



Chapter 4:

Fire Effects on Flaked Stone, Ground Stone, and Other Stone Artifacts

Although the action of fire upon building stones is well understood by engineers and insurance specialists, it is commonly supposed that its effect upon rocks in nature is only of minor consequence... on the contrary, fire is in some regions very important; and, under suitable conditions, it overshadows all the other factors [of weathering] combined (Eliot Blackwelder 1927).

Introduction

Lithic artifacts can be divided into two broad classes, flaked stone and ground stone, that overlap depending on the defining criteria. For this discussion, *flaked stone* is used to describe objects that cut, scrape, pierce, saw, hack, etch, drill, or perforate, and the debris (debitage) created when these items are manufactured. Objects made of flaked stone include projectile points, knives, drills, scrapers, planes, burins, graters, spokeshaves, choppers, saws, cores, flakes, fish hooks, hoes, and hand axes, among others. These were commonly made from chert, flint, chalcedony, petrified and opalized wood,

slate, siltsone, mudstone, quartz, quartzite, obsidian, basalt, metamorphic rocks, and vitrified and welded tuff.

Ground stone distinguishes items used to pound, mash, crack, pulverize, grind or abrade minerals or plant and animal products, and includes such objects as metates, millings, manos or handstones, pestles, portable mortars, abraders, hammerstones, mullers, polishing stones, and paint palletes. Ground stone was often fashioned of granite, diorite, gabbro, gneiss, basalt, andesite, rhyolite, greywacke, steatite, dolomite, limestone, slate, shale, sandstone, schist and quartzite, among other types of rock.

All other stone artifacts, including a wide range of ornamental and utilitarian items made from numerous material types, are grouped and discussed separately from flaked and ground stone.

Data and research potentials associated with flaked stone objects include information related to technology, subsistence, economic exchange, and site chronology. Obsidian, basalt, tuff and chert can be subjected to geochemical analysis to identify their geographic source of origin, thus yielding information on material acquisition, economic exchange and trade networks. Obsidian and chert artifacts can also

be dated, providing manufacturing and site occupation dates. The presence of particular artifact types or the selection and/or relative frequency of certain stone material types may reflect social stratification, or ethnic, linguistic, and tribal affiliations. Plant and animal residues on stone tools may yield information about tool function, food processing and consumption. It has also been speculated that some data resident in lithic artifacts may be useful in landscape reconstructions, fire histories, and determining past fuel loads.

Lithic Artifacts and Fire

Artifacts made of stone are generally the best preserved of all material types in the archaeological record, often providing the only evidence of where people lived and worked in the past. Despite its durability, stone can be affected by fire, as well as by efforts to suppress wildfires and to rehabilitate burned areas following fires.

Reported fire effects on stone artifacts include breakage, spalling, crenulating, crazing, potlidding, microfracturing, pitting, bubbling, bloating, smudging, discoloration, adhesions, altered hydration, altered protein residue, and weight and density loss. Surface artifacts tend to be altered more than those located in subsurface contexts, with protection often afforded by even a few centimeters of soil. Fewer negative effects are noted in light fuels, with increasing effects in moderately and heavily fueled fires, or at specific locations within fires where fuels are heavy, such as near or under logs. Most researchers suggest that effects in heavier fuels are a result of the increased amount of time artifacts are exposed to heat (see, for instance, Benson 2002; Buenger 2003; Deal 2002; Gaunt and others 1996; Linderman 1992). In general, the higher the temperature and the more severely charred the ground surface, the greater the reported effect.

Some Caveats

Despite the long list of effects that can occur to stone artifacts in fires, it should be noted that not all effects are adverse, nor does a single effect, even if adverse, necessarily limit the recovery of all data resident in the artifacts. For example, discoloration may hinder identification of material type, but have little impact on the recognition of artifact type or other macroscopic information, such as manufacturing technique. Likewise, few or no visible effects to artifacts may be present, but microscopic data associated with these objects, such as plant protein, blood residue or hydration rinds, may be altered or destroyed. Some effects can be both adverse and beneficial—for instance, the increased visibility afforded after fires can lead to vandalism and illegal collecting, although for archaeologists, this condition

often allows more accurate recording of site features and constituents (Biswell 1989; Blakensop and others 1999; Davis and others 1992b; Hester 1989; Likins, personal communication, 1999; Moskowitz 1998; Pilles 1982 and 1984; Racine and Racine 1979; Romme and others 1993; Silvermoon 1987; Switzer 1974).

Overall, relatively little is known or reported in the literature about thermal effects on most types of stone artifacts, primarily because most research has been conducted in the aftermath of wildfires. Without pre-fire information on the material affected, or collection of standardized data concerning the fire environment, fire history, fire behavior, temperature, burn intensity, or ground charring, no inferences may be made about fire-caused damage to artifacts. This lack of information makes it difficult to compare or meaningfully summarize effects. The data on effects that is available is heavily weighted to flaked stone, and primarily to obsidian and chert.

Another difficulty in assessing fire effects on stone tools results from reports lacking explicit descriptions of criteria used to measure effects. Many articles lacked methodology of both temperature collection and how specimens were heated, making it difficult to assess if reported temperatures could be comparable. Other reports clearly indicated techniques, but were lacking important fire related information, such as weather conditions and fuel type. Yet another problem is the variability of methods used to collect temperature data. Sayler and others (1989), and Picha and others (1991) used a suite of temperature sensitive crayons, which change color according to the maximum temperature. Some researchers have used temperature sensitive pellets, lacquers and pyrometric cones (Halford 2002; Kelly and Mayberry 1980; Solomon 2002) and others used no temperature measurement at all. Pellets, lacquers, and crayons generally provide few temperatures per measured plot, present no timeframe of when the maximum temperature was reached, or fire residence time within a site. Another problem with pellets is related to their placement and where the pellets should be placed to appropriately measure temperature affecting cultural materials. In Solomon (2002), pellets were placed below the artifact; whether the pellet measured the temperature of the artifact's underside, the heat flux surrounding the artifact or the soil surface temperature is unknown. In Bennett and Kunzmann (1985), the team heated artifacts in a muffle furnace, a controlled and consistent environment where temperature change is gradual. Several others (Biswell 1989; Hemry 1995; Solomon 1999) placed artifacts within a prescribed fire management area, where heating is rapid, uneven, and temporally variable. These researchers measured pre- and post-fire conditions of the pieces and the incongruence between studies was likely due to burn location, seasonal

weather patterns, fuel composition, and fuel loading differences. Buenger (2003) assessed effects using a combination of field-based and laboratory experimentation, combined with a sampling of burned-over archaeological sites. Buenger's prescribed burn experiments were conducted in a variety of fuel types, and his lab experiments were conducted by heating artifacts in a muffle furnace, and in wildland fire simulations within a large combustion chamber/wind tunnel. Buenger's wildland fire simulations, conducted at the USDA Rocky Mountain Research Station's Fire Sciences Laboratory in Missoula, Montana, are especially relevant, as he was able to simulate fires of variable intensities, while recording both time and temperature data, as well as heat flux data. In addition, Buenger placed thermocouples, set to record temperatures every second, on the upper and lower surfaces of artifacts in order to assess temperature differences on artifacts as they were burned over (2003). Buenger's study and others using thermocouples and data loggers indicate that this is at present the best method of temperature assessment. Temperatures are collected periodically during heating and provide maximum, average, and minimum temperatures and duration of heating. The collection of data is systematic and different studies may be compared to show variability of effects between sites and artifacts.

Even when the data collection criteria are stated, results can be misinterpreted. For instance, one widely referenced source (Bennett and Kunzmann 1985) states "severe alteration of inorganic materials is not to be expected at temperatures below 400 to 500 °C (752 to 932 °F)." This temperature range has been cited in training documents and prescribed burn plans as a critical temperature threshold below which few, if any, effects are expected. Bennett's and Kunzmann's (1985) primary criterion for determining effect was a change in weight, and they qualified their statement with "if [burned for] less than 1/2 hour." Reported "critical threshold temperatures" for inorganic materials vary widely, ranging from a relatively cool 200 °C (392 °F) (Silvermoon 1987), to 300 °C (572 °F) (Hemry 1995; Lissoway and Propper 1988), to 400 °C (752 °F) (Biswell 1989), to between 400 and 500 °C (752 to 932 °F) (Bennett and Kunzmann 1985), to 426 °C (800 °F) (Linderman 1992), to a hotter range of 500 to 600 °C (932 to 1112 °F) (Kelly 1981).

In addition to the wide range of temperatures reported, another problem with using the "critical temperature" approach is that it implies that temperature alone accounts for the effects, without consideration of other critical elements, such as heating methods, temperature measurement mechanisms, burning conditions, fuel loading, or residence time. In fact, if the duration of heat is extended, some effects can occur at dramatically lower temperatures, similar to those

occurring at more extreme temperatures in shorter periods of time.

Further, many reports cite the critical temperature threshold for effects without defining exactly what it is that is being critically altered. For instance, these reports often lump all lithic items together, and often without discussions of "artifact-stored information" (Bennett and Kunzmann 1985), such as obsidian hydration, pigments or protein residues. In these instances, effects statements are based on visual observations alone, without attempts to discern whether other data potentials have been affected. In addition, few studies have looked at the effects of slow versus rapid cooling.

Flaked Stone

Much of the research and available data on thermal effects on flaked stone has been categorized by toolstone type, with most research focused primarily on chert and obsidian.

Chert: Flint, Jasper, Chalcedony, and Related Silicates

Chert was sometimes deliberately heated during the prehistoric manufacture of tools in order to improve its flaking characteristics. Researchers have found that slowly heating chert can improve flaking characteristics and enhance workability. Replicative studies of heat-treating techniques have provided substantial data relating temperatures and duration of heating to changes in chert (Bleed and Meier 1980; Griffiths and others 1987; Luedtke 1992; Rick 1978). The temperature range that improves flaking characteristics for most chert is from 250 °C to 450 °C (482 °F to 842 °F) when heated and cooled slowly, with the length of exposure to heat varying from 30 minutes to as long as 72 hours (Luedtke 1992). Several researchers report similar effects from heating chert at lower temperatures for an extended period of time, or from heating at higher temperatures for a shorter amount of time (Griffiths and others 1987; Rick 1978). Chert has a temperature range below which there will be no improvement to flaking, no matter how long it is exposed to heat, and above which the chert becomes unworkable, probably due to impurities, water content, and grain size (Luedtke 1992). Compositionally dissimilar chert will react differently to heat.

The most obvious changes to heat-treated cherts are in color and internal luster. In areas where chert sources vary by visible characteristics such as color (see Luedtke 1992), external color change can make visual source determinations difficult or impossible (Perkins 1985), or lead to misidentification as another type of toolstone (Anderson and Origer 1997). Although not all cherts change color when heated, most will

change luster on the *interior*, often going unnoticed until a flake is removed after heat treatment. Temperatures at which color and luster are altered vary by chert source. Color changes have been noted between 240 °C (464 °F) and as high as 800 °C (1472 °F), and luster between 121 °C (249.8 °F) and 400 °C (752 °F) (Mandeville 1971; Perkins 1985; Picha and others 1991; Purdy 1974; Purdy and Brooks 1971).

Internal change in luster is often the best indication that artifacts have been thermally altered, although distinguishing between deliberate cultural heat treatment and the effects of fires can prove difficult (Luedtke 1992; Rogers and Francis 1988; Rondeau 1995). When heated, the external surfaces of cherts tend to become optically dull (that is, non-reflective of light). Bennett and Kunzmann (1985) found this occurred at temperatures of 600 °C to 800 °C (1112 °F to 1472 °F), whereas Buenger (2003) first noted this effect at 300 °C (572 °F). Perkins (1985) suggested the presence of lustrous and relict dull flake scars on the same piece is a good indication the object was deliberately heat-treated, and not subsequently altered in a fire. Complete artifacts displaying all optically dull surfaces, combined with potlidding and crazing, are likely to have been subjected to a post-manufacturing fire.

Chert from different sources will fracture at different temperatures, although most reportedly fracture between 350 °C and 550 °C (662 °F and 1022 °F) (Buenger 2003; Luedtke 1992; Purdy 1974; Rick 1978; Schindler and others 1982). At temperatures between 350 °C and 400 °C (662 °F and 752 °F), chert can become distorted or brittle in as little as 20 minutes (Luedtke 1992; Purdy 1974). Some chert will explode when raised to these temperatures rapidly, but not when temperatures are elevated slowly (Luedtke 1992; Purdy 1974). Impurities in chert can result in alterations at temperatures as low as 150 °C (302 °F), or as high as 650 °C (1202 °F), with recrystallization causing chert to coarsen, appear foliated, and take on a sugary appearance (Luedtke 1992).

Heating or cooling chert rapidly or unequally can cause fracturing and breakage from thermal shock (Buenger 2003; Luedtke 1992). Thin flakes are less susceptible than bulkier cores and cobbles to thermal shock (Bennett and Kunzmann 1985; Buenger 2003; Perkins 1985; Picha and others 1991). Once heated, rapidly cooled chert will break (Luedtke 1992). Fine-grained cherts become altered at lower temperatures and suffer more thermal shock than coarse-grained ones (Mandeville 1971). Chert protected from direct heat, even if insulated by as little as one to two centimeters of sand or other material, is less susceptible to thermal shock than unprotected pieces (Flenniken and Garrison 1975; Perkins 1985). Buenger found that chert nodules were prone to thermal fracturing

“when the upper surfaces are precipitously heated to approximately 550 °C [(1022 °F)] for 20 seconds, and when the temperature between the upper and lower surfaces approaches or exceeds 60 percent” (2003). After direct contact with flames, chert can become calcinated to the point of being easily crushed (Luedtke 1992; Weymouth and Williamson 1951).

Cherts altered in wildland and prescribed fires have suffered external color changes, patination, cracking, crenulated breaks, potlidding, fracturing, exploding, shattering, crazing, reddening, blackening, sooting, smudging, and vitrification (see fig. 4-1) (Ahler 1983; Bayer 1979; Benson 1999; Buenger 2003; Eisler and others 1978; Gaunt and others 1996; Katz 1999; Lentz and others 1996; Likins, personal communication, 1999; Lissoway and Propper 1998; Patterson 1995; Picha and others 1991; Tremaine and Jackson 1995). These modifications have occurred in low to high intensity fires of varying duration, temperature, and ground surface damage severities. In general, the longer and/or hotter fire burns, the greater the reported damage. Luedtke (1992) reports that the most common type of thermal damage to chert is fracture, either in blocky, angular chunks



Figure 4-1—Potlidding, crazing and cracking on chert thermally damaged during a heat-treatment replication experiment (sample courtesy of Rob Jackson).

with no bulbs of percussion, or more distinctively, in “pot lid” fractures, which are small, circular, convex fragments that have popped off flat surfaces (table 4-1).

Other data associated with chert artifacts can be extracted using laboratory techniques such as protein residue analysis, sourcing through macroscopic fossil content and trace element analysis, and dating via thermoluminescence (TL) or electron spin resonance (ESR) spectroscopy (Julig 1994; Luedtke 1992; Newman 1994). Fire impacts some artifacts to the point where these laboratory techniques cannot be used, or the data gathered using these techniques is suspect. TL and ESR spectroscopy have been used to determine if chert has been previously heated (Luedtke 1992; Melcher and Zimmerman 1977; Robins and others 1978). Unfortunately, we do not yet know at what temperature the ability to use these analytic techniques on chert from different sources are lost.

Obsidian

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 (Bowman and others 1973). Few studies analyzed whether fires affect the sourcing potential of obsidian, but several studies used X-ray fluorescence and were successful in obtaining source information from surface samples subject to intense fires (Davis and others 1992b; Keefe and others 1998; Skinner and others 1995, 1997; Steffen 2002; Tremaine and Jackson 1995). However, Shackley and Dillian (2002) reported potential problems with sourcing thermally altered obsidian artifacts, noting that bonding of melted sand to the obsidian surface could create sourcing errors. Steffen (2002) observed a slight increase in trace elemental values with heating, although none to the extent that sourcing was affected. Skinner and others (1997) noted problems using X-ray fluorescence on fire-affected obsidians that had a dark patina believed to be a silica-based encrustation.

Anderson and Origer (1997) reported the exterior surface of some obsidian was altered enough to make sourcing via macroscopic attributes difficult one year after a wildland fire.

The temperatures and duration of heating reported to affect obsidian varies widely. It has been suggested that some component of the fire environment (such as wood ash, soil chemistries, or soil moistures) may be contributing to observed changes (Deal 2002; Nakazawa 2002; Steffen 2002; Trembour 1979). Variation in heating within respective fires (chapter 2) may explain some of the differences in reported effects. Differences in water content in obsidian might be causing divergent heat effects (Steffen 2002). Some apparent inconsistencies may be due to observer technique, or the result of various source materials reacting differently to thermal environments because of unique chemical compositions (although Steffen 2002 documented variations in heat effects on obsidian from the same source).

Obsidian is thermally affected at varying temperatures and at differing lengths of exposure to heat. In field and lab fire experiments, obsidian has been reported to fracture, crack, craze, potlid, exfoliate, shatter, oxidize, pit, bubble, bloat, melt, become smudged, discolored, covered with residue, or rendered essentially unrecognizable (see fig. 4-2) (Anderson and Origer 1997; Bayer 1979; Buenger 2003; Davis and others 1992b; Deal 2002; Eisler and others 1978; Gaunt and Lentz 1996; Hull 1991; Johnson and Lippincott 1989; Kelly and Mayberry 1979; Lentz and others 1996; Likins, personal communication, 1999; Lissoway and Propper 1988; Nakazawa 1999, 2002; Origer 1996; Pilles 1984; Rogers and Francis 1988; Skinner and others 1997; Steffen 1999, 2002; Steffen and others 1997; Stevenson and others 1985; Traylor and others 1983; Trembour 1979). Buenger (2003) found that some of these effects could be produced when temperatures peaked between 500 and 600 °C (932 and 1112 °F) within 40 to 50 seconds, and when the temperatures were sustained within 100 °C (212 °F) for as little as 5 to 32 seconds. Steffen (2002)

Table 4-1—Some reported thermal effects on chert.

Temperature (°C)	Temperature (°F)	Effect ^a
150	302	Impurities may result in fractures
121 - 400	249.8 - 752	Change in interior luster
240 - 800	464 - 1472	Change in color on external surface
350 - 400	662 - 752	Becomes distorted, brittle, or explosive
350 - 550	662 - 1022	Fractures
600 - 800	1112 - 1472	Optical dulling of external surface

^a Note: Cherts from different sources react differently to heat. Some effects can occur at lower temperatures if duration of heat is long enough. Not all cherts change color or luster when heated. Temperatures for other effects summarized in text are unknown, or variable from Luedtke (1992).



Figure 4-2—Obsidian flake altered in a prescribed fire experiment displaying adhesions, smudging, and light surface pitting.

noted the need for a standardized set of definitions to describe heat effects to obsidian, and offered (in part) the following:

Matte finish: A dulling of the surface resembling weathering or a lusterless patina;

Surface sheen: A metallic-like luster, with a reported “gun-metal” sheen attributed to organic buildup on the surface of obsidian, and a “silvery, reflective” sheen attributed to shallow microscopic crazing and the formation of small bubbles;

Fine crazing: A delicate network of very shallow surface cracks (similar to, but contrasted with, the internal crazing observable on fire altered chert) that form a network of closed polygons, probably caused by differential thermal expansion and/or cooling;

Deep surface cracking: Shallow crevices splitting the surface, probably due to the continued expansion and stretching of finely-crazed surfaces;

Fire fracture: Fracture initiating from within the object, resembling deliberate reduction, but lacking bulbs of percussion, and often resulting in the complete fracture of the artifact;

Incipient bubbles: Individual bubbles developing below the surface; and

Vesiculation: Abundant, interconnected bubbles on the surface and interior resulting in the “puffing up” of thermally altered obsidian; in its extreme form, vesiculation can transform artifacts into a frothy, Styrofoam-like mass.

Sidebar 4-1—Stone Artifacts

Yellowstone Fires, Yellowstone National Park, 1988

References: Ayers (1988); Connor and Cannon (1991); Connor and others (1989); Davis and others (1992b)

General Information:

- Elevation: about 1,830 m (6003.9 ft) above sea level
- Vegetation: mostly forested areas of mixed lodgepole pine and Douglas Fir
- Topography: mountainous
- Type of study: post-burn assessment

Fire Description:

- Temperature range: 32.2 °C (90 °F)+ temperatures on June 24 and July 21, 25, 26, 30.
- Relative humidity: dry
- Fuel: high fuel load
- Type of fire: wildland (about 8 separate fires)
- Energy Release Component (ERC): July, August, and early September saw ratings of 22 and 23.
- Burning Index (BI): values in July and August reached 90-105

Discussion

In the summer of 1988, a series of wildfires burned approximately 6070 km² (1.5 million acres) of Yellowstone National Park and surrounding forestland. The high intensity wildfires created a mosaic burn pattern of severely burned areas and spots of land that had not been affected (Connor and Cannon 1991; Connor and others 1989).

After the Yellowstone fires, researchers from the Midwest Archeological Center of the National Park Service excavated archaeological sites in the burned area and assessed fire effects to the soil matrix (Connor and Cannon 1991; Connor and others 1989). Fire was found to have burned the surface layer of duff, leaving a 5-10 cm (2-3.9 in) thickness of burned material. The soil beneath this burned material was generally unaffected. The researchers also observed heavily oxidized soil beneath deadfall trees. They noted that similar lenses of burned and oxidized soil were found in the local archaeological record and interpreted as cultural features.

In 1989, Montana State University researchers, under a contract with the National Park Service, conducted fieldwork at Obsidian Cliff lithic procurement site (Davis and others 1992b). Two thirds of this lava flow had been burned severely during the 1988 fires. The researchers recorded information necessary to nominate the site as a National Historic Landmark, taking advantage of the increased ground visibility to record 59 obsidian procurement loci. The researchers observed site erosion caused by vegetation loss and noted that soil loss had caused trees to fall and upturn several cubic meters of sediment. They also described visual fire effects to obsidian and compared geochemical analyses of obsidian collected before and after the fire (Davis and others 1992b).

Minor vesiculation has been reported on obsidian heated for one hour to 700 °C (1292 °F) (Shackley and Dillian 2002). Obsidian has melted at 760 °C (1400 °F) (Trembour 1979), or suffered extreme vesiculation between 815 °C and 875 °C (1499 °F and 1607 °F) (Steffen 2001, 2002) to 1000 °C (1832 °F) (Buenger 2003) (figs. 4-3, 4-4). Extreme vesiculation has been



Figure 4-3—Bloated and melted obsidian, oven heated to 800 °C (1472 °F) (sample courtesy of Anastasia Steffen).

noted in a backfire, a prescribed fire, and a campfire (Steffen 2002). Some of the most severe fire effects have been noted at quarry sites and source areas, such as those reported from the Dome Fire in New Mexico (Steffen 1999, 2001, 2002).

Obsidian is particularly valued for its dating potential. Over time, freshly exposed surfaces on obsidian absorb atmospheric moisture, creating distinct hydration bands (Evans and Meggers 1960; Friedman and Smith 1960; Michels and Tsong 1980). After certain variables such as the obsidian source, soil moistures, soil pH, and temperatures have been accounted for, the thickness of the hydration band can indicate how long a surface on a piece of obsidian has been exposed to atmospheric moisture, offering a means for establishing prehistoric site chronologies and depositional integrity. A major factor influencing the integrity of hydration bands is elevated temperature, which forces resident moisture within the hydrated layer further into, as well as out of, the obsidian, creating wide, diffuse bands with unreadable or blurred margins (Jackson, personal communication 1997; Trembour 1979, 1990).

The percentage of obsidian with measurable bands recovered after wildland fires varies widely, from a low of only 9 percent to as high as 71 percent (Jackson and others 1994b; Pilles 1984; Skinner and others 1995, 1997; Trembour 1990). Obsidian located in lightly



Figure 4-4—On right: Extreme vesiculation in obsidian oven heated to 800 °C (1472 °F); sample also suffered severe weight and density loss. On left: Unheated obsidian from same source (samples courtesy of Anastasia Steffen).

fueled areas is more likely to retain hydration than those burned under moderate or heavy fuels (Benson 2002; Deal 2002; Green and others 1997; Linderman 1992; Origer 1996). Obsidian located on the ground surface is more likely to be altered, although Skinner and others (1997) reported that hydration was erased on obsidian at depths of 6 cm (2.4 in.) in one high intensity fire.

Preliminary results of lab and prescribed fire experiments indicate, even at very low temperatures, extended exposure to heat can alter hydration bands (Benson 2002; Deal 2002; Linderman 1992; Solomon 2002). Hydration bands can become too diffused to accurately measure after 2 hours at 200 °C (392 °F) and after 1 hour at 300 °C (572 °F) (Solomon 2002). Hydration bands have been erased completely after 12 hours at 200 °C (392 °F), and after 1 hour at 400 °C (752 °F) and 432 °C (809.6 °F) (Skinner and others 1997; Solomon 2002).

As part of a post-fire hydration study, Skinner with others (1997) conducted an experiment to determine heat effects to hydration on obsidian from a single source. Skinner and others (1997) used a single flake of obsidian cut into six pieces, with each piece heated for one hour at temperatures of 100 °C to 600 °C (212 °F to 1112 °F), in 100 °C (212 °F) increments. At 100 °C (212 °F), the hydration bands were still distinct. At 200 °C (392 °F), band width had increased slightly, but was still visible and measurable. At 300 °C (572 °F), the band was difficult to measure, due to diffuse and indistinct diffusion fronts. At 400 °C (752 °F), the diffusion front was gone and the band was not measurable, but a slight bluish tint marked where the band had been. At 500 °C and 600 °C (932 °F and 1112 °F), there was no sign of a hydration band. Skinner and others (1997) concluded, in dating obsidian, interpretation problems may occur in cases of lower temperature exposures when band width is not completely erased, and the hydration age may be misread indicating an artifact is older than it really is. Conversely, with high temperature exposures, the band may be read to date an artifact as younger than it is. Similar interpretive problems

have been reported by Trembour (1979, 1990) and Stevenson and others (1989b).

Steffen (2002) demonstrated that intact hydration could exist on portions of fire-affected obsidian artifacts where hydration was erased from other areas of the artifacts, when objects were partially buried during a fire, or various surfaces experienced differential exposure to intense heat. She suggests that better recognition of fire effects to obsidian could aid in selecting specific surfaces of artifacts on which to focus hydration analysis. For instance, Steffen (2002) notes that the surface of artifacts displaying crazing or vesiculation may have been exposed to heat sufficient to alter measurable hydration (table 4-2).

Since high temperatures and smoldering fires of extended duration can destroy hydration bands, Deal (2002) speculated that intact obsidian hydration data could be used as an indicator of the absence of fire or heavy fuel loads in past landscapes. Many areas of the continent bear evidence of past fire return intervals shorter than those expected from lightning (Abrams 2000; Agee 1993; Anderson 1993, 1999; Anderson and Moratto 1996; Barrett 1980; Barrett and Arno 1999; Blackburn and Anderson 1993; Bonnicksen 2000; Boyd 1999; DeVivo 1990; Hicks 2000; Johnson 1999; Kay 2000; Komarek 1968; Lewis 1973, 1980; MacLeery 1994; Pyne 1982; Olson 1995, 1999; Turner 1999; Van Lear and Waldrop 1989; Yarnell 1998). In landscapes with frequent, periodic fires, such as areas that Native Americans were managing with fire, fuels would have been reduced to the point that areas burned at fairly low temperatures with very restricted fire residence times (Deal 2002). When obsidian is found in these areas, the presence of numerous hydration readings from surface settings could help support fire history reconstructions based on ethnographic accounts of deliberate burning (Deal 2002). However, if further research indicates hydration is re-establishing relatively quickly on fire altered obsidian (see Anderson and Origer 1997), the potential to use obsidian hydration to date past fires or to indicate prior fuel conditions may be compromised.

Table 4-2—Thermally altered hydration bands on obsidian from a single source; subjected to varying temperatures for 1 hour (source: Skinner and others 1997).

Temperature °C	Temperature °F	Change to hydration band ^a
100	212	Band still distinct
200	392	Band width increased slightly, but still measurable
300	572	Band diffuse and difficult to read
400	752	Band no longer visible; faint blue tint present where band was
500+	932+	No sign of hydration band

^a Note: Changes in hydration bands can occur at lower temperatures if exposure time is long enough. For instance, hydration bands have been erased after heating for 12 hours at 200 °C (Solomon 2002).

Several researchers have suggested past fire events are discernible on obsidian through retained alterations such as surface crazing, bubbling, partial vesiculation, diffused hydration bands (Friedman and Trembour 1983; Steffen 2002), or re-established hydration bands (Green 1999; Linderman 1992; Trembour 1979, 1990). Some obsidian samples sent to labs for hydration studies display wide, unreadable, diffuse bands, with a second distinct, readable band retained on the surface of the sample (Jackson, personal communication 1997; Origer, personal communication 1997), suggesting that the bands may have rehydrated after fires. Labs usually note the presence of diffused bands, and provide a micron reading on the intact, thinner, secondary hydration band, if one is present (Jackson, personal communication 1997). This micron reading may prove to mark a past high intensity fire event, rather than a past cultural (manufacturing) event, as has often been assumed. If one could use data from rehydrated obsidian to determine a site had been previously subjected to a fire, this could help explain why other data (pigments, protein residues, organic material) were missing.

Steffen (2002) makes the intriguing suggestion that multiple hydration rim measurements from single specimens may provide the heat exposure history of the specimen, allowing for reconstructions of fire histories. Researchers in northeastern California are plotting the distribution of what are believed to be rehydrated Archaic points as an indicator of where fires may have occurred in the past, and are using this data to reconstruct landscape-level fire histories (Green 1999). Should it prove possible to secure dates for past fires from obsidian rehydration, these approaches could potentially extend fire history data well beyond the limit of several centuries reached when dating fires from tree cores.

Basalt

Lentz (1996a) noted sooting, potlidding, oxidation, reduction, crazing, luster changes, and adhesions on lithic material, including basalt that had been in a wildfire. Eisler and others (1978) found basalt to be covered with a shiny, smooth, tar-like, brittle residue, with basalt boulders fractured into angular chunks, possibly due to rapid cooling. Tremaine and Jackson (1995) reported thermal fractures on basalt bifaces. Tremaine and Jackson (1995) were able to secure sourcing information on basalts using X-ray fluorescence after a high intensity fire (see also Skinner and others 1995 for similar results from another moderate to severe wildland fire). Blood residue analysis has been successful on basalt artifacts burnt at high intensities (Newman 1994; Tremaine and Jackson 1995). Pillis (1984) noted that thermoluminescence dates from basalt could be as much as 24 percent more

recent than expected, due to fires (see also Rowlett and Johannessen 1990).

In lab experiments, Blackwelder (1927) reported 12 periods of rapid heating and cooling of a small piece of basalt resulted in no effects, although a similar piece, heated to 300 °C (572 °F) showing no visible effects, fractured after being rapidly cooled in cold water only twice. Another specimen was heated to 300 °C (572 °F) for 30 minutes with no visible changes, but when the temperature was raised to 325 °C (617 °F), the basalt lost “a few thin flakes... from the sides” (Blackwelder 1927). After heating basalt pieces to 375 °C (707 °F) for 30 minutes, a fourth sample “broke violently into a considerable number of pieces while still in the oven” (Blackwelder 1927). A block of basalt (presumably a cube about 7.6 cm (3 in) to a side) was heated to 150 °C (302 °F), with no visible changes. The temperature was then raised to 400 °C (752 °F), and after 10 minutes, flakes began to spall off, continuing “until the block was almost wholly reduced to fragments.” Another 7.6 cm (3 in) basalt cube was placed in a furnace at 600 °C (1112 °F), resulting in “small scales” breaking off after 3 minutes, and continuing for another 10 minutes (Blackwelder 1927). Blackwelder’s experiments suggest that basalt may be extremely susceptible to thermal damage in fires.

Quartz, Quartzite, Mudstone, Rhyolite, Siltstone, Slate, and Vitrified and Welded Tuff

Very little data is available on other kinds of tool-stone. Quartz is an excellent thermal conductor and expands first in one direction, then another, which adds stress to the rock and leads to fractures (Luedke 1992). Thermal expansion in quartz crystals, compared as a percent increase from the volume recorded at 20 °C (68 °F), is noted as a 0.36 percent increase at 100 °C (212 °F), 0.78 percent at 200 °C (392 °F), 1.9 percent at 400 °C (752 °F) and 4.5 percent at 600 °C (1112 °F) (Dane 1942). Quartz undergoes changes in crystalline structure at 573 °C (1064 °F), and liquifies beyond the range of temperatures experienced in wildland fires, at 1723 °C (3133.4 °F) (Luedtke 1992). In lab experiments, Bennett and Kunzmann (1987) detected no weight loss to cryptocrystalline quartz at temperatures of less than 500 °C (932 °F), and Purdy (1974) found only 0.01 percent weight loss in a quartz crystal after 24 hours at 350 °C (662 °F). In areas with moderate to severe ground charring within one fire in the Sierra Nevada Mountains, milky and crystalline quartz was often covered with a black, shiny residue on all surfaces except those in contact with the ground, making it extremely difficult to identify material type during post-fire archaeological investigations (Deal 1995, 2001; Tremaine and Jackson 1995). In less severe cases, quartz was blackened and discolored.

Lentz (1996a) reported wildland fire effects (sooting, potlidding, oxidation, reduction, crazing, luster changes, and adhesions) to several different toolstone materials, including rhyolite, quