneity within the Rabbit Mountain rhyolite (Qtr) obsidians across various outcrops of the deposit. This geological baseline analysis indicates that, based on the trace elements and selected minor elements measured, there is no evidence for intrasource geochemical variability that would explain variation in the forest fire effects to obsidian observed within the Dome Fire. In other words, significant trace element variation was not found within this source. This, of course, is not the same thing as saying there is no intrasource variation in glass composition, but rather identifies that if relevant variation exists it is a kind not usually measured using x-ray fluorescence analysis.

Experimental Heating of Obsidian. In order to examine causes of fire-induced vesiculation in obsidian, I have conducted several preliminary laboratory heating experiments. However, as these were only initial attempts to identify a minimum temperature required to cause vesiculation, the experimental conditions (e.g., firing duration, rate of heating, specimen shape, specimen size) were not sufficiently controlled to justify reporting those results here. Further lab heating experiments are planned. I will, however, report on one heating experiment that produced results useful for this discussion. Results from this heating test, while preliminary, give some indication of the temperatures required for vesiculation, variability in the response to heat by obsidian from within this source, and trace element measurements before and after heating.

Experimental heating was conducted on a small electric bench furnace, donated to me by Fred Trembour.[v] For this experiment, I used four obsidian nodules collected at three geological sampling locations: GS 7 (2 nodules: A & B), GS 8, and GS 10 (see Figure 7). The four nodules were selected as representative of two kinds of obsidian common in the materials observed across the geological deposit.

- Samples 7A and 10 are a very "pure" clear black material with no opacity and nearly free of inclusions (GS 7A has very few, and GS 10 has none);
- Samples 7B and 8, in contrast, are opaque, medium grey (GS 7B) or dark grey (GS 8) in color with a slight greenish tint, with speckles, tiny bubbles, and, in the case of 7B, small inclusions (which may be spherulitic or amygdaloidal).

The experimental set consisted of a total of 16 flakes: four detached from each of the four (non-artifact) nodules.[vi] These 16 flakes were then distributed into four groups of four flakes (each batch having one flake from each of the four nodules). Each group was then subjected to one of three different firing temperatures, except the fourth group that remained unheated. During heating, specimens rested on the wire rack that serves as a midline shelf in the oven chamber. One batch of four flakes was heated to a maximum temperature of 425˚C (810˚F), another batch to 625˚C (1150˚F), and another to 875˚C (1600˚F)[vii]. Vesiculation occurred only in the latter, the batch heated to the highest temperature range.

I will discuss the implications of two aspects of this experiment. The first does not consider chemical composition, but rather looks at variation in the temperature of vesiculation across the four materials in response to rising heat *as expressed during the highest temperature firing run only*. The second implication does involve the measurement of elemental composition, and considers slight variations in the XRF results obtained among the different materials subsequent to all four firing runs.

Heating effects observed at 875˚C/1600˚F. The results of the highest temperature firing run indicate that the minimum temperature of vesiculation was inconsistent among the four nodules (Table 3). The four temperature columns on the right side of the table include observations of the four flakes (one from each material) in the oven chamber at increasing temperatures as the furnace heated from room temperature to a maximum of 875˚C/1600˚F. Note that in this table I am showing how four flakes in the oven together responded to rising heat.

There appears to be a correspondence of heat response with cloudy versus clear obsidian. The two cloudy specimens (GS 7B and 8) appear to have a lower threshold of vesiculation (815˚C/1500˚F) than does either of the clear specimens. One clear specimen (GS 7A) began vesiculation at around 850˚C/1550˚F, and the other (GS 10) did not initiate vesiculation even at 875˚C/1600˚F. These results suggest that there are differences in heat response in obsidians within this geological source. However, as shown in Table 4 (discussed below), there are no significant differences in the trace element profiles of each nodule. All four are reliably "sourced" to Rabbit Mountain/Obsidian Ridge. Presumably the observed variation in vesiculation as a heat response is due to an undetermined factor

Table 2. Trace element values for geological samples.

Sample Location		GS 1	GS 2	GS 3	GS 4	GS 6	GS 7*	GS 8*	GS 10*
Element	XRF sample	6	4	5	3	3	2	4	3
Ti Ppm	Avg	435	436	445	424	450	363	459	449
	SD	11	11	28	10	10	1	46	53
	CV%	3	3	6	2	2	0	10	12
Mn	Avg	614	598	597	590	606	573	600	606
	SD	15	12	19	20	11	3	22	24
	CV%	2	2	3	3	2	1	4	4
$Fe_2O_3^T$ (wt %)	Avg	1.22	1.20	1.19	1.17	1.20	1.12	1.20	1.21
	SD	0.03	0.02	0.04	0.03	0.03	0.01	0.07	0.07
	CV%	2	2	3	3	2	1	6	6
Zn	Avg	91	93	92	85	90	83	84	88
	SD	6	6	4	4	3	6	5	6
	CV%	6	6	5	4	4	8	6	7
Ga	Avg	22	18	21	20	24	21	20	24
	SD	3	10	3	2	5	3	5	1
	CV%	12	59	12	8	21	14	24	2
Rb	Avg	206	203	202	192	200	191	195	201
	SD	6	7	5	2	9	1	4	11
	CV%	3	4	2	1	4	1	2	6
Sr	Avg	4	4	3	3	4	4	4	1
	SD	1	1	2	1	1	1	1	2
	CV%	16	17	58	17	25	20	20	173
Y	Avg	60	59	58	56	59	55	58	59
	SD	2	3	1	2	3	1	2	5
	CV%	4	4	3	3	5	1	4	9
Zr	Avg	167	164	164	158	165	159	162	166
	SD	5	3	4	2	6	1	4	12
	CV%	3	2	2	1	4	1	3	7
Nb	Avg	88	86	87	84	87	83	79	87
	SD	2	3	3	1	6	2	18	4
	CV%	2	3	3	1	6	3	23	5

*Specimen(s) used in the heating experiment discussed later are included in the *n* for this location.

in the chemical composition of the obsidian. One strong candidate is variation in the water content of the glass. In any case, it is clear that in this experiment trace element analysis was not the means for identifying causal variation in the chemical composition of the four nodules. Two important aspects of future Dome Fire Effects Study research are 1) using additional experimentation to substantiate the validity of intrasource variation in heat response, and 2) pursuing potential geochemical/petrological causes of this variation.

Table 3. Response of four materials under experimental heating conditions.

Geological Sample	Material	650˚C (1200˚F)	720˚C (1320˚F)	815˚C (1500˚F)	875˚C (1600˚F)
GS 10	Clear black	no change	specimen glows red	no further change	no further change
GS 7A	Clear black	no change	specimen glows red	no further change	Vesiculation well underway*
GS 7B	Cloudy grey (with speckles)	no change	Specimen glows red	vesiculation well underway	full vesiculation
GS 8	Cloudy grey (with inclusions)	no change	Specimen glows red	vesiculation begins	full vesiculation

* *Vesiculation in this specimen was first observed at 850˚C/1550˚F.*

Trace element measurements of heated samples. Turning to the XRF analysis of all 16 specimens included in this heating experiment, the results of XRF analysis conducted on the experimentally heated obsidian can be used to address the question of whether forest fires might alter x-ray fluorescence measurement of trace elements. Here I describe the results obtained when all sixteen flakes from the four batches (one batch of four flakes unheated, and the three batches each heated to different temperatures) were sent to Richard Hughes for chemical composition analysis. Table 4 shows the trace element values obtained for flakes in the unheated and the three heated batches.

Reading across the values for each element, and comparing among the four temperatures (unheated, 425˚C, 625˚C and 875˚C) for each sample material, there appears to be a trend toward an increase in values--except for GS 10 specimens. An increase is especially apparent for Rb, Ti, Mn, Zn, and $Fe_2O_3^T$, less so for Ga, Y, and Zr, and ambiguous or not at all apparent for the remaining elements, Sr, and Nb.

This apparent trend toward increase in ppm with heating can be illustrated graphically as well, as shown in Figure 8. Sr concentrations are so low in this glass, however, that this element is of little value and is not included in the comparisons below. Total iron also is excluded from this boxplot comparison because it is measured on a very different scale. All values in the figure are in parts per million (ppm).

The line charts show the elemental values obtained for each specimen without heating and at each of the three firing temperatures. The trend toward increase in elemental value with heating is clearly illustrated in the line charts. Also clear in the illustrations is that GS 10 is an exception to this tendency and does not show increasing values at higher temperatures. The three boxplots show the distribution of elemental values for eight of the trace elements measured for the combined 16 heated and unheated specimens. These boxplots illustrate that the high elemental values obtained for certain elements (Ti, Rb, Zn and Y) are expressed as outliers and extreme values only among specimens heated to the highest firing temperature (875˚C/1600˚F). There is one low extreme value, for unheated Nb. This may be an anomaly of measurement rather than a result of heating or, conversely, the element Nb could be especially sensitive to heat--responding with an increase at the lowest heating temperature (425˚C (810˚F).

Table 4. XRF element values for heated samples.

	GS 10				GS 7A				GS 7B				GS 8			
Temp	0˚C	425˚C	625˚C	875˚C	0˚C	425˚C	625˚C	875˚C	0˚C	425˚C	625˚C	875˚C	0˚C	425˚C	625˚C	875˚C
Ti	389	422	406	405	363	397	390	472	362	393	423	502	403	368	408	483
	±14	±13	±13	±14	±14	±14	±14	±19	±14	±14	±14	±15	±13	±13	±14	±15
Mn	589	603	595	591	571	578	568	626	575	576	593	661	571	574	622	662
	±8	±8	±8	±8	±8	±8	±8	±9	±8	±8	±9	±9	±8	±8	±8	±9
$Fe_2O_3^T$	1.14	1.15	1.13	1.14	1.11	1.10	1.08	1.24	1.12	1.11	1.14	1.27	1.12	1.10	1.18	1.31
	±.08	±.08	±.08	±.08	±.08	±.08	±.08	±.08	±.08	±.08	±.08	±.08	±.08	±.08	±.08	±.08
Zn	84	89	90	86	87	80	83	91	78	86	85	116	86	87	93	139
	±5	±5	±5	±5	±5	±6	±5	±6	±5	±5	±6	±6	±5	±5	±6	±7
Ga	24	16	21	20	23	21	19	25	19	21	17	27	16	20	23	27
	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3
Rb	190	202	203	195	192	187	188	199	190	190	189	227	191	185	202	243
	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4
Sr	3	3	3	3	4	3	4	3	3	4	3	3	3	3	0	4
	±3	±3	±3	±3	±3	±4	±3	±4	±5	±3	±5	±4	±5	±4	±4	±3
Y	55	58	62	54	54	55	55	58	55	55	54	62	55	54	57	66
	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3
Zr	153	163	169	155	159	153	158	163	158	156	156	167	161	160	158	173
	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4	±4
Nb	82	83	86	83	84	80	82	83	81	82	80	89	52	80	82	89
	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3	±3
Fe/Mn	20	20	20	20	20	20	19	20	20	20	20	20	20	20	20	20

Values in parts per million (ppm) except total iron (in weight percent) and Fe/Mn ratios; ± = pooled estimate (in ppm and wt. % composition) of x-ray counting uncertainty and regression fitting error at 300 seconds livetime.

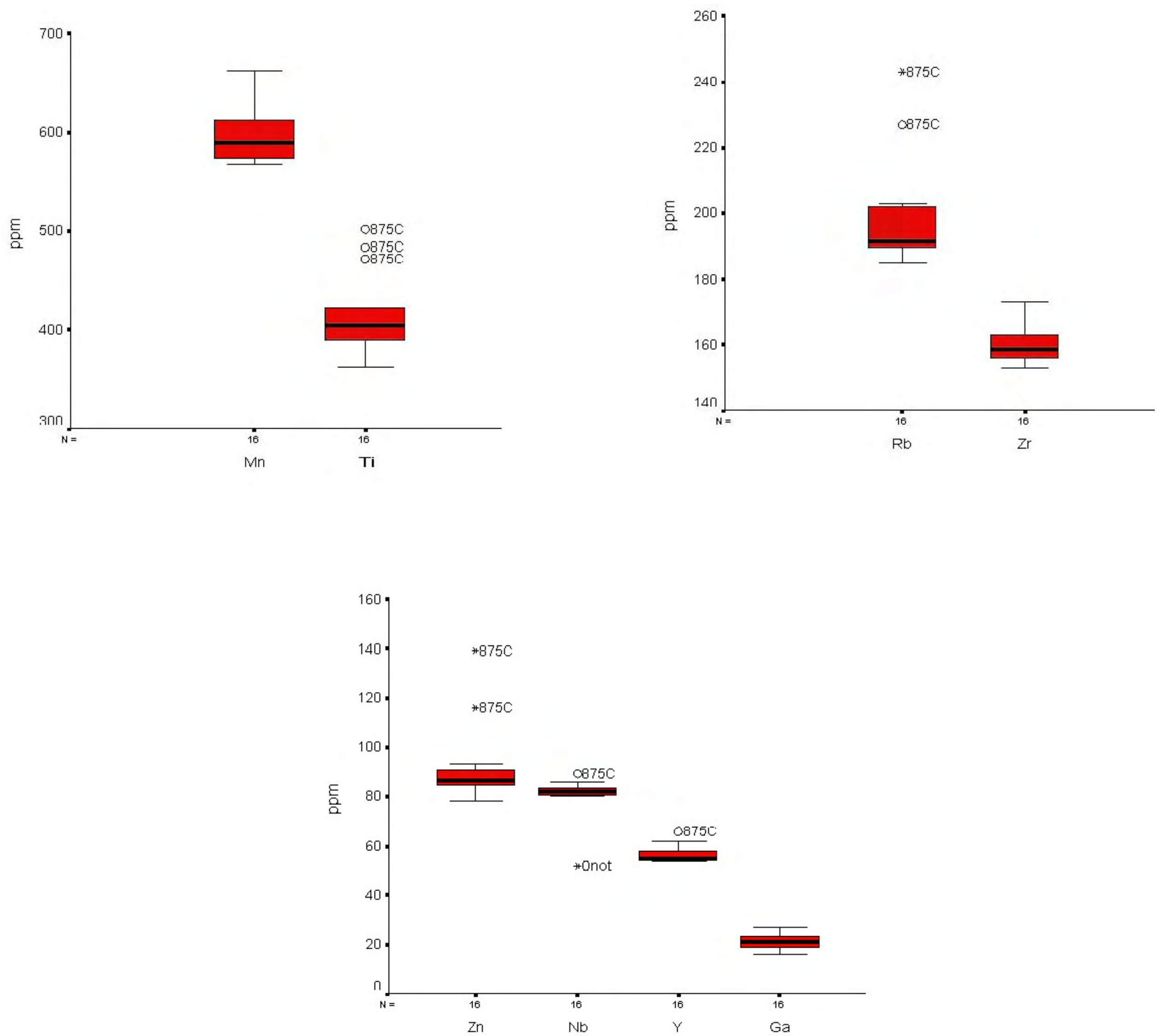


Figure 8. (Caption on next page).

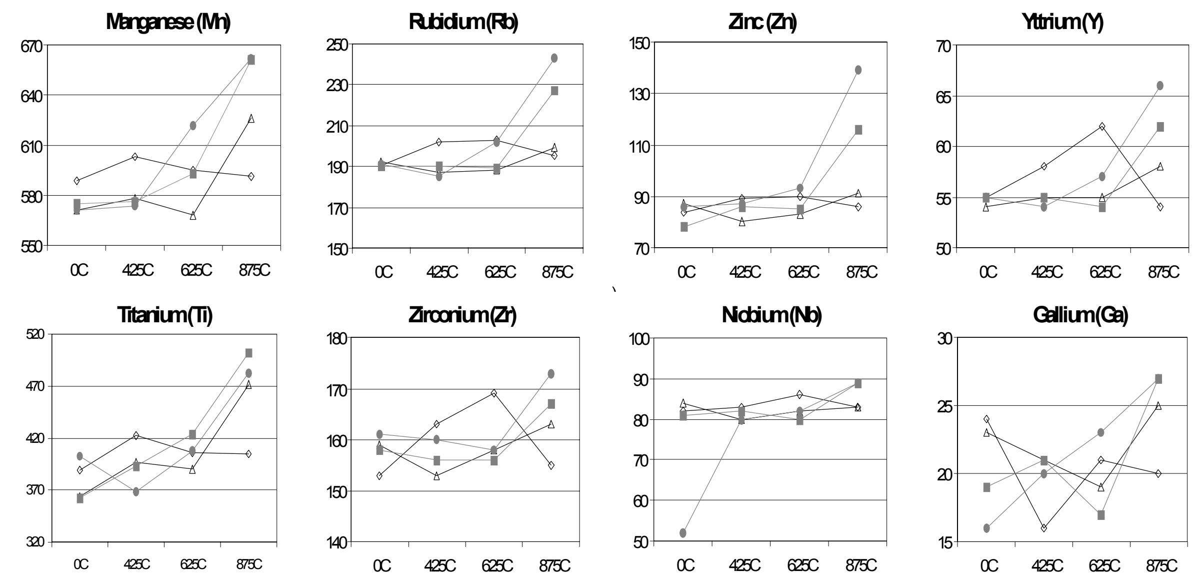


Figure 8. Boxplots and line charts for trace element values in experimental specimens: unheated and heated to 425˚C, 625˚C and 875˚C. Boxplot charts show the interquartile range (which is the difference between the 25^{th} and the 75^{th} percentiles, shown as the length of the box), the median (indicated by the horizontal line within the box), and the span of the values that are within 1.5 interquartile ranges of the edge of the box (shown as the vertical lines called whiskers). Also plotted are outliers (cases with values between 1.5 and 3 box lengths from the edge of the box, indicated by "o"), and extreme values (cases with values greater than 3 box lengths from the edge of the box, indicated by "&"). Because the scales are different among the three plots, the relative lengths of the boxes and whiskers should not be compared among the boxplots.

- To summarize, the results of XRF trace element analysis obtained among the experimentally heated specimens suggest that: there is a directional change in the trace element measurements obtained through XRF analysis among the different firing temperatures,

- where these differences occur they are in the direction of increased elemental value with increasing firing temperatures,

- there are wider distributions of values with increasing firing temperatures,

- the increases in values are more apparent in the cloudy materials than in the clear materials, the largest and most notable increase in elemental values occurs at the highest firing temperature.

The latter three points actually are linked to another phenomenon: only the run at the highest firing temperature resulted in vesiculation, and the greatest increases in elemental values are observed in the three materials that did vesiculate. Stated another way, the specimen that did not vesiculate, GS 10, shows the least difference in elemental values at the highest temperature firing run. Finally, the wider distribution of values is due to the marked increase in values in the vesiculated and/or cloudy specimens without a similar increase in the unvesiculated and/or clear specimens. Hughes (1998) suggests that some increases in elemental values may be related to changes in the surface topography--and therefore the x-ray reflection geometry--of the vesiculated pieces. Further explanation will be needed to fully understand these results, as there are increases in elemental values across the lower temperature ranges as well as at the highest temperature. Although the patterns apparent in these data evoke curiosity and invite further examination, the immediate relevance for the research questions in the current this study is limited--both because the sample sizes are so small, and also because no differences observed in elemental values are great enough to alter how any specimen would be geochemically "sourced".

XRF Measures of Burned Obsidian at the Capulin Quarry Site

The final chemical composition analysis reported in this study is an XRF analysis conducted on 35 specimens collected from burned and unburned parts of Capulin Quarry, the large lithic procurement site where the most extreme fire effects were observed following the Dome Fire. One goal of this XRF analysis was to examine whether there were any differences in trace element values among these burned specimens compared to the unburned geological samples. Another goal was to confirm, rather than assume, the geochemical source of the burned quarry artifacts to Rabbit Mountain/Obsidian Ridge, especially with an eye toward subsequent interpretation of obsidian hydration data.

Trace element values for the 35 specimens collected from Capulin Quarry are listed in Table 5. The table is split into two parts because of its large size. The first part of the table includes specimens from "unburned" portions of the site as well as "burn areas" (Table 5a), while the second part includes specimens from "near clusters" and "in clusters" (Table 5b).

The XRF results show that all specimens collected at Capulin Quarry have the same trace element composition as Rabbit Mountain/Obsidian Ridge. Therefore, the apparent source of these burned and unburned specimens as Rabbit Mountain/Obsidian Ridge is supported by the x-ray fluorescence analysis. Hughes (1998) observed that "there appears to be no significant difference in trace element and selected minor element composition--specifically, Rb, Sr, Y, Zr, Nb, Ti, Mn, $Fe_2O_3^T$ concentration, and Fe/Mn ratios--between the majority of artifacts subjected to various degrees of fire-alteration and (apparently) unheated source samples". As observed in the data collected for the experimentally heated samples, burning within the forest fire did not alter XRF trace element measurements so as to affect the "sourcing" of the materials. This is true among burned and unburned specimens, despite variation in the severity of heat effects observed in the immediate area from which the specimens were recovered.

In addition to asking the specific question of whether a forest fire might have the potential to change how XRF measurements represent the geochemical composition of the glass, this analysis also was, in part, an exploratory venture to record any variation in elemental values between the geological samples and burned specimens. While the results clearly indicate that burning in the Dome Fire did not alter how a specimen would be "sourced", a few burned specimens do have elevated measurements for certain elements. These individuals are highlighted in Table 5b with ***bold-italic*** text for the specimen number and for the elemental value that is especially high. Four specimens have elevated values for Ti, while a fifth has high values of Rb and $Fe_2O_3^T$.

These five specimens have a good deal in common. All five burned within vesiculation clusters. In fact, all but one are from a single intensely-burned cluster (Cluster 2), while the other (1691-10) is from Cluster 3. Only one of these XRF readings is from a location on a specimen that is vesiculated (1691-07[a]); but this and all the other measurements that produced a high Ti value were taken on artifact surfaces that have either a coating of tiny soil particles or a matte/shiny residue. In other words, all the XRF measures with elevated Ti are where the surfaces are "dirty" to some degree or another. This is not true for the specimen (1691-26A) with the high values for Rb and $Fe_2O_3^T$. This reading was taken on a surface that was freshly fire-fractured, crazed, and free of residue (see Figure 5 for a view of the surface of the piece [1691-26B] that is the other half of this fire fracture). This single case does not provide enough information to speculate as to possible causes for the high Rb and total iron readings. However, for the other four cases, it seems likely that organic residue and/or soil-matrix material adhering to surfaces of burned specimens have the potential to result in high XRF elemental values for Ti. If nothing else, this observation supports the standard practice in XRF analyses of creating newly fractured surfaces or rinsing surfaces with distilled water--a practice that intentionally was not followed in this case so as to preserve the altered condition of burned surfaces.

Table 5a. Elemental values on burned and unburned specimens from Capulin quarry: Unburned specimens and specimens collected from throughout the burn area.

Spec #	**Multiple readings**	**Ti**	**Mn**	**$Fe_2O_3^T$**	**Zn**	**Ga**	**Rb**	**Sr**	**Y**	**Zr**	**Nb**	**Fe/Mn**	**Area**
1691-05		429 ±14	582 ±8	1.16 ±.08	84 ±5	21 ±3	197 ±4	0 ±5	57 ±3	165 ±4	86 ±3	nm	unburned
1691-42		429 ±14	596 ±8	1.17 ±.08	89 ±5	23 ±3	195 ±4	5 ±3	57 ±3	162 ±4	82 ±3	20	unburned
1691-45		574 ±16	594 ±9	1.25 ±.08	84 ±6	15 ±3	190 ±4	0 ±3	53 ±3	154 ±4	82 ±3	22	unburned
1691-47		455 ±15	638 ±9	1.25 ±.08	92 ±6	18 ±3	206 ±4	0 ±4	59 ±3	169 ±4	88 ±3	19	unburned
1691-01	a	449 ±14	564 ±8	1.14 ±.08	87 ±5	20 ±3	196 ±4	4 ±3	56 ±3	166 ±4	87 ±3	nm	burn area
1691-01	b	480 ±14	613 ±8	1.21 ±.08	94 ±5	22 ±3	202 ±4	0 ±3	60 ±3	169 ±4	86 ±3	nm	
1691-01	c	438 ±15	612 ±9	1.22 ±.08	89 ±6	21 ±3	196 ±4	3 ±6	56 ±3	159 ±4	80 ±3	nm	
1691-02	a	429 ±14	582 ±8	1.17 ±.08	96 ±5	16 ±3	189 ±4	3 ±12	57 ±3	159 ±4	83 ±3	nm	burn area
1691-02	b	500 ±14	611 ±8	1.22 ±.08	134 ±6	19 ±3	203 ±4	0 ±5	59 ±3	166 ±4	86 ±3	nm	
1691-03		430 ±14	603 ±8	1.20 ±.08	89 ±5	16 ±3	193 ±4	3 ±5	58 ±3	159 ±4	81 ±3	nm	burn area
1691-4A	a	467 ±14	607 ±8	1.21 ±.08	88 ±5	20 ±3	196 ±4	3 ±3	55 ±3	160 ±4	80 ±3	nm	burn area
1691-4A	b	457 ±14	615 ±8	1.23 ±.08	107 ±5	18 ±3	213 ±4	3 ±7	62 ±3	174 ±4	92 ±3	nm	
1691-4B	a	490 ±14	597 ±8	1.22 ±.08	92 ±5	23 ±3	199 ±4	3 ±3	59 ±3	162 ±4	87 ±3	nm	burn area
1691-4B	b	591 ±14	620 ±8	1.21 ±.08	92 ±5	19 ±3	193 ±4	3 ±5	59 ±3	162 ±4	83 ±3	nm	
1691-33		398 ±15	597 ±9	1.16 ±.08	81 ±6	20 ±3	190 ±4	0 ±4	55 ±3	156 ±4	78 ±3	20	burn area
1691-35		448 14	596 ±8	1.18 ±.08	85 ±6	17 ±3	197 ±4	4 ±3	56 ±3	158 ±4	80 ±3	20	burn area
1691-36		408 ±14	567 ±8	1.14 ±.08	79 ±5	25 ±3	191 ±4	4 ±3	55 ±3	156 ±4	81 ±3	20	burn area
1691-39		487 ±16	632 ±9	1.23 ±.08	90 ±6	21 ±3	198 ±4	4 ±3	57 ±3	157 ±4	85 ±3	20	burn area
1691-41		401 ±15	623 ±9	1.17 ±.08	91 ±6	16 ±3	191 ±4	3 ±3	56 ±3	162 ±4	79 ±3	20	Burn area

Values in parts per million (ppm) except total iron (in weight percent) and Fe/Mn ratios; ! = pooled estimate (in ppm and wt. % composition) of x-ray counting uncertainty and regression fitting error at 300 seconds livetime.

Table 5b. Elemental values on burned and unburned specimens from Capulin Quarry: specimens collected from in clusters and near clusters.

Spec #	Multiple Readings	Ti	Mn	$Fe_2O_3^T$	Zn	Ga	Rb	Sr	Y	Zr	Nb	Fe/Mn	Area
1691-06		557 ±15	584 ±8	1.20 ±.08	100 ±5	17 ±3	199 ±4	4 ±3	58 ±3	166 ±4	85 ±3	nm	in cluster
1691-07	a	***955*** ±17	*740* ±9	1.58 ±.08	133 ±6	32 ±3	230 ±4	19 ±3	63 ±3	194 ±4	86 ±3	nm	in cluster
1691-07	b	***880*** ±16	590 ±8	1.39 ±.08	84 ±6	2 ±3	199 ±4	5 ±3	61 ±3	163 ±4	84 ±3	nm	
1691-08		***672*** ±16	569 ±9	1.23 ±.08	85 ±6	20 ±3	193 ±4	6 ±3	55 ±3	158 ±4	83 ±3	nm	in cluster
1691-09	a	435 ±14	604 ±8	1.19 ±.08	91 ±5	20 ±3	201 ±4	0 ±5	58 ±3	166 ±4	86 ±3	nm	in cluster
1691-09	b	607 ±15	599 ±8	1.23 ±.08	90 ±5	20 ±3	187 ±4	4 ±3	58 ±3	160 ±4	83 ±3	nm	
1691-10		***892*** ±16	667 ±8	1.26 ±.08	101 ±5	25 ±3	218 ±4	12 ±3	62 ±3	172 ±4	87 ±3	19	in cluster
1691-11A	a	598 ±15	669 ±9	1.27 ±.08	103 ±6	27 ±3	220 ±4	5 ±3	60 ±3	172 ±4	90 ±3	nm	in cluster
1691-11A	b	518 ±16	654 ±9	1.27 ±.08	94 ±6	22 ±3	207 ±4	3 ±6	57 ±3	162 ±4	86 ±3	nm	
1691-11A	c	579 ±15	622 ±8	1.23 ±.08	95 ±5	23 ±3	199 ±4	6 ±3	59 ±3	163 ±4	85 ±3	nm	
1691-11B	a	488 ±14	608 ±8	1.24 ±.08	95 ±5	20 ±3	199 ±4	3 ±7	58 ±3	163 ±4	86 ±3	nm	in cluster
1691-11B	b	453 ±14	595 ±8	1.20 ±.08	88 ±6	20 ±3	196 ±4	0 ±5	57 ±3	161 ±4	86 ±3	nm	
1691-12A		520 ±14	578 ±8	1.21 ±.08	90 ±5	19 ±3	199 ±4	4 ±3	58 ±3	163 ±4	86 ±3	nm	in cluster
1691-14B		532 ±14	558 ±8	1.15 ±.08	87 ±5	19 ±3	189 ±4	4 ±3	54 ±3	151 ±4	80 ±3	21	near cluster
1691-15E		454 ±14	603 ±9	1.21 ±.08	87 ±6	18 ±3	199 ±4	3 ±4	57 ±3	164 ±4	86 ±3	20	near cluster
1691-18		402 ±14	593 ±8	1.14 ±.08	83 ±6	22 ±3	192 ±4	3 ±4	56 ±3	161 ±4	83 ±3	20	near cluster
1691-21		371 ±14	560 ±9	1.08 ±.08	81 ±5	17 ±3	176 ±4	4 ±3	49 ±3	149 ±4	77 ±3	20	near cluster

Spec #	Multiple Readings	Ti	Mn	$Fe_2O_3^T$	Zn	Ga	Rb	Sr	Y	Zr	Nb	Fe/Mn	Area
1691-22		437 ±14	605 ±8	1.12 ±.08	92 ±6	25 ±3	199 ±4	3 ±3	61 ±3	166 ±4	83 ±3	19	near cluster
1691-23		443 ±14	592 ±8	1.15 ±.08	83 ±6	19 ±3	191 ±4	3 ±3	54 ±3	158 ±4	81 ±3	20	near cluster
1691-25A		435 ±14	593 ±8	1.16 ±.08	94 ±5	23 ±3	199 ±4	4 ±3	55 ±3	161 ±4	82 ±3	19	near cluster
1691-25B		397 ±14	576 ±8	1.13 ±.08	80 ±6	17 ±3	190 ±4	3 ±4	56 ±3	153 ±4	80 ±3	20	near cluster
1691-26A		546 ±16	685 ±9	***1.32*** ±.08	110 ±6	27 ±3	***231*** ±4	4 ±3	65 ±3	185 ±4	96 ±3	19	in cluster
1691-26B		434 ±14	591 ±8	1.13 ±.08	83 ±6	20 ±3	190 ±4	4 ±3	54 ±3	158 ±4	77 ±3	20	in cluster
1691-27		***982*** ±19	557 ±9	1.27 ±.08	90 ±6	17 ±3	186 ±4	5 ±3	52 ±3	156 ±4	80 ±3	24	in cluster
1691-28		468 ±14	591 ±8	1.18 ±.08	91 ±5	18 ±3	202 ±4	5 ±3	58 ±3	165 ±4	87 ±3	20	in cluster
1691-31		435 ±13	590 ±8	1.13 ±.08	92 ±5	21 ±3	197 ±4	3 ±3	58 ±3	159 ±4	83 ±3	20	in cluster

Values in parts per million (ppm) except total iron (in weight percent) and Fe/Mn ratios; ! = pooled estimate (in ppm and wt. % composition) of x-ray counting uncertainty and regression fitting error at 300 seconds livetime.

Summary of Chemical Composition Analyses

The results for the XRF trace element composition analyses conducted on 65 burned and unburned specimens offers a significant increase in the XRF database for Cerro Toledo Rhyolite obsidians. These results support trace element homogeneity of obsidians from the Rabbit Mountain/Obsidian Ridge deposits, and reject the possibility of broad significant alteration of trace element geochemistry of these obsidians when exposed to low, moderate, or even high intensity burning in this forest fire. In these forest fire-burned samples, some unusual trace element measurements were found (especially those for the element Ti), but these results might be due to accretionary materials adhering to analyzed surfaces. In terms of geochemical "sourcing", there is no evidence in this study for significant changes to volcanic glass trace element geochemistry caused by fire exposure. In the experimentally heated samples, directional trends in XRF measures of element values were noted for Mn, Ti, Rb, Zn, Nb, Y and Fe among certain specimens. The trend is toward increasing ppm (or weight percent composition), and is expressed in the three materials that vesiculated at temperatures >800˚C (GS 7A, 7B, & 8) but not in the material that did not vesiculate (GS 10). Due to the small sample size, these results can only be taken as suggestive, supporting the use of XRF analysis and other measures of obsidian geochemistry applied to future heating experiments conducted under better controlled conditions. Perhaps the most important outcome of the experimental heating study is to identify variation in vesiculation (as heat response) in four obsidian samples that all have similar trace element composition. This suggests that another factor or combination of factors not measured by trace element analyses--such as minor or major element composition of the glass, structural characteristics of this material (e.g., inclusions and vesicularity of the unheated glass), or the volatile content in the obsidian (e.g., water content)--may be responsible for promoting vesiculation in obsidian burned in forest fires.

Obsidian Hydration Analysis

Measuring the effect of the Dome Fire on hydration bands on artifacts at Capulin Quarry has two purposes. The first is to evaluate the impact of the forest fire at a site where the most extreme kind of fire effect--vesiculation--is observed in abundance. Assuming that this extreme response is evidence of high heat, it makes sense that this site would experience substantial impact to hydration bands, and also that the greatest proportion of hydration band alteration or loss would occur on artifacts in close spatial association with vesiculated materials. These assumptions are evaluated at the scale of assemblage by comparing OH analysis results among artifacts distributed across the site in areas with varying degrees of burning intensities and differing amounts of obsidian fire effects. Early in the assemblage-scale OH analysis there were indications that some artifacts did not conform to the intuitive expectation that the presence of vesiculation meant the absence of hydration bands. The second purpose of this OH analysis, therefore, is to examine peculiarities in the relationship between artifact vesiculation and hydration band alteration that occur at the scale of specimen.

Hydration band analyses were undertaken by Tom Origer at the Sonoma State University Obsidian Hydration Laboratory, using techniques outlined in the following condensed version of his description. Thin sections were reduced by manual grinding with a slurry of #500 silicon carbon abrasive to thicknesses determined by the "touch" technique and "transparency" test, then mounted with coverslip using Lakeside Cement. Extant hydration bands were measured with a strainfree 60 power objective and Bausch and Lomb 12.5 power filar micrometer eyepiece on a Nikon petrographic microscope. Six measurements were taken at several locations along the edge of each thin section, and these measures as well as the calculated means were provided as data. The hydration measurements produced have a range of plus or minus 0.2 microns due to normal limitation of the equipment. Origer recorded observations regarding the quality (condition) of the hydration bands, noting particularly the external edges where fire effects would be. Also, Origer videotaped several thin sections and photographed examples of especially interesting features observed in association with fire effects including sheen, crazing, and vesiculation. The photographic slides and the three videotapes are an invaluable resource--both for developing an understanding of microscopic heat effects and as a communication tool.

The selection and examination of specimens was an iterative process between Origer, Hughes, and myself, with samples processed in several batches.[viii] Specimens were selected to represent a full range of the fire effects observed at Capulin Quarry, as well as differences in raw material appearance and texture, and differences in the reduction aspects of the artifacts (e.g., to include cores and flakes--and less identifiable reduction items--representative of the variety in reduction apparent in the quarry assemblage). X-ray fluorescence analysis was conducted on most of the specimens included in the hydration analysis. The table below that lists OH results by specimen also indicates whether XRF measurements were taken.

In summary, examination of hydration surfaces was conducted for 58 obsidian specimens from Capulin Quarry. These included both artifacts (n=46) and non-artifacts (n=11), with the majority of non-artifacts being pieces with either fresh or older fire fracture surfaces. In numerous cases, multiple cuts were made per specimen, often to provide information on the most altered as well as the least altered portions of the item. This produced more than one hydration band measurement per item. Multiple outcomes also were obtained when differing hydration bands could be detected within a single thin section. Thus the number of OH observations (n = 91) well exceeds the number of items examined. The analyses presented here include only artifacts (i.e., no non-artifacts) collected from Capulin Quarry, and provide a summary of these data to address three questions:

1) do hydration bands appear to have been altered by the fire within the burned areas of the site?;

2) are there differences in apparent alteration depending on the degree of burning evident where the artifacts were collected?;

3) does alteration of hydration bands necessarily co-occur with vesiculation of obsidian artifacts?

Obsidian Hydration Analysis of the Burned Assemblage

Table 6 lists hydration observations for 41 artifacts collected at a variety of locations within Capulin Quarry. Only eight specimens (20 percent) are from unburned areas, while 33 specimens (80 percent) are from various burned areas of the site. The categories used to describe differences in burning severity are listed near the beginning of this article. To re-state, locations within the burned areas of the site are grouped by proximity to the vesiculation clusters. They are either "in cluster" (within the maximum 1 m diameter central core of vesiculation clusters), "near cluster" (within 2 m of the center of a cluster), or "burn area" which indicates that the specimens were collected from throughout the burned portions of the site, without proximity to clusters.

Comparing between burned and unburned areas of the site (Figure 9), specimens with hydration bands are present in a much higher relative frequency in the unburned areas (seven specimens; 87.5 percent) than in the burned areas (nine specimens; 27.3 percent). Further, comparing among the areas with different degrees of burning (Figure 10), the distribution of specimens without measurable bands present follows the pattern expected: the relative frequency of specimens with bands is highest in the unburned areas of the site, decreases in the general burned areas and near clusters, and is lowest within clusters.

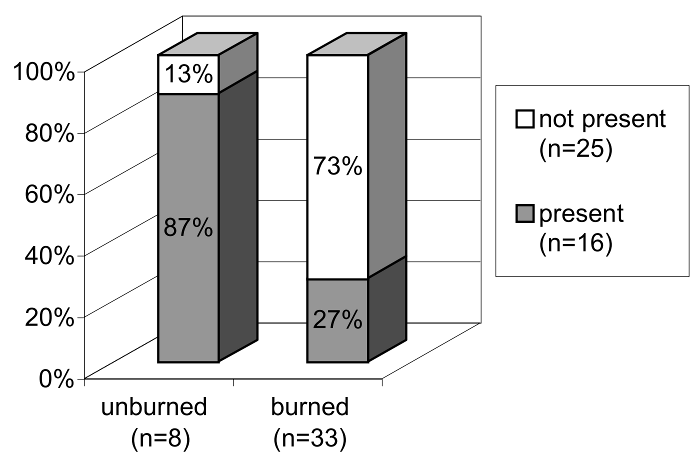


Figure 9. Proportion of intact/measurable hydration bands in unburned and burned areas at Capulin Quarry.

Table 6. Obsidian hydration analysis of artifacts at Capulin Quarry.

XRF[a]	**Spec# 1691-**	**03-1691 Location**	**Burn exposure**	**Visual Effects**	**Origer Notes[b]**	**Band Cond[c]**	**Measurements**	**Item Qty**	**#Cuts/ Bands[e]**
✓	01	burn area	burn area	sheen	wea	nvb	none	1	1
✓	02	burn area	burn area	craz, vesic	none	ok	2.8, 3.4, 4.8, 5.8 6.0, 6.3, 6.4	1	7
✓	03	burn area	burn area	craz, vesic	wea	dh	none	1	2
✓	04	by Clust 1	burn area	sheen	wea	nvb, ok	none, 1.1	1	2
✓	05	in road	unburned		none	ok	2.5	1	1
✓	06	in Clust 2	in cluster	craz, vesic	none	nvb	none	1	1
✓	07	in Clust 2	in cluster	craz, vesic	wea	dh, nvb	none	1	2
✓	08	in Clust 2	in cluster	craz	wea	dh	none	1	1
✓	10	in Clust 3	in cluster	craz, vesic, sheen	wea	dh	none	1	1
✓	14A	in Clust 7	in cluster	craz	wea	dh	none	1	2
✓	14B	in Clust 7	in cluster		wea	dh	none	1	1
	17	Unit 1	near cluster		2 bands	dh	3.4	1	2
✓	18	Unit 1	near cluster		none	nvb	none	1	1
	19	Unit 1	near cluster	sheen	wea	nvb	none	1	1
	20	Unit 1	near cluster		2 bands	ok	4.8, 5.7	1	2
✓	22	Unit 1	near cluster		wea	nvb	none	1	1
✓	27	in Clust 2	in cluster	craz, vesic	none	dh	none	1	1
✓	28	in Clust 3	in cluster	craz, vesic	wea	dh	none	1	2
	29	in Clust 3	in cluster	craz, sheen, fract	wea	dh	none	1	2
✓	31	Collect 1	burn area		none	dh	none	1	1
	32	Collect 1	burn area		none	ok	5.1	1	1
✓	33	Collect 1	burn area		none	dh, ok	none, 5.6	1	2
	34	Unit 1	near cluster		wea	dh	none	1	1
✓	35	Collect 1	burn area		none	nvb	none	1	1

✓	36	Collect 1	burn area	craz, sheen	none	nvb	none	1	1
	37	Collect 1	burn area		none	dh	10.3	1	1
	38	Collect 1	burn area		none	ok	1.2	1	1
✓	39	Collect 1	burn area		none	nvb	none	1	1
	40	Collect 1	burn area		wea	ok	5.7	1	1
✓	41	Collect 1	burn area		wea	dh	none	1	1
✓	42	Collect 2	unburned		none	ok	1.5	1	1
	43	Collect 2	unburned		wea	ok	3.3	1	1
	44	Collect 2	unburned		wea	ok	5.1	1	1
✓	45	Collect 2	unburned		wea	dh, ok	none, 1.6	1	2
	46	Collect 2	unburned		none	ok	3.8	1	1
✓	47	Collect 2	unburned		none	nvb, ok	none, 5.3, 5.3, 5.9	1	4
	48	Collect 2	unburned		none	nvb	none	1	1
	49	Burn area	burn area		2 bands	dh, ok	none, 2.9	1	2
	50	Burn area	burn area	craz, vesic	wea	dh	none	1	4
	106	Burn area	burn area		none	ok	1.7	1	1
	107	Burn area	burn area	sheen, fract	none	dh	4.3	1	1

[a]Check mark indicates specimens were included in x-ray fluorescence analysis. 41 64
Totals:

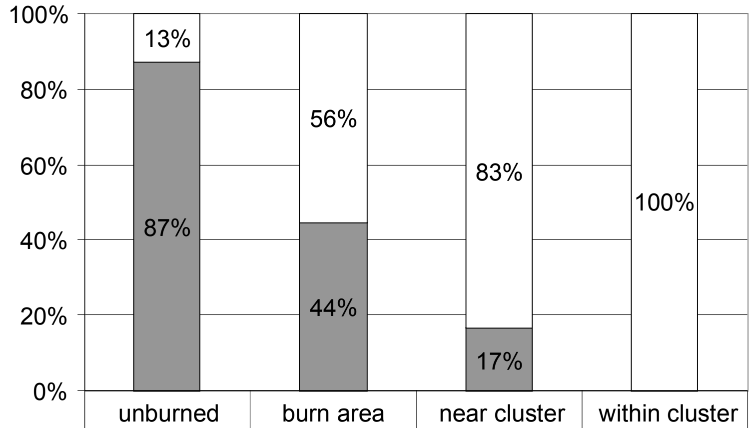
[b]Observations made during OH analysis: wea = weathering of surface was noted; 2 bands = two measurable bands were observed within one cut.

[c]Band condition as assessed during hydration band measurement: ok = normal measurable hydration band;

dh = diffuse hydration (not measurable); nvb = no visible band.

[d]Mean values of six measurements made for each band, in microns; approximate estimates of diffuse bands are indicated by "□".

[e]Number of thin section cuts examined per specimen, including total number of bands observed where multiple bands were present for a single cut.



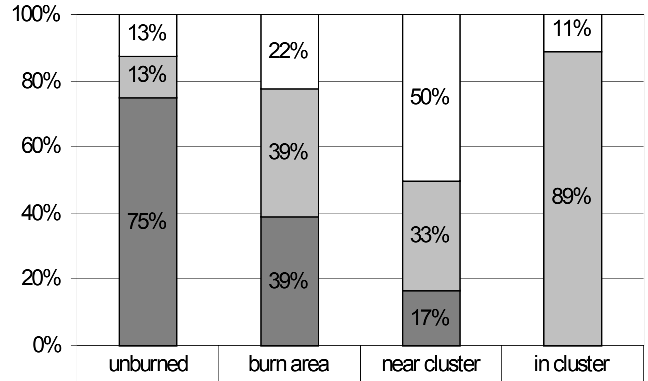
	unburned	burn area	near cluster	within cluster
☐ band not present	1	10	5	9
■ band present	7	8	1	0

Figure 10. Distribution of intact/measurable hydration bands by degree of burning.

To summarize Figure 10, there does appear to be an inverse relationship between the proportion of bands present and the degree of burning the artifacts experienced. This figure shows the relative frequencies of specimens with bands present versus bands not present in each of the four burning categories. In the unburned areas, the relative frequency of artifacts with bands present is highest: seven of eight artifacts (87.5 percent) have measurable bands. In contrast, no artifacts exhibit measurable hydration bands within the "in cluster" areas where evidence of burning is most severe. In between, artifacts with bands present represent 44 percent and 17 percent in the general "burn area" and in the "near cluster" areas, respectively. Overall, these results show a trend toward decreasing presence of measurable hydration bands with increasing degree of burning.

This discussion considers only whether measurable bands are present, but cannot conclude with certainty that absent bands are the result of fire-alteration. An additional line of evidence, the distribution of diffuse hydration, can be used to support that interpretation. Trembour (1990) and other researchers (e.g., Deal, this volume; Hatch et al. 1990; Origer, personal communication) have recognized the occurrence of diffuse hydration and the potential for its use in identifying heat exposure. Figure 11 compares relative frequency within each burn category of three groups of artifacts: 1) those with no visible hydration present, 2) those with at least one surface with diffuse hydration (ignoring the condition of other bands on these specimens), and 3) those with intact, measurable hydration bands present and without any incidence of diffuse hydration. The results suggest that the presence of diffuse hydration bands correlates with degree of burning. The proportion of specimens with diffuse hydration increases with degree of burning, while the proportion of specimens with only non-diffuse bands present decreases.

The pattern evident in Figure 11 agrees with the results reported by Trembour (1990) in his analysis of experimental heating effects on hydrated obsidian. Trembour describes a progression of heat response in experimental specimens where the hydration rind under polarized light changed in color, then showed "increasing broadening and blurring of the interface 'line'", followed by "virtual obliteration of all traces of the rind and its inner boundary" (Trembour 1990:175). The results shown in Figure 11 do indicate higher relative frequencies of diffuse hydration occurring in artifacts associated with areas of greater severity of burning at Capulin Quarry.



	unburned	burn area	near cluster	in cluster
no visible hydration	1	4	3	1
diffuse hydration present	1	7	2	8
hydration band(s) present but none diffuse	6	7	1	0

Figure 11. Distribution of diffuse hydration bands by degree of burning.

The information on diffuse hydration presented in Figure 11 is complex and difficult to interpret, but does invite speculation. Obviously, the proportion of artifacts with diffuse hydration increases with degree of burning, ballooning to 89 percent of artifacts from the "in cluster" contexts. A more complicated pattern can be seen in the relationship between artifacts with diffuse hydration present and artifacts with no visible hydration. As shown in this figure, the proportion of specimens with no visible hydration decreases substantially among the "in cluster" artifacts; making it appear that artifacts with diffuse hydration not only replace artifacts with hydration bands present, they also seem to replace some proportion of artifacts with no visible hydration. This may be an oddity of this assemblage--a good possibility given the small sample size in the analysis. However, one interpretation is that diffuse hydration can result from a process at least partially independent of the hydration band that occurred on that surface prior to heat exposure. This would run counter to the perception that diffuse hydration occurs solely as the result of expansion of extant hydration into the body of the glass. It might be that diffuse hydration could also result from a process of water diffusion that is responding directly to heat, or that might even involve introduction of "new" water into the glass surface. One way to evaluate this alternative is to directly measure the concentration of water with depth below the glass surface. Anovitz et al. (1999) discuss the measurement of depth versus concentration profiles of water in glass using secondary ion mass spectrometry (SIMS). Application of SIMS analysis to burned or experimentally-heated obsidian artifacts might be a productive exercise, with the potential to provide information useful not only for interpreting heat-alteration of hydrated artifacts, but also for increasing knowledge about glass hydration processes. If so, artifacts with diffuse hydration bands in burned (and unburned) obsidian assemblages should not be ignored nor should their existence be treated only as a spoiler for obsidian hydration dating. Reporting the occurrence of diffuse hydration in standard OH analyses, regardless of whether fire effects are an explicit subject of the study, would assist in determining how common and how widespread is the phenomenon.

To summarize, the results of the obsidian hydration analyses of artifacts from the burned quarry support the interpretation that the Dome Fire altered hydration bands on artifacts burned during the fire. Not only is the proportion of artifacts with measurable bands present much lower in the burned areas compared to unburned areas, the results also indicate that the proportion of bands present decreases with each increase in the severity of burning at this site. The occurrence of diffuse hydration in the assemblage appears to follow a similar pattern, with a high frequency of artifacts with diffuse hydration in the most severely burned parts of the site and a low frequency of diffuse hydration on artifacts from unburned parts of the site. Use of diffuse hydration as an indicator of heat exposure seems to work well in this case. However, the information about diffuse hydration obtained here is difficult to interpret and would be best used to suggest future study rather than to draw conclusions.

Overall, it is clear that the Dome Fire created conditions sufficient to alter the obsidian hydration information contained in artifacts at Capulin Quarry: over 85 percent of unburned artifacts have intact measurable hydration bands, compared to less than 30 percent of artifacts in the burned areas. This study joins the body of archaeological fire effects literature showing that forest fires can and do alter obsidian hydration bands, and therefore can have a measurable, redundant, and *potentially* significant effect on the chronometric potential of obsidian hydration data in burned assemblages. However, the implications of these results for managing and interpreting the archaeological record are not necessarily so clear. Although the information in this and other similar studies will be useful to inform decisions about whether these fire effects constitute a "negative impact" or an "adverse effect", such management decisions are independent of these findings.

Obsidian Hydration Analysis of Individual Burned Specimens

In the obsidian analysis above the emphasis was on assessing the extent of fire alteration of hydration bands in the entire assemblage, especially as expressed depending on variation in the severity of burning across the site. In this section I examine how alteration of hydration bands is expressed depending on macroscopic fire effects on specific obsidian artifacts. Do specimens that are vesiculated still retain measurable hydration bands? Are hydration bands retained in specimens with crazing? First, I review briefly the data presented in the assemblage analysis to assess relationships among vesiculation, crazing, and hydration bands. Second, I discuss the results of an "intensive" hydration analysis of several partially vesiculated artifacts that Origer conducted to augment the assemblage analysis.

As shown in Table 6, there are eight artifacts with vesiculation. All but one of these specimens either have no visible hydration band or have only diffuse hydration. Therefore, in this sample almost no artifacts with vesiculation have intact hydration bands. It appears that the heat exposure that resulted in vesiculation reached or surpassed the heat exposure required to alter or obliterate hydration. The one exception is specimen 1691-02. This particular artifact has a number of unusual obsidian hydration characteristics, and will be discussed in detail below. As for specimens with crazing, the results are similar to those with vesiculation. Except for specimen 1691-02, all artifacts with crazing have no visible hydration or only diffuse hydration. Note that eight of the twelve artifacts with crazing also have vesiculation--so the condition of hydration bands would be expected to be poor. However, the results are the same for the four artifacts with crazing but without vesiculation: none have measurable hydration. It is a reasonable inference that, as with vesiculation, artifacts with crazing experienced heat exposure capable of altering hydration bands. For this sample, the presence of either crazing or vesiculation is sufficient evidence to anticipate a lack of measurable hydration.

The one specimen that differs from this generalization is 1691-02. This artifact has vesiculation, crazing, incipient bubbling, and some deep cracking yet still has intact measurable hydration bands on all the surfaces examined. Further, the hydration band measurements obtained are quite complicated. As shown in Table 6, all of the bands on this artifact are intact and distinct, with band widths ranging from 2.8 to 6.4 microns (including several intervals represented along the way). These unexpected results were in part responsible for the specimen analysis I will discuss now. Because the results obtained for specimen 1691-02 are so complicated and challenging to explain, a full description of that artifact is saved until the end of the following section.

Intensive obsidian hydration analysis. After considering the results obtained in the overall assemblage analysis and especially for 1691-02, I returned to the site in February 1999 to find and collect additional examples of partially vesiculated flakes. It was important to obtain specimens with identifiable artifact form that had well-developed vesiculation in combination with intact or nearly-unaltered portions of the glass. Four new artifacts (1691-52 through 55) were judgmentally collected, and these were submitted to Origer for analysis along with another good example of partial vesiculation on a flake (1691-51) that had been collected in July 1996.

Figure 12. Five partially vesiculated flakes: specimens 1691-51, 52, 53, 54, and 55.

All five of the flakes (Figure 12) have moderate vesiculation (enough to expand or swell part of the body of the flake), and all but one have clear crazing. Multiple cuts were made on each artifact in order to examine the parts of each flake that had greater and lesser fire alteration visible (except for 1691-51 where a single cut was made to crosscut both vesiculated and unvesiculated parts). Origer's examination of these five flakes was especially careful and provided more information about band condition and the nature of diffuse hydration than is usual in OH analysis. As a result, the observations collected for each specimen are especially detailed and, consequently, more complicated. Summary results of OH analysis of the five partially vesiculated flakes are presented in Table 7. Discussion of additional details follows below.

Three outcomes of this analysis address the questions posed about potential alteration of obsidian hydration bands on artifacts with crazing and/or partial vesiculation. First, all five flakes have surfaces without measurable hydration. Second, all five flakes show diffuse hydration on at least one location. Finally, two flakes (1691-51 and 52) have no measurable hydration bands at any location, while three flakes (1691-53, 54, and 55) have *both* measurable and non-measurable hydration.

The first and greatest implication of these results is that heat exposure during the Dome Fire is shown to have caused alteration of hydration bands in all five flakes, but that partial vesiculation does not always indicate that alteration of hydration is complete across the whole specimen. Somehow, heat exposure that can cause vesiculation on one part of the artifact does not necessarily affect the entire specimen equally or evenly. This is surprising, especially after watching how vesiculation occurs during lab experiments: in the bench furnace, specimens being heated first glowed red for some time before vesiculation occurred. Intuitively, it is difficult to imagine how hydration bands could remain on a specimen that had reached such a high temperature. One possibility is that the three flakes that have intact hydration were partially buried, or were exposed to an intense heat source from one direction only. In any case, the implication is that during a fire an artifact can lose all hydration information in one portion while retaining some kind of hydration in another.

Table 7. Obsidian hydration analysis of five partially vesiculated flakes from Capulin Quarry.

XRF	Spec#	03-1691 Location	Burn exposure	Visual Effects	Origer Notes	Band Cond	Measure ments	Item Qty	#Cuts/ Bands
	1691-51	by Cluster 2	near cluster	vesic, craz	none	dh	none	1	1
	1691-52	by Cluster 1	near cluster	vesic, craz	wea	dh	none	1	3
	1691-53	area of Cluster 2	burn area	vesic, craz	wea, 2 bands	dh, ok	none, 1.5, 2.1	1	3
	1691-54	burn area	burn area	vesic, slight craz	wea	dh, ok	none, 5.8	1	2
	1691-55	burn area	burn area	vesic, craz	wea	dh	none,.3.0	1	3
See notes for Table 6, above							Totals	5	12

These results for the five flakes differ from the larger analysis of the burned assemblage. In that sample all but one of the artifacts with vesiculation and/or crazing was found to be without measurable hydration. Two sampling factors may help to account for finding a higher proportion of intact hydration bands in this set of five specimens. First, the partially vesiculated flakes were collected specifically because they were expected to have a greater chance for variable hydration. Second, multiple cuts were taken on each of these samples at locations selected with the purpose of encountering the greatest range of variation in hydration bands that might occur. In other words, more cuts, strategic placement of cuts, and specially chosen specimens will likely increase the chances for finding all possible results. Better recognition of the full range of fire effects may help guide decisions about how hydration analysis cuts are placed on pieces that have been exposed to fires.

Describing how heat alteration varies across a specimen requires more detailed examination than is usually undertaken in a standard obsidian hydration analysis. I wanted to understand precisely how hydration was retained when in association with macroscopic fire effects. How close could hydration bands be to vesiculated areas and still be measurable? Did diffuse hydration vary according to proximity of vesiculation and crazing? Here I describe in detail each of the three specimens (1691-53, 54, and 55) that retained hydration bands. These brief summaries include the macroscopic fire effects on each flake, placement of cuts, and a review of the observations made during microscopic OH examinations. The descriptions are presented not in specimen number order, but rather according to my perception of the complexity of results.

Specimen 1691-54. This is a complete flake or a fragment of a core (the morphology is slightly warped by vesiculation). The glass is opaque and dark grey with faint flow banding and occasional tiny speckles. When collected the artifact had the dorsal surface up and the ventral surface down. Fire effects are different on each side of the flake, with the ventral surface nearly free of macroscopic effects. This surface of the flake is fully intact with almost no vesiculation--except at small portions of the edges at each end of the flake. Crazing is not visible on the ventral surface. On the dorsal surface, however, vesiculation occurs at each end of the flake and along a dorsal ridge. Vesiculation is well developed at each end of the flake, resulting in exposure of fragile vesicles that are now broken and abraded. However, along the dorsal ridge much of the vesiculation is less developed and occurs just below the "skin" of the surface, creating a smooth surface with intact vesiculation preserved beneath. Many areas of the dorsal surface have crazing, but rather than the network of fine lines found on the other specimens, there is instead cracking on the flake that appears to be caused by deformation of the piece (and consequent stretching).

Obsidian hydration cuts were made at the mid-section of the flake (Cut 1) and at one end (Cut 2). In both cases, the cuts included mostly unvesiculated glass. Hydration was observed on all surfaces of the cross-sections but varied greatly between cuts: one has a measurable hydration band and the other does not. Cut 1, located at the mid-section of the flake in the least vesiculated part of the specimen, had measurable hydration along all surfaces, measuring an average of 5.8 microns. For this cut, there were no effects of heat exposure apparent during the OH examination. In contrast, Cut 2 exhibited no measurable hydration or had diffuse hydration. Diffuse hydration also was observed on two vesicles, with several other bubbles having no hydration. Interestingly, Origer describes differences in the diffuse hydration depending on proximity to vesiculation--with fainter and more diffuse hydration on the dorsal surface, and brighter, darker diffuse hydration further from the vesiculated part of the flake.

Specimen 1691-55. This is a nearly complete flake with a portion broken from the distal end. The material is opaque and dark grey with flow banding, occasional tiny speckles, and one larger inclusion apparent on the dorsal surface. When collected the dorsal side of the artifact was facing up. Fire effects are similar on each face of the flake, and include vesiculation at the proximal end of the flake that is apparent on both sides but somewhat more developed on the dorsal surface. There also is a small area of vesiculation on the distal tip. At the proximal end, the vesiculation has broken through the surface, but elsewhere the vesiculation is beneath the "skin" of the surface. Both faces have crazing, and on both faces the crazing is much more apparent nearest to the vesiculation. Crazing is also apparent on the broken surface where the end of the flake snapped off, and this surface appears to have some sheen as well. Away from vesiculated areas, crazing is difficult to detect and probably is absent.

Three obsidian hydration cuts were made on this flake. One cut (Cut 1) is located at the distal end of the flake and well away from any vesiculation. Two cuts (Cut 2 and 3) are located at the proximal end of the flake within and adjacent to the vesiculated glass. The results of OH analysis do not follow any clear pattern. Despite differences in the location of the cuts relative to macroscopic fire effects, all three cuts show diffuse hydration or no visible bands. However, the hydration bands were in better condition at Cuts 1 and 2 making it possible to estimate the hydration band width at 3.0 microns. Further, hydration band condition does not correlate with one or another side of the artifact as greater diffusion or absence of bands occurs on either the dorsal or the ventral surface depending on which cut is examined. Therefore, neither the proximity to vesiculation and crazing nor the side of the artifact have apparent correlation with hydration band condition on this specimen.

Specimen 1691-53. This is a complete flake of translucent black obsidian with fine flow banding that is apparent only with transmitted light. The glass has no inclusions. When collected the dorsal surface of the flake was down, and the unvesiculated portion of the distal end was slightly buried. Fire effects include full vesiculation on one unburied corner of the flake, and crazing covering the ventral surface with little to no crazing on the dorsal side. This specimen also is an excellent example of incipient or subsurface bubbling. Bubbles occur just below the surface and deep into the glass, beginning very small and increasing in size and density with proximity to the vesiculated area until they grade into full vesiculation. Because the glass is translucent, it is possible to see that the subsurface bubbling is unevenly distributed inside the glass: more bubbles occurring along the internal flow bands. This is a phenomenon that is present in specimens 1691-54 and 55 but is even more apparent and readily observable in this flake. The significance of differential bubbling or vesiculation along flow banding is that it suggests that there are differences in heat response that correspond with some kind of compositional, textural, or structural variation within the glass of an individual specimen or nodule.

Three cuts were made on this specimen and they are numbered Cuts 2, 3, and 4 (a Cut 1 was planned but not undertaken; although awkward, the original numbering is used here to maintain correspond with the OH laboratory records). Two cuts (Cuts 2 and 3) are located adjacent to the vesiculated portion of the flake and included areas with bubbles. In both cases, hydration is diffuse, with slightly less diffuse hydration on the ventral surface allowing an estimate of approximately 2.1 microns hydration depth on that surface. Also observed in Cut 2 are vesicles with diffuse hydration. The third cut (Cut 4) is located away from vesiculation and bubbling and had different results. Here the ventral surface had a distinct measurable hydration band (1.5 microns), while the dorsal surface had unmeasurable diffuse hydration. In part, these are the results expected: the areas nearest the vesiculation and bubbling have the worst band condition, while the area furthest from vesiculation has a measurable hydration band. Also, the cut with measurable hydration (Cut 4) is located on the part of the flake that was buried when the specimen was collected. What is surprising is that the greatest alteration of hydration is observed on the surface that was facing up when collected (ventral) rather than the dorsal surface which was resting on the ground. One explanation is that the artifact was not in the same position during the fire as it was when collected. Another interesting aspect to the OH observations on this specimen. is the greater width of diffuse hydration (approximately 2.1 microns; Cuts 3 & 4) compared to the intact hydration band (1.5 microns; Cut 4). This matches Trembour's (1990) observation that the hydration band deepens as it becomes more diffuse in response to heat.

Discussion of Specimens 1691-53, 54, and 55. To summarize, the OH results on these specimens show that there are general relationships between the macroscopic fire effects and the expression of hydration on these partially vesiculated flakes. On flakes where intact hydration bands are retained, they are located on parts of the specimen where macroscopic fire effects are least apparent or are absent. However, despite the relative distance from vesiculation and crazing, the areas with intact hydration are nonetheless quite close to fire effects in absolute terms. On specimen 1691-54, the location with the intact (5.8 microns) hydration band is less than five millimeters from vesiculated glass. On specimen 1691-53, the intact (1.5 microns) hydration band is more than 200 mm from the closest vesiculation. However, at that cut, the opposing face of the flake--where only diffuse hydration was observed--is only nine millimeters at the thickest part of the cut, placing intact and diffuse hydration very close together indeed.

This intensive examination also offers new information on the nature of diffuse hydration. First, the analysis shows there can be a direct relationship between the proximity of vesiculation and the degree of diffusion (as observed on specimen 1691-54). However, on another specimen (1691-55), less diffuse hydration occurs at the two locations (Cuts 2 and 3) that are closest to vesiculation, while more diffuse hydration occurs at the cut furthest from extant vesiculation[ix]. Second, the results show that diffuse hydration can occur in direct association with vesiculation. This occurs in all three of these specimens, as well as on 1691-51 and 52 (see Table 7, above).

Finally, the direct association of diffuse hydration and vesiculation is expressed most enigmatically where there are actual vesicles with diffuse hydration (as on specimens 1691-53 and 54). In these cases, bubbles below or at the surface of the glass exhibit hydration along their internal bubble surfaces (i.e. on the interior of the bubble). This is difficult to explain because if the vesicles were caused by heat, how did the diffuse hydration occur so rapidly after the fire? There seem to be two possibilities. First, the vesicles are inherent in the glass (i.e. are not caused by heat exposure) and had hydration prior to the fire; when the artifact was heated, the existing hydration on the bubble surface became diffuse. Second, the vesicles were caused by heat exposure during the fire, and the diffuse hydration occurred through some process that is different than the process described by Trembour (1990). I would prefer the former explanation because it is simpler--unfortunately it is not supported because in these specimens the vesicles clearly appear to be heat-caused bubbles--created as part of vesiculation and not inherent to the glass. It is possible to identify hydration on vesicles that are inherent to the glass. One example did occur in the artifacts analyzed from Capulin Quarry. This is specimen 1691-05, a biface collected from a roadbed where it was protected from the fire. On this specimen the hydration band on the vesicle is distinct and unaltered, measuring 6.0 microns (the same as the hydration on the specimen exterior). If the vesicles with diffuse hydration on specimens 1691-53 and 54 are not inherent to the glass, this leaves the second, perplexing option: that the vesicle hydration occurred upon or after heating through some other process than inward "diffusion" of extant hydration. Perhaps alternate explanations can be devised, or the model described by Trembour can be augmented or clarified to include the phenomenon of diffuse hydration on heat-caused vesicles.

Turning to the final artifact in this "intensive" analysis, specimen 1691-02 offers a good contrast to these five partially vesiculated flakes. For this artifact, an entirely different set of explanations apply: most likely, this flake was burned during a fire that occurred long before the Dome Fire.

Specimen 1691-02. This artifact is a nearly complete flake with a flake break or snap at the distal end (Figure 13). The flake is relatively thin and the dorsal surface is covered with shallow multidirectional flake scars; this appears to be a biface reduction flake. It is difficult to describe the obsidian. One half of the flake (nearest the vesiculated edge) is translucent and medium to light grey. The other half of the flake is opaque and brown. There is no apparent demarcation between these two visual variants within the glass; instead they grade into each other rapidly with some feathering of the brown material into the translucent grey. While neither visual variant is uncommon in obsidian from this source, their combination on one flake is unusual.

The specimen was collected from within the burned area of the site but in a roadbed that probably experienced relatively little heat exposure during the Dome Fire. Unfortunately, no information was recorded on the position of the flake when it was collected (it was one of the first artifacts removed from the site, prior to systematic documentation and collection). This specimen has several fire effects. It is vesiculated from the platform down along one edge, with incipient bubbles at the gradual boundary of the vesiculation. It is important to note that the vesiculation had to have occurred after the flake was detached from a core. This is certain because the vesiculation "wraps around" onto both the ventral and dorsal surfaces, and occurs on both the interior and exterior surfaces of the platform. Much of the vesiculation is contained within the "skin" of the surface, and only breaks through to expose the vesicles at the most exterior part of the vesiculated flake margin. Vesiculation is only observed in the translucent grey portion of the flake; the opaque brown portion has no vesiculation. Crazing occurs across the entirety of both faces, and is expressed most strongly nearer to the vesiculated portion. There does not appear to be crazing on the surface of the distal flake break.

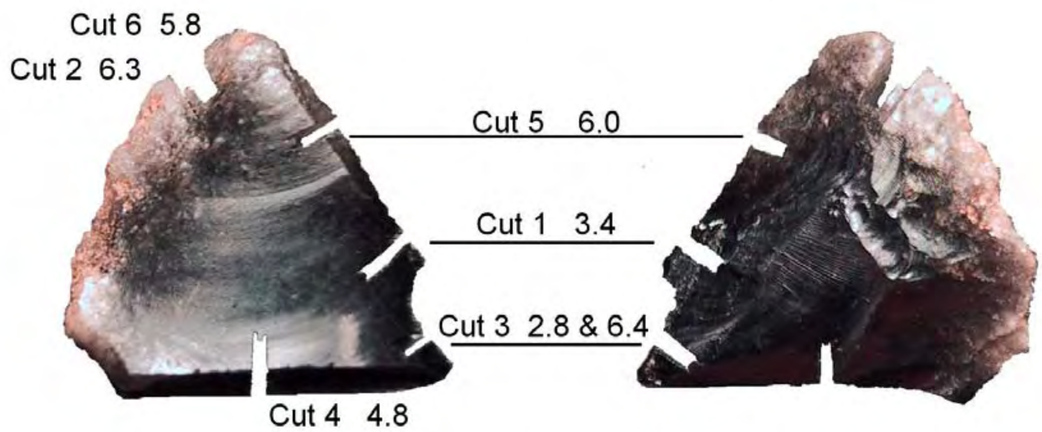
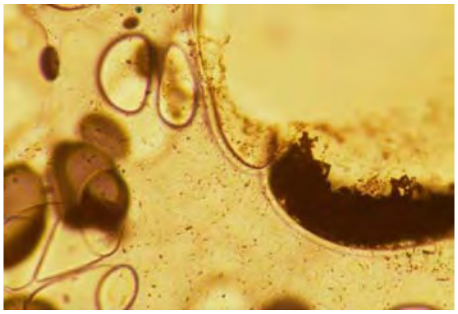


Figure 13. Ventral and dorsal views of Specimen 1691-02; OH measurements are in microns.

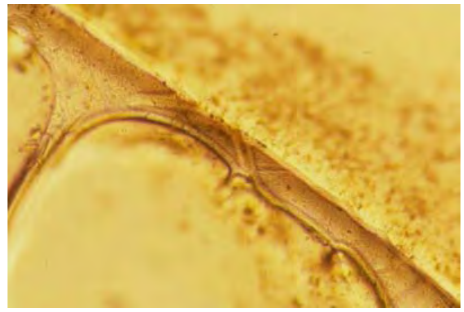
Six obsidian hydration cuts were made on this flake (Table 8). This is the most on any of the specimens in this study, and certainly a high number for any analysis. Despite this abundance, there is no redundancy in the results: each cut yielded different obsidian hydration band widths. Clearly, this makes the OH results for this artifact complicated, but the results are also significantly different from the other burned specimens in this study in two ways. First, there is no diffuse hydration on this flake. All of the five partially vesiculated flakes included in the intensive OH analysis, and all but one of other seven vesiculated specimens in the burned assemblage OH analysis, have diffuse hydration. Second, this specimen has vesicles with hydration--and in this case, these are intact, measurable hydration bands (Figure 14). The other burned specimens with hydration on vesicles, 1691-53 and 54, have only diffuse hydration. The conclusion I draw from these two pieces of evidence--no diffuse hydration and intact hydration on heat-caused vesicles--is that the fire effects on specimen 1691-02 may be from an earlier fire. In other words, the flake did not burn during the Dome Fire, and did burn in a fire some time in the past.

If the artifact was burned in the past rather than in the recent fire, this helps--somewhat--with the interpretation of the OH results obtained in the multiple cuts. The measurements presented in Table 8 suggest there are two groups of hydration band width measurements. The three cuts made in vesiculated areas of the artifact (Cuts 2, 5, and 6) have band measurements that range from 5.8 to 6.3 microns, and this includes the band width of 6.3 microns on vesicles in Cut 2. The three cuts made in the unvesiculated parts of the artifact (Cuts 1, 3, and 4), have band measurements of 2.8, 3.4, and 4.8 microns, respectively. The band widths in the vesiculated areas are the widest and are roughly similar, while the band widths in the unvesiculated areas are narrower but relatively diverse.

No standard obsidian hydration interpretations can be made from this suite of measurements. The greatest band widths occur in the vesiculated areas, so the normal interpretation would require this portion of the flake to be the oldest. Narrower band widths occur on the rest of the flake, in the unvesiculated portions, which would indicate that they are younger. However, the technological information is straightforward on this flake. Except for the flake break at the distal end, this is a flake without significant post-detachment modification. Because the vesiculation occurs on the platform and bulb of percussion, as well as on top of the proximal dorsal scars behind the platform, this means that the heat exposure that resulted in vesiculation occurred after all of these surfaces were created--after the flake was detached from the core. All the dorsal scars overlap as if they were made while the



(a)



(b)

Figure 14. Hydration bands on heat-caused vesicles on Specimen 1691-02: (a) hydration on vesicle surface (6.3 microns)--note that hydration band only occurs on exposed vesicle; (b) hydration on exterior surface and on vesicle surface (6.3 microns)--note hydration bands lining the walls of the crack or "canal" that connects the artifact surface to the vesicle.

Table 8. Band width measurements in multiple cuts on Specimen 1691-02.

Cut Number	Observed Effects	Ventral Band	Dorsal Band	Other Measurements
1	crazing	3.4	3.4	
2	vesiculation	6.3	6.3	6.3 = bands on vesicles
3	crazing	2.8	2.8	6.4 = band on damaged area where dorsal and ventral surface converge
4	crazing on flake surfaces, none on flake break	4.8	4.8	4.8 = band on flake break surface
5	vesiculation	6.0	6.0	
6	vesiculation	5.8	5.8	

All measurements in microns.

the flake was still attached to the core, and none of the dorsal scars initiate on the flake edges (i.e. all of the dorsal scars were there before the flake was created). Finally, the band width on the distal flake break is 4.8 microns, which is greater than the band widths on the nearest flake surfaces (2.8 and 3.4, in Cuts 3 and 1, respectively). One additional observation also eludes technological explanation. On Cut 3 there are two bands, one measuring to 2.8 microns (on both the dorsal and ventral surfaces) and one measuring to 6.4 microns (which occurs on a small portion of the edge of the flake where the two surfaces converge). In the OH thin-section, the area appears weathered. Under lower magnification of the hand specimen (e.g., 20x), this area has a rough appearance that at first glance looks like microfracture associated with edge chipping but on closer examination is not normal edge damage but rather a craggy irregular surface. I think this damaged area is the result of vesiculated glass spalling off--perhaps a "sloughing" off of vesiculated glass or a separation of the surface along a plane of shallow incipient bubbles (for example, as expressed on specimen 1691-12 and illustrated in Figure 4b).

This set of observations leads to two conclusions about the obsidian hydration history of this artifact. First, none of the usual explanations about sequential removal can explain the differences in the band widths across the flake. In fact, in every cut the measurements on the dorsal and ventral surfaces are identical (Table 8), thus excluding the most important indicator that a flake has been modified at a time more recent than when the flake was originally created. The distal flake break should either have the same band width as the adjacent surfaces (if it occurred at or near the time of flake detachment), or have a narrower band width (if it occurred after the flake was created). Second, even applying what we know about fire alteration to obsidian hydration bands does not provide an obvious alternate post-fire obsidian hydration history, and raises many more questions than can be answered. If the fire simply "reset" the obsidian hydration clock on this artifact, why do the hydration bands vary so much across the piece? Why are the bands at the vesiculated locations less variable than the bands in the unvesiculated areas?

I can speculate about how heat exposure could account for certain band widths or groups of OH results, but I cannot yet formulate a coherent explanation to explain the combined hydration analysis results across the entire specimen. For example, one possibility to explain the wider bands in vesiculation-area cuts is that they represent the manner in which diffuse hydration hydrated after the episode of heat exposure--where the hydration band was widened during heating and with re-hydration became distinct again at this increased width. Or, the wider bands in the vesiculation-area cuts show that post-fire re-hydration occurs at a different rate where heat alteration of obsidian is extreme. This might apply also to explaining the diverse band widths in the unvesiculated areas. Another possible factor to consider in understanding these diverse bands is the observed differences in the material across the flake. While the differences in glass color and translucency are most likely unrelated to the fire effects--either as cause or effect--perhaps there is some kind of compositional difference between the two areas that could influence the response of the glass to heat or to post-fire hydration. Invoking glass composition as an explanation for the odd OH results on this flake is implausible. However, it is interesting to note that in the data on elemental values in the burned assemblage (Table 5a), there are some differences between the two XRF readings on 1691-02. Reading "a" was located at the distal end of the ventral surface (unvesiculated), while reading "b" was located at the proximal end of the dorsal surface (atop or beside vesiculated glass). The elemental values are all (except Sr) slightly higher in reading b than in a, and the elemental value for Zn is particularly high. In fact, Zn is higher in this reading than in any other instance except for two: 1691-07 (Table 5b) and the experimentally heated sample GS-8 after heating to 875˚C (Table 4). In all three cases, the readings that are high in Zn were taken in areas with vesiculation.

In summary, the obsidian hydration results obtained for specimen 1691-02 are unusual and puzzling, and cannot readily be explained in terms of the artifact's technological history, speculation as to its fire history, or compositional disparities in the piece. A satisfactory explanation for the obsidian hydration on specimen 1691-02 will require a more complete understanding of how obsidian hydrates following significant heat exposure. For now, however, an important use of these results is to recognize that obsidian does form hydration bands after substantial heat exposure, that these bands can be intact and measurable. Any obsidian hydration analysis that includes fire altered artifacts will benefit from not only from an informed attempt to identify any macroscopic fire effects that evidence past heat exposure, but also a thorough or "intensive" obsidian hydration analysis that includes multiple cuts. Such analyses could change the overall interpretation of the OH information in a burned assemblage, and more importantly for now, will contribute to our understanding of past heat alteration and subsequent hydration of obsidian artifacts.

Conclusion

The analyses conducted for this pilot project suggest some preliminary answers to questions raised at the beginning of the article. The most basic question--why did obsidian vesiculate at this quarry during the Dome Fire--can be partially answered. The study did not identify any factors other than the heat of the fire, and the specific circumstances of local burning conditions, as causes of the phenomenon of vesiculated obsidian at Capulin Quarry. The initial perception that this was the only location where vesiculated obsidian occurred is incorrect. Further survey at obsidian sites in the Dome area found several other instances of vesiculation, although nowhere did this fire effect occur in as large an area or with so many dense clusters as observed at Capulin Quarry. Pieces of vesiculated obsidian were found at Obsidian Ridge (which experienced back-burning during Dome Fire suppression), in a location outside the Dome Fire where prescribed burning occurred in the early 1990s (at sampling location GS 9), and most revealing, within a recent campfire at a location outside of the Dome Fire (near sampling location GS-3). In all three cases, these burning conditions that resulted in obsidian vesiculation would be considered anything but extreme.

My impression is that for obsidian at this source, all that is needed to cause vesiculation is a sufficient source of heat and *a high density of obsidian.* I believe that vesiculated obsidian is not likely to be found at locations with sparse obsidian not only because archaeologists may miss the phenomenon but also because a high density of surface obsidian significantly increases the quantity of material affected in each instance that the sufficient heat conditions occur. That is, if conditions sufficient to cause vesiculation occur in only a small percentage of the burned area of a given forest fire, the presence of abundant obsidian available on the surface to respond is a critical factor. Despite our surprise at finding the vesiculated glass after the Dome Fire, there may be nothing unusual about this fire effect at this source. Perhaps what was unusual was that this time we noticed it. Hopefully the descriptions here will spread the word on vesiculated obsidian, increasing the chances that the phenomenon will be documented again soon.

The experimental results reported here, while limited, hint at what may constitute "sufficient heat" to cause obsidian to vesiculate. In the lab heating experiment, three of the obsidian samples vesiculated at 815˚C, 850˚C, and 875˚C, while the fourth sample did not vesiculate even at 875˚C. These temperatures suggest minimum ranges for this extreme fire effect in obsidian from this source. The most interesting aspect of these results is that they indicate a surprising range of variation in the temperature of vesiculation despite little variation in the trace element composition of the samples.

When compared to the results of the baseline geological XRF analysis, which obtained little variation among the trace and minor elements measured, the observed variation in temperature of vesiculation suggests intrasource compositional variation in some constituent not measured in this XRF analysis of obsidians from the Rabbit Mountain/Obsidian Ridge source locations. I suspect that the relevant component may be the water content of the glass. It is well-established in petrology that water can play a role in lowering the temperature of melting in igneous materials (e.g., Winter 2001:120-126). Measuring intrasource variation in the Rabbit Mountain/Obsidian Ridge source and exploring the potential role of water content in obsidian fire effects are important components of my on-going dissertation research.

Understanding the compositional data produced for burned and unburned obsidian materials also required knowing if exposure to fires alters the elemental composition of the glass or, alternately, if heat exposure changes how XRF measures elemental values. Again, this study yielded partial answers. Overall, the XRF data for burned specimens differs little from unburned specimens in this sample. For the few specimens where elevated elemental values were noted in the burned materials from Capulin Quarry, it is possible that materials adhering to the artifact surfaces may have affected the measurements. In the laboratory heating experiment, some intriguing patterns were noted that suggest small increases in many of the elements measured after the samples were heated. Because the differences in elemental values are small, these results do not indicate that heating of this obsidian would result in misidentification of the geochemical source. However, it may be important that the pattern of increasing elemental values was not consistent among the specimens. Samples from one nodule, GS-10, did not show the increases in elemental values exhibited by the other three materials. This material also differed from the other samples in that it did not vesiculate at the highest temperature of heating. These results warrant further examination to explore whether the occurrence of vesiculation contributes to differences in XRF results (e.g., by altering the surface geometry of specimens). The alternate possibility that differences in chemical composition play a role in determining the temperature of vesiculation also should be explored. That is, materials with a tendency to vesiculate at lower temperatures may be consistently associated with changes in elemental values after heating. Conversely, materials with a resistance to vesiculation at higher temperatures may be consistently associated with unchanged elemental values after heating.

In summary, the analyses of obsidian chemical composition in this study returned some expected results, including the relative homogeneity of the selected minor and trace elements measured, and that fire exposure did not significantly alter these elements for the purposes of sourcing. The composition analyses also produced some surprises, including the slight but patterned changes in elemental values with increased temperatures in the controlled heating conditions, the observed differences in temperatures of vesiculation among the four obsidian sample materials, and the possibility of linkages among these two variables and a third variable, the cloudy vs. clear visual appearance of the glass.

Compared to the results of the XRF analyses, the obsidian hydration analysis of the burned and unburned assemblage at Capulin Quarry produced results that are somewhat more straightforward. There is clear evidence that heat exposure during the Dome Fire altered obsidian hydration bands in the burned specimens, and that the proportion of specimens without measurable hydration increased with the degree of burning in this sample. The results also suggest that the presence of diffuse hydration could be used as an indicator of recent exposure to heat. However, when the scale of analysis is shifted from the assemblage to the specimen, the results are more complex. While crazing and vesiculation are associated with both the presence of diffuse hydration and a lack of measurable hydration, the "intensive analysis" of several partially vesiculated flakes showed that within a specific specimen a single hydration cut might not represent all of the hydration information--or the range of relationships between macroscopic and microscopic fire effects--on that artifact. Finally, one specimen in the analysis, 1691-02, appears to be an example of an artifact burned during an earlier fire, and then re-hydrated in a way that is not yet understood. This artifact illustrates both that new kinds of obsidian hydration information may exist on artifacts burned in past or prehistoric fires, but that there is much that must be learned before beginning to develop any potential for using obsidian hydration dating to estimate the age of past fire exposure on such artifacts.

As with most pilot projects, this study has raised as many or more questions than it has begun to answer. I pursue some of these questions in my dissertation research: the description of a full range of obsidian fire effects, the necessary temperature and duration of heating required for vesiculation in obsidian from this and other sources, the occurrence of unusual hydration on burned artifacts (such as diffuse hydration, and hydration on vesicles), the relationships between visual variation in glass from this source and variation in heat response, and the potential role of intrasource compositional variation in obsidian fire effects. Many other questions about obsidian and fire await further exploration. With the current high interest in obsidian fire effects, and new archaeological and material science research such as the studies included in this volume, we can look forward in the next few years to rapid advancement in our knowledge of glass-heat interactions.

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NOTE

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[i] "Collect 1" includes materials from within a road judged to have not experienced direct fire exposure--an assessment that may not be entirely correct.

[ii] Bennett and Kunzmann (1985) also give descriptions of heat alterations to obsidian under experimental heating conditions. Their report is not discussed here as it was preliminary, and identified as "not for citation or publication".

[iii]Almost all of Rabbit Mountain dome is within a large land parcel, known as the Baca Location No. 1, that at the time of fieldwork for this study was privately owned. The area was federally acquired in July 2000, and is now designated as the Valles Caldera National Preserve (VCNP). As the first United States Forest Service National Preserve, the VCNP is under a unique management arrangement headed by a Board of Trustees who will determine the nature and timing of future research access to the Preserve.

[iv] Most of these samples are non-artifacts, but a few artifacts were included (n=6; from GS 1, GS 2, and GS 4). As noted in Table 1, many of the geological sampling locations are near documented archaeological sites. In the Dome area it is difficult to avoid the overlap of geological exposures of obsidian-bearing deposits and archaeological sites. At each location, the natural nodules selected are clearly in their actual geological context. I decided to include data from artifacts in the sample because the results obtained do not indicate any variation among the natural and artifact samples.

[v] The furnace is a Thermolyne electric muffle furnace--the same one that Trembour used for his heating experiments following the 1977 La Mesa Fire (Trembour 1979, 1990).

[vi] There also was an additional batch in this experiment (heated to 260°C/500°F). This was not included in the XRF analysis, and is excluded from the discussion here. As expected, no heat effects were observed on any of the flakes during this low-heat firing run.

[vii] The rough conversion figures for the °F to °C temperatures are due to imprecision (but not inaccuracy) in the furnace dial. I recorded the instrument readings in °F, and then rounded to even intervals when converting to °C.

[viii] The completed microslides are curated in the Sonoma State University Obsidian Hydration Laboratory under File numbers 98-H1772, 98-H1730, 99-H1848, 99-H1855, and 99-H1857.

[ix] The distal end of specimen 1691-55 is broken. This seems to offer the possibility that a vesiculated part of the artifact could have snapped off that, if still intact, would show that Cut 1 was in fact close to vesiculation. I suspect this is not the case because 1) there is crazing on the break surface, and 2) at the other tip of the break, vesiculation curls around slightly onto the break surface. Thus, if the end of the flake did break off, it had to have done so during the fire to allow the opportunity for these fire effects to occur on the new surface.

AN EXPERIMENTAL EXAMINATION FOR DETECTING THERMAL TRAITS ON OBSIDIAN ARTIFACTS

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Introduction

The obsidian artifacts recovered from sites often are lusterless on their surface. Most Japanese prehistoric archaeologists have treated these lusterless obsidian artifacts as the results of fire effects on assemblages in the Upper Paleolithic and Jomon (Hata and Tahara 1983; Kato et al. 1971; Kojima and Sozu 1995; Kubo et al. 1980). The surface luster itself, however, can also be due to obsidian hydration rim, surface abrasion with post depositional displacement of artifacts, and weathering constrained by temperature and humidity at the location of the site, and intrinsic chemical composition of the obsidian (cf. Mori and Matsufuji 1994). Variable factors can affect the surface conditions that cause the loss of the glassy shine of obsidian. Thus, it is necessary to use a method that verifies the exact traits of thermal alteration of obsidian in order to detect thermally altered obsidian artifacts from obsidian assemblages (Nakazawa 1998b, 1999).

Previous field experiments demonstrated that obsidian specimens, heated for 1-12 hours in outdoor campfires, resemble the unusual obsidian artifacts from prehistoric sites with an unaided eye (Kato 1970; Kato et al. 1970; Kojima and Sozu 1995). In a laboratory experiment using an electric furnace to determine the temperatures at which fission tracks are lost, obsidian specimens from four Japanese provenances, were heated for an hour at 650°C. The results show that the glassy shine was lost only on the part of the specimen covered in wood ash (Koshimizu and Fukuoka 1991).

The purpose of this paper is to elucidate the generation processes of the trait of thermal alteration on obsidian artifacts explicitly by means of experimentation. With detecting the trait of thermal alteration, I attempt to discuss the mechanism behind the generation of the trait of thermal alteration in terms of physical chemistry.

Identified anomalous characteristics on obsidian artifacts and their relations in the lithic assemblage

As an analytical unit, a lithic assemblage excavated from an Upper Paleolithic site was examined. Classifications and descriptions of the classified units were done based on the assumption that observable unusual characteristics of obsidian surface and breakages had been generated by thermal alteration, although identification of thermal alteration on obsidian artifacts is not determined *a priori*. In order to justify whether or not distinguished traits resulted from thermal alteration, a series of experiments was conducted in association with subsequent observations on obsidian artifacts under an optical microscope.

1. Outline of the study assemblage of Meboshigawa 2

The lithic assemblage examined was recovered from Meboshigawa 2, a site located in southern Ishikari Lowland, central Hokkaido, northern Japan (Chitose Board of Education 1983). Among the 5,552 lithic artifacts, the principal rock type is obsidian, composing 4,963 artifacts (89%), while smaller amounts of shale, chert and agate are also present. Dominant tools of this assemblage are microblades and end scrapers on blades. Most of them were from a horizontally concentrated scatter included in the deposition of silty acid loam which had accumulated on an eolian sand dune with a matrix provided by pumice of Spfa1 erupted in the middle Upper Pleistocene dated ca. 40,000 years B.P. (Kato et al. 1995).

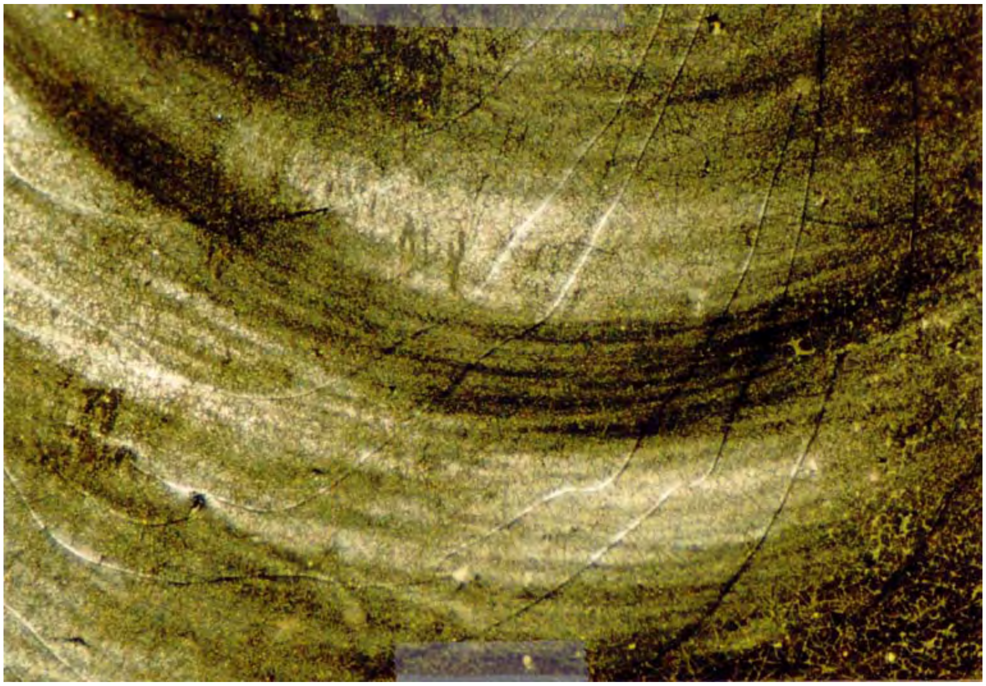
A layer of Holocene black humus soil 30 centimeters thick overlaid the artifacts and prevented the sudden falling of volcanic pumice on the scattered artifacts. Only 160 grams of carbons were associated with this assemblage, though any burnt soil had not been identified. Although obsidian source analysis has not been applied either by EDXRF or NAA, the nearest source from the site is Akaigawa which is 70 kilometers distant to the north. The assemblage is dated at ca. 17,000 to 10,000 ^{14}C years B.P. as determined by tephrachronology and AMS radiocarbon. The age of the lithic assemblage in terms of the relevant component of stone tools recovered from loess deposits compatible with the strata of Meboshigawa 2, accompanied with Oshorokko-type microbladecores (Tsurumaru 1979), approximately 6 km from Meboshigawa 2 site, called Osatsu 16 site provide two dates of 14,590 ± 200 ^{14}C years B.P. (Gak-19469) and 10,600 ± 200 ^{14}C yr B.P. (Gak-19468) of conventional radiocarbon dates (Tsujimoto 1997). Thus, the age of study site is estimated at between ca. 15,000 and 10,000 ^{14}C years B.P.

2. Observation of obsidian artifacts

In cryptocrystalline chert, several fracture features have been determined to be the result of thermal alteration (Flenniken and Garrison 1975; Hofman 1986; Olausson and Larsson 1982; Price et al. 1982; Purdy 1974, 1975; Purdy and Brooks 1971; Schindler et al. 1982; see also Luedtke 1992). In obsidian, detailed description of surface scattered thermally altered obsidian made by large forest fires provides variable traits (Steffen 1999, 2000). Steffen (2000:4) discerned seven characteristics, which are “matte finish”, “surface sheen”, “fine crazing”, “deep surface cracking”, “incipient bubbles”, “vesiculation”, and “fire fracture” at the macroscopic level of observation. While most traits described below are fairly consistent with these descriptions, application of microscope observation at the magnification of 15 to 60 power to the obsidian artifacts from Mebosigawa 2 site, discerned six prominent characteristics in terms of the anomalous fracture patterns on the surfaces and the breakages (Nakazawa 2000).

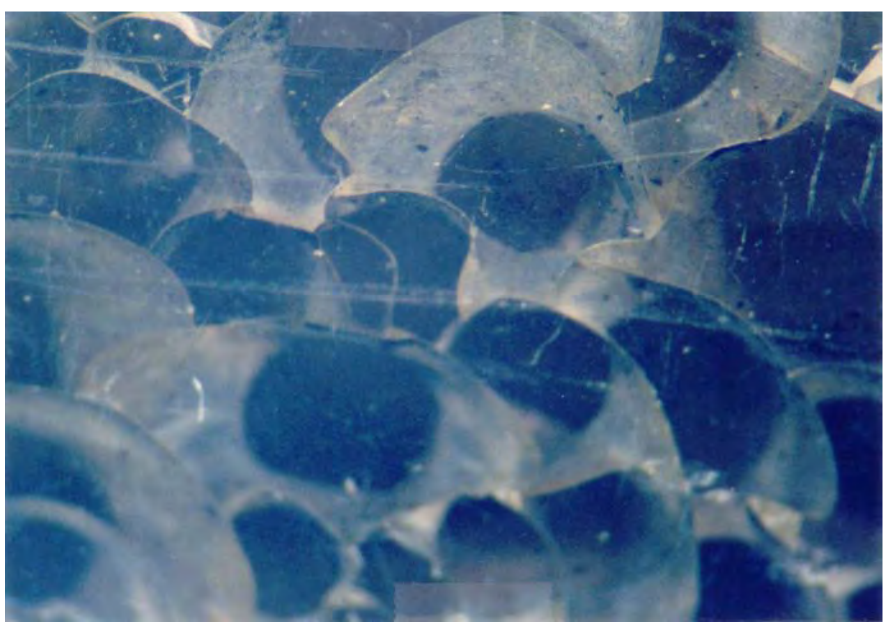
These observed heat induced features are described in the following sections, and they are illustrated in the accompanying photographs. Three general categories of alteration are noted. The first includes surface or near surface fractures of three types: 1a (crazing); 1b (squamoid); and 1c (tiny cracks). The second alteration (type 2), vesiculation, involves a major physical change on the surface and at depth. Finally, two types of breakage are identified that result in flat surfaces (type 3a) and irregular surfaces (type 3b).

Type 1a Alteration: Crazing is like a fingerprint pattern (Photograph 1). This is curved crazing. It looks like a fingerprint when some of these fractures have a parallel distribution. The density of distribution is different depending on the artifact.



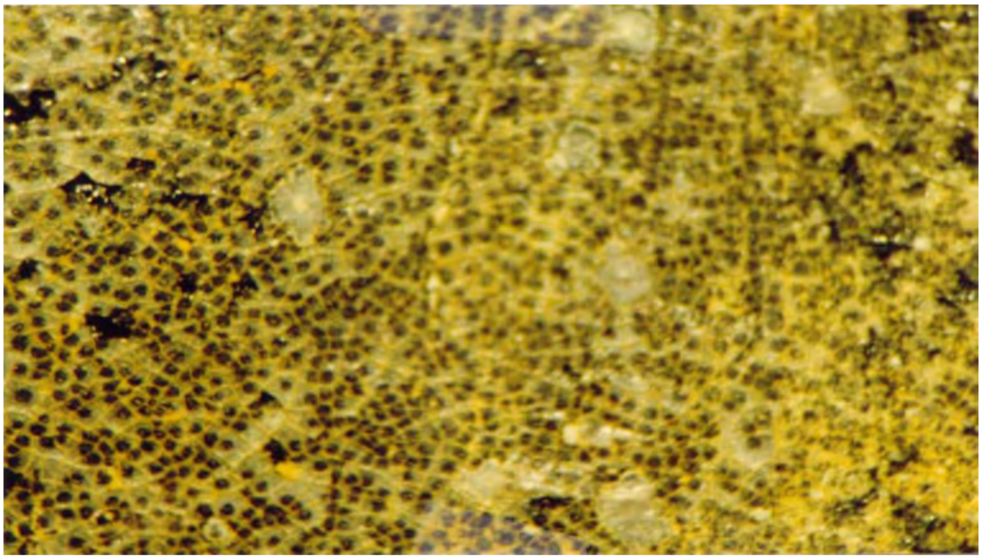
Photograph 1. Fingerprint-like crazing.

Alteration 1b: Squamoid crazing (Photograph 2). This is completely different from type 1a fractures in that type 1b fractures are well below the surface and have the appearance of fish scales. The size of each fracture is almost the same and easily detectable.



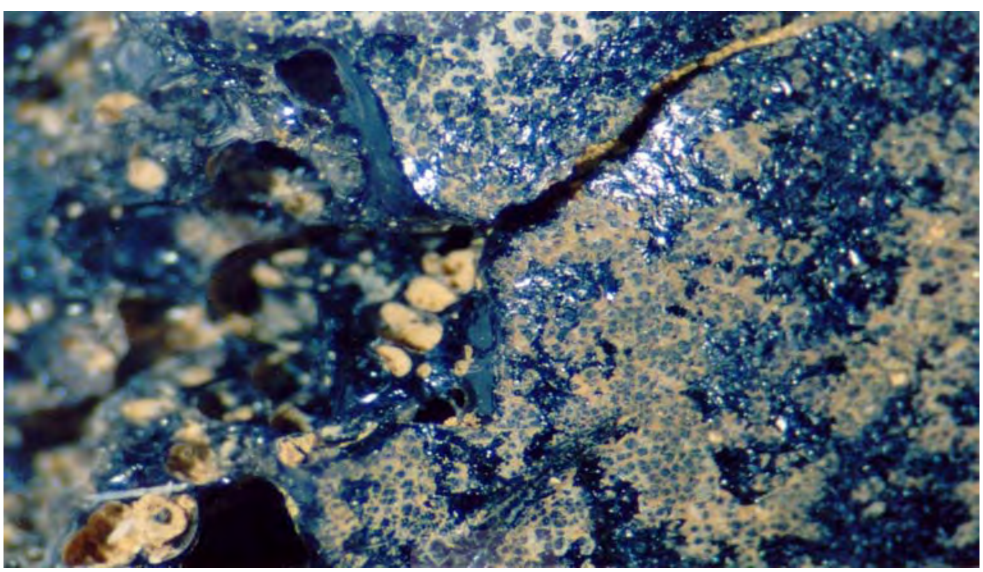
Photograph 2. Squamoid crazing.

Alteration 1c: Tiny cracks (Photograph 3). These cracks distribute on the surface, and their features are the same as the one described as "cross hatched" (Friedman and Smith 1960:485). Their density of distribution is higher than type 1a and 1b crazing. Some are distributed with type 1a crazing succeeding.



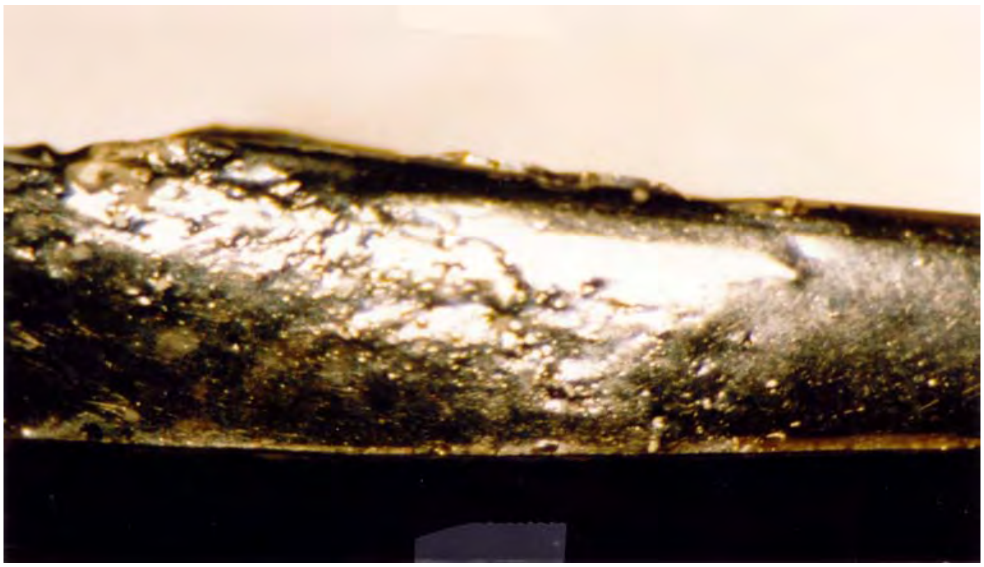
Photograph 3. Tiny cracks.

Alteration 2: Vesiculation (Photograph 4). There is a wide cleft in which an interior sponge-like texture with a white appearance is visible. Vesiculated obsidian is lighter in weight than non-vesiculated specimens of the same size and shape.



Photograph 4. Vesiculation.

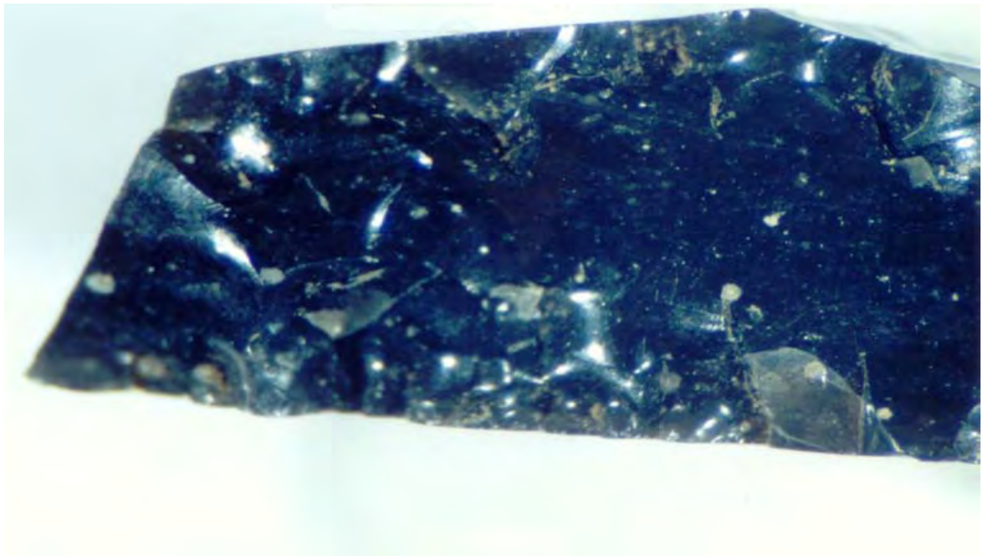
Alteration 3a: Breakage with flat surface (Photograph 5). On the flat surface of breakage, neither bulb and bulbar scars, nor finials are identified, contrary to the normal breakage (Cotterell and Kamminga 1987). Wedged fracture, typically formed by direct percussion of hard hammer (Bergman et al. 1987), is also not identified. Instead of clear ripples, which are recognized on normal obsidian flake scars, very weak ripples are distributed as a concentric circle mostly from crystallite in the obsidian. The appearance of this breakage has heavy glassy shine (luster). The outline of the breakage adjacent to dorsal and ventral surfaces represents a wavy form, which is almost compatible with crenated fracture on thermally altered chert (Purdy 1975).



Photograph 5. Breakage with flat surface.

Alteration 3b: Breakage with irregular surface (Photograph 6). The marginal part of breakage has an irregular surface and is sometimes crenated. Observed from the side of a flake, length of this crenated surface measures from 0.5 to 1.0 mm and does not reach the center of the obsidian. This crenation is often in connection with 1b crazing. The appearance also shows glassy shine in which clear ripples are not recognized as well as a type 3a breakage.

Although the above descriptions are based on a series of observations under the light microscope, it is possible to recognize almost of all characteristics with an unaided eye except the tiny cracks of 1c. Since crazing of type 1a, type 1b and tiny cracks of type 1c are regularly distributed on the obsidian surface, they are apparently different from the characteristics of naturally occurred scars in post-depositional processes (Keeley 1980) and striations of a type of use-wear (Barton et al. 1998, Midoshima 1986, Miyasu 1996, Tsutsumi 1995). It is not likely that these morphological characteristics are generated by frost fracture (Dibble et al. 1997, Loutridou et al. 1986, Luedtke 1992, Sieveking and Clayton 1986) due to intrinsic water in obsidian that might be frozen under colder environment during Oxygen Isotope Stage 2 in the Upper Pleistocene, because all characteristics described above are recognized on only a portion of obsidian artifacts in the assemblage (Table 1).



Photograph 6. Surface with irregular breakage.

Both breakages of type 3a and 3b show heavier glassy shine than those of on the normal scars of obsidian flakes. These breakages are associated with fractures of type 1a, 1b, and 1c, and the sequence of flake scars indicate that they are formed after the generation of these fractures.

3. Quantitative measurements of recognized characteristics

Most artifacts with these characteristics retain more than one characteristic. The quantity of these recognized characteristics is examined in order to estimate their generation processes. First, Table1 summarizes quantified numbers of characteristics in anomalous characteristics. It shows that the dominant is 1a (51.2%, n=1,507) and 1c is subsequently (34%, n=1,000). About 3 to 6 % of anomalous obsidian have either 3a (n=162) or 3b (n=79) breakage patterns. Only 3% (n=87) of vesiculated obsidian is recognized.

Table 1. Frequency of heat induced alteration types.

Alteration Type	n	%
1a	1507	51
1b	108	4
1c	1000	34
2	87	3
3a	162	6
3b	79	3
∑	2943	

Second, scrutinizing these characteristics on each obsidian artifact results in 33 combinations (Table 2). Either only type 1a or only type 1c is dominant. Type 3a is often combined with type 1a (n=67), while type 3b is often combined with type 1b (n=21). Third, on the basis of the results of Table 2, the relationship between each morphological characteristic shows that principal combinations are type 1a-1c and type 1a-3a (see Table 3). Considering that types 1a and 1c are often combined, these two morphological characteristics are possibly generated under the same or similar conditions. The result that type 3b does not combine with type 2 indicates that irregular breakage does not relate to the generation of vesiculated obsidian.

Table 2. Alteration characteristic combinations.

Combined Characteristics	
1a	1049
1a/1b	12
1a/1b/1c	9
1a/1b/1c/3a	1
1a/1b/1c/3a/3b	1
1a/1b/1c/3b	9
1a/1b/2/3a	1
1a/1b/3a	6
1a/1b/3a/1c/2	1
1a/1b/3a/3b	3
1a/1b/3b	15
1a/1c	213
1a/1c/2	51
1a/1c/2/3a	1
1a/1c/3a	30
1a/1c/3a/3b	1
1a/1c/3b	9
1a/2	18
1a/2/3a	4
1a/3a	67
1a/3a/3b	1
1a/3b	5
1b	16
1b/1c	7
1b/1c/3b	5
1b/3a/3b	1
1b/3b	21
1c	606
1c/2	5
1c/3a	43
1c/3a/3b	1
1c/3b	7
2	6
∑	2225

Table 3. Morphological type relationships.

Combined Characteristics	n
1a-1b	58
1a-2	76
1a-3a	117
1a-3b	44
1a-1c	326
1b-2	2
1b-3a	14
1b-3b	55
1b-1c	33
2-3a	7
1c-2	58
3a-3b	8
1c-3a	79
1c-3b	33
∑	910

Experimentation

Laboratory experiments under controlled condition were conducted in order to detect whether the above-described characteristics are generated. Previous experiments regarding fission-track loss indicated that temperature, application of wood ash, and duration of heating could cause the loss of glassy shine inherent in obsidian (Koshimizu and Fukuoka 1991). Referring to this study, temperature, application of wood ash, and duration of heating are set as the variables for the experiments.

Methods

The experimental specimen included 72 obsidian flakes chosen randomly enough to fit in the crucible from a number of flakes knapped from 3 nodules from terrace sediments of Oketo-Tokoroyama, northeastern Hokkaido. Wood ash was provided from pines in the forest located at Shunbetsu, Atsuta village, central Hokkaido.

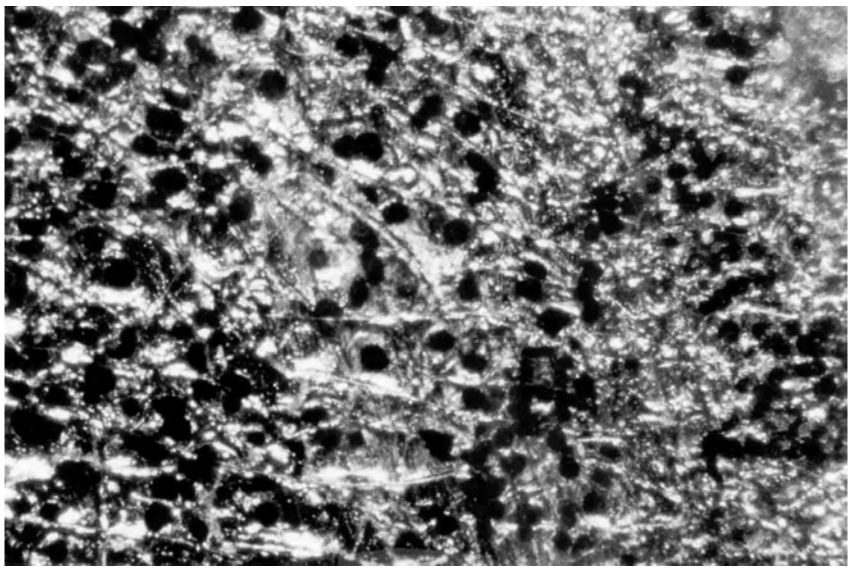
Under the artificially controlled temperature in an electric furnace (BF-340 type produced by Yamada Electrical Corporation), sequential change of appearance in obsidian surface according to duration of heating was traced. Controlled temperature and duration of heating were 1 to 12 hours at 450˚C, 500˚C, 550˚C, and 600˚C, while 1 to 6 hours at 700˚C and 800˚C. Each specimen was embedded in 10 grams of wood ash in a crucible at half-length of a flake. Then all crucibles, each of which has an obsidian flake, were set in the electric furnace preheated to the temperature. At each interval, each crucible was removed from the furnace, and wood ash on the obsidian was washed away after the crucible cooled completely. All specimens were observed under the light microscope at the magnification of 15 to 60 power, to compare the area where wood ash had been applied and the area in the atmosphere.

Results

The systematic observation of all obsidian specimens in the experiments results in 10 indications as follows.

(1) Only the part where the wood ash had been attached lost glassy shine of obsidian. This result coincides with the results of previous experiments (Koshimizu and Fukuoka 1991).

(2) Under the microscope, the part where glassy shine is lost is composed of tiny cracks and its morphology is the same as type 1c crazing (Photograph 7).



Photograph 7. Heat alteration with tiny cracks and loss of glassy shine.

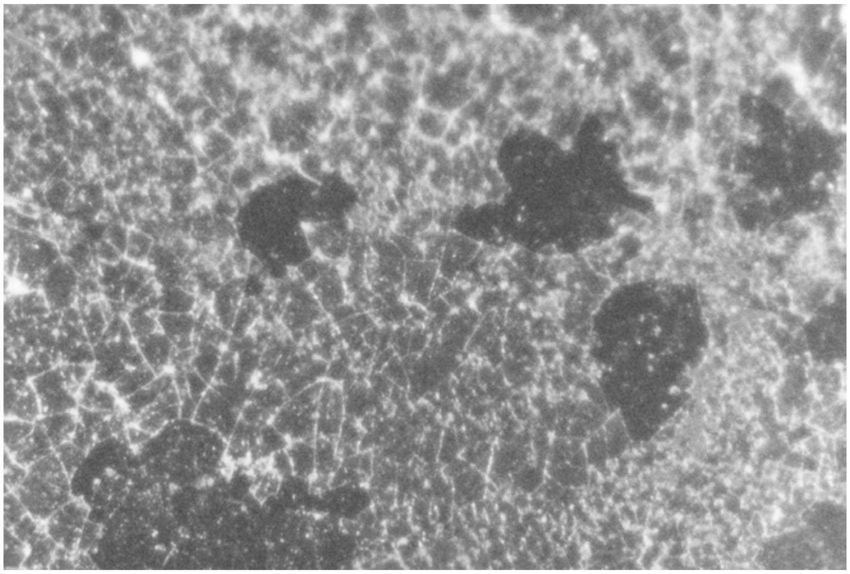
(3) There are a number of tiny bubbles beneath the surface of the specimen. It is inferred that those tiny bubbles and tiny cracks cause the glassy shine to be lost and those are responsible for disturbing the reflection of the spectrum. No definite tiny bubbles were identified in this study of obsidian artifacts. It is inferred that tiny bubbles were released through small surface cracks during long period after deposition.

(4) On the specimens heated for over nine hours at 550˚C, over three hours at 600˚C and over one hour at 650˚C, many apparent tiny cracks are observed. There are no visible thermal traits on the specimens heated for 1 to 12 hours in 450˚C and 1 to 12 hours at 500˚C. These results indicate that tiny cracks are generated above nine hours at 550˚C.

(5) Tiny bubbles were generated in four hours at 550˚C and one hour at 600˚C, which is a shorter duration of heating than that which created tiny cracks.

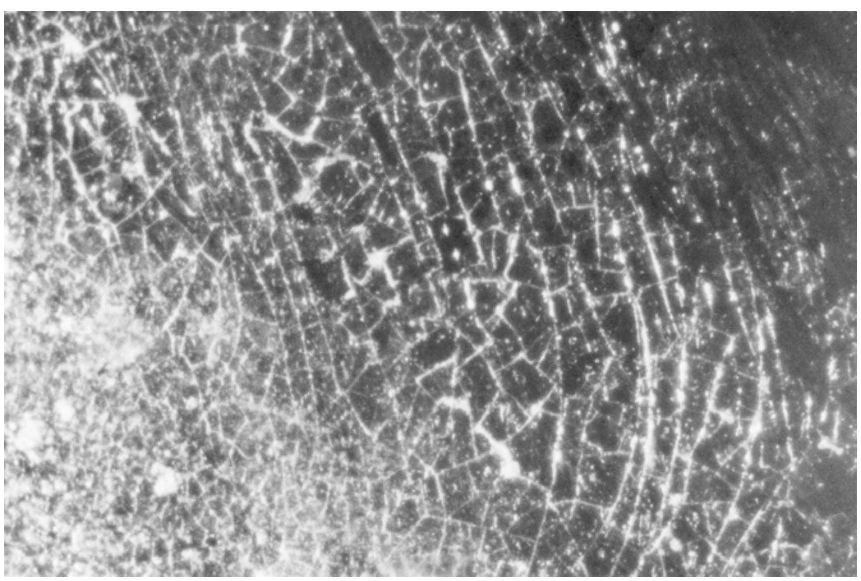
(6) The specimens heated for 4, 6, and 8 hours at 550˚C have a number of tiny bubbles partly overlapped with tiny cracks. This indicates that the range from 4 to 8 hours at 550˚C is the critical state in generation of tiny cracks.

(7) Part of the surface area does not have tiny cracks due to flaking off in the specimens heated for 4 to 12 hours at 650˚C, 4 to 6 hours at 700˚C and 2 to 6 hours at 800˚C (see Photograph 8).



Photograph 8. Surface showing lack of cracks in areas (irregular dark patches) that spalled.

(8) The specimens heated for 7, 10, and 12 hours at 600˚C have curved crazing within the area where tiny cracks are identified (Photograph 9). This curved crazing is very similar to type 1a crazing. It is estimated that some type 1a crazing could be generated with tiny cracks (1c).



Photograph 9. Curved crazing.

(9) A breakage with flat glossy surface was formed accidentally when the specimen in a crucible had been removed from the electric furnace after heating for four hours at 650˚C. A very weak ripple from crystallite is identified on this breakage and this characteristic is coincident with that of type 3a breakage in the obsidian artifacts (Photograph 10). Type 3a breakage can be formed by thermal alteration, although it cannot be determined that all of them were accidentally formed.

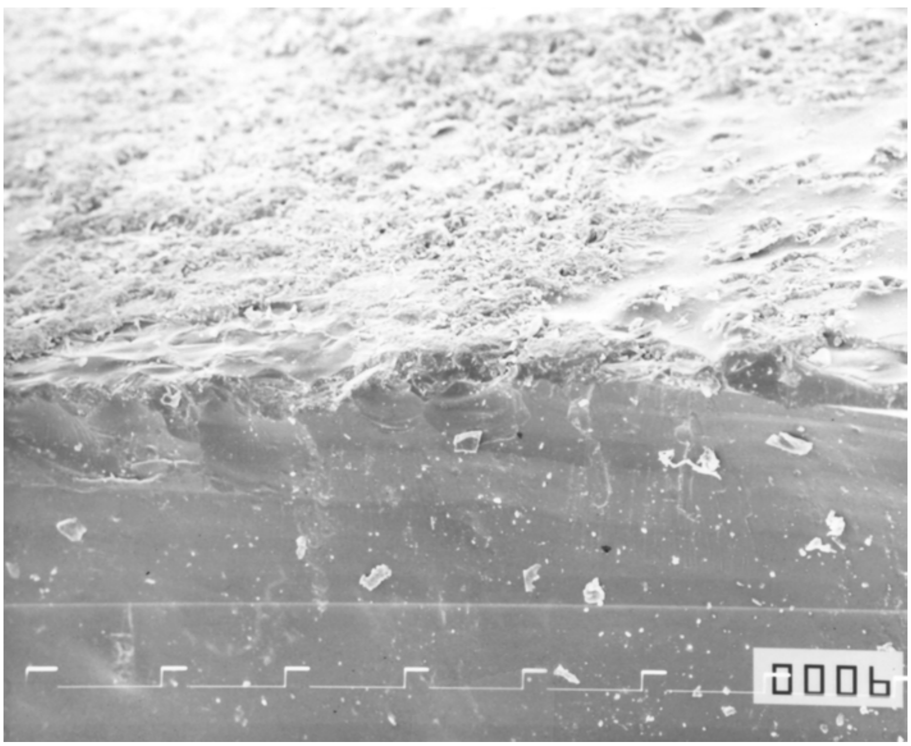
Photograph 10. Flat glossy surface with ripple.

(10) Types 1b, 2, and 3b were not generated in these experiments.

Discussion

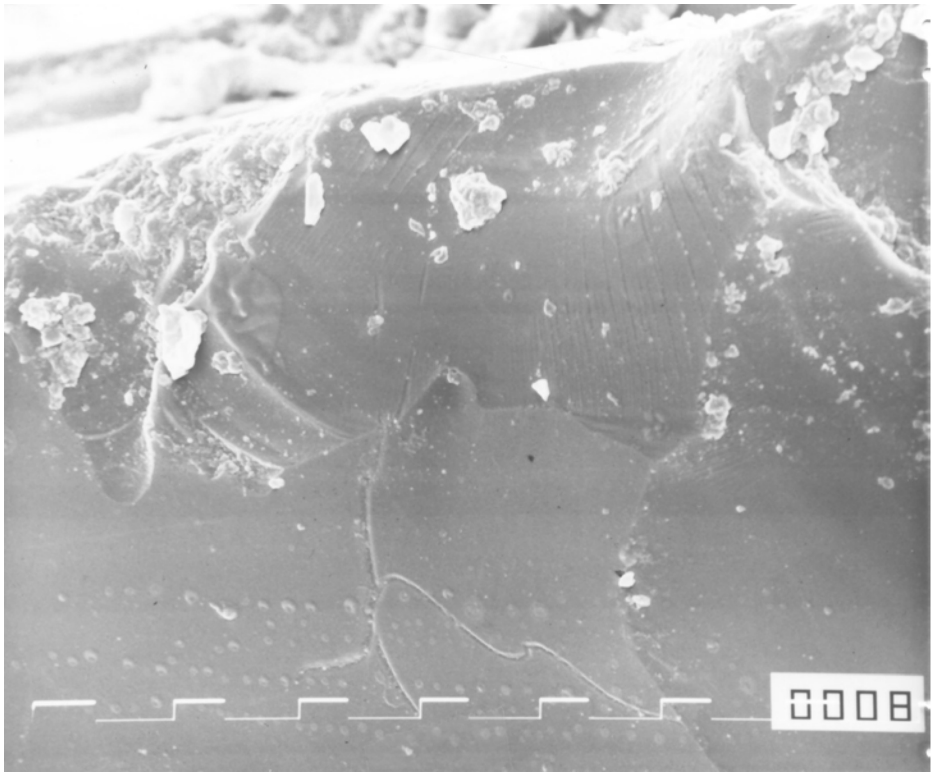
The results of these experiments address two mutually related issues. First is the issue of generation processes. The experiments revealed that two patterns recognizable in obsidian artifacts, the tiny cracks on the surface of obsidian and breakage with flat surface, are the results of thermal effects. Especially, generation processes of tiny cracks on the surface are firmly traced by these experiments. We are, however, still uncertain on the generation processes of other characteristics observed on the artifacts. Additional experimentation will be required in order to identify whether each characteristic on the surface of obsidian artifacts corresponds to a certain heating condition. The rate of heating - rapid or slow- would be one cause to provoke other patterns of thermally altered traits, as well as longer duration heating under low temperatures below 500˚C. The controlling factor for heating rate would be the size of obsidian flakes. If the surface area is larger, the rate of heating becomes slower under certain temperature. The amount of water content also may be a crucial constraint factor (Steffen 1999, 2000). Moreover, the chemical composition of obsidian that is different between provenances would be the constraint factor for the morphological variability, although tentative experiments showed there is no difference in the condition of generation of tiny cracks between two provenances of obsidian (Nakazawa 1998a).

Second is the issue of a mechanism that may constrain the generation processes of tiny cracks and bubbles. The results of these experiments strongly indicate that some sort of physical and chemical reactions on the surface of obsidian occur. In order to elucidate the essential causes constraining the generation of tiny cracks (type 1c), I observed the section and surface of artificially heated obsidian surface made by above experiments under the SEM. Application of the SEM to thermally altered surface of an 11 hour-heated specimen showed that the tiny cracks (type 1c) are apparently scattered and some circular spots also existed within the cracks (Photograph 11). At the section of same specimen, a part of tiny cracks intrudes into the obsidian at approximately 50 micrometers beneath its surface (Photograph 12). In comparison with the section of unheated specimen (Photograph 13), the surface with tiny cracks is severely modified. Specimens hated for 11 hours have the appearance of being melted at the very surface (Photograph 14). This indicates that the texture at quite shallow level beneath the surface of the specimen is probably eroded due to a chemical reaction under an extended duration.

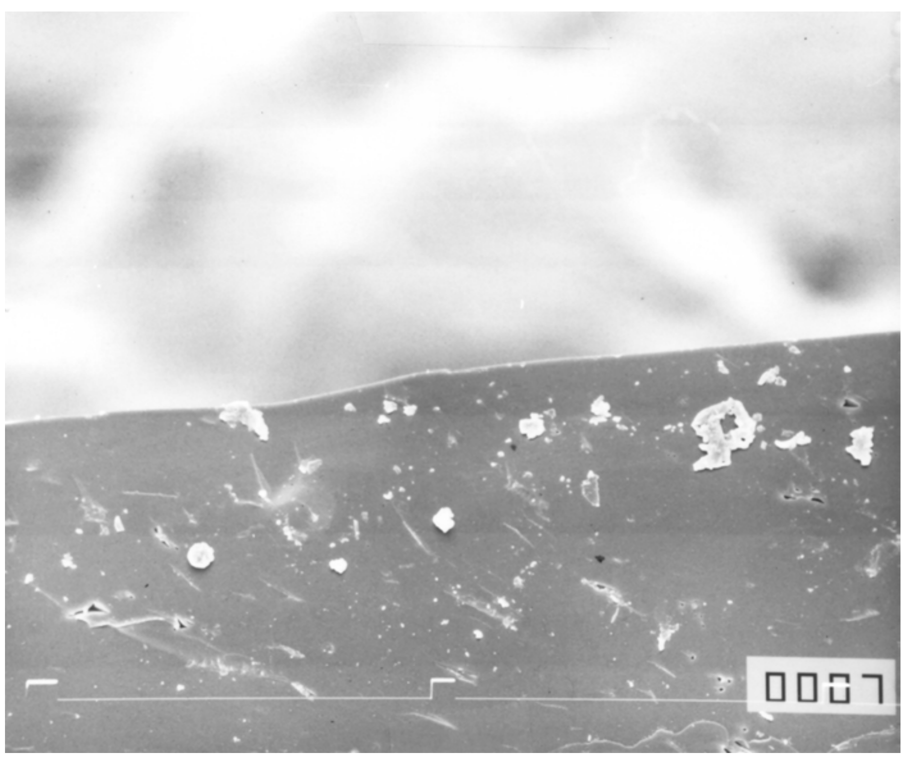


Photograph 11. SEM view of specimen heated 11 hours.

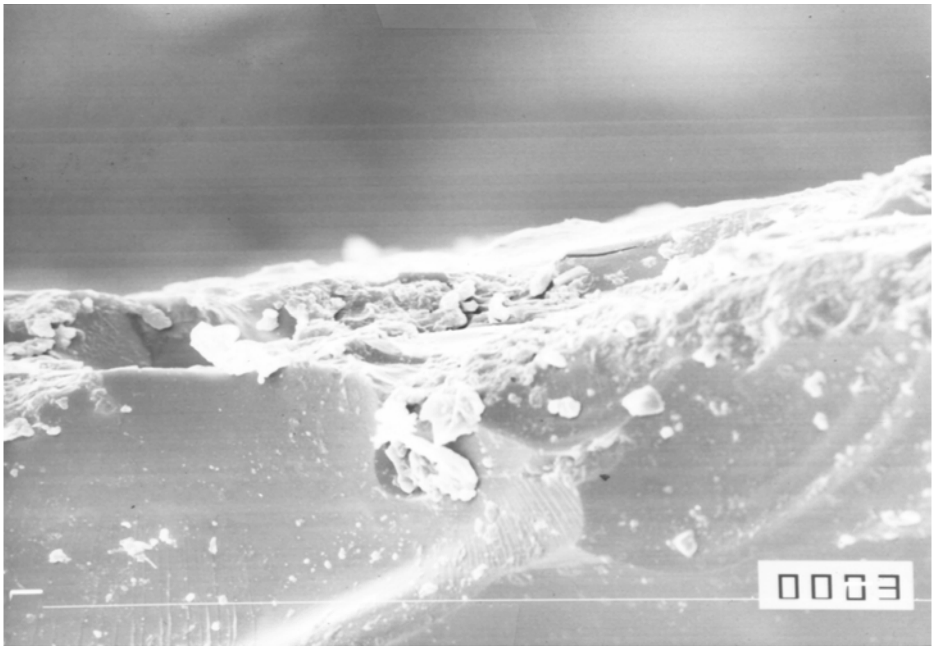
These observations at high resolution indicate that some sort of reciprocal actions occurred between the surface of the obsidian flake and the heated wood ash in the generation of tiny cracks (type 1c), considering the fact that no visible change has been identified in the part where the obsidian surface was exposed to the atmosphere on each specimen. In other words, this indicates that generation processes should be explained in terms of chemical reactions between two inorganic materials, which are obsidian and wood ash.



Photograph 12. Tiny cracks intruding approximately 50 micrometers beneath obsidian surface



Photograph 13. Section of unheated specimen.



Photograph 14. Specimen hated for 11 hours with melted appear at surface.

The tiny bubbles below the cracked surface implies that intrinsic water in obsidian is released with the generation of tiny cracks (cf. Steffen 1999, 2000). This leads to propose a model that explains the generation processes of tiny cracks and tiny bubbles. The generation processes proposed below is in terms of compositional structure of SiO_2. Obsidian as a glass is an amorphous solid and its structure is less stable than a crystal solid. When wood ash is applied to the surface of obsidian in a heated condition, hydroxyl (OH^-) may be released from Si-O glass network. This destruction of glass network may result in the release of volatile components that yield tiny bubbles. In addition to this process, it is expected that depolymerizing the SiO_2 structure of obsidian glass provokes the formation of tiny cracks (type 1c), due to volume expansion of intrinsic water (H_2O). Which chemical element(s) affect this process is still not completely understood. Referring to the silica fusion model in chert (Luedtke 1992), it is doubtless that fluxing ion(s) in wood ash may act as the trigger to release intrinsic H_2O (Nakazawa 1998a). It will be necessary to develop analytical methods to test this causal hypothesis.

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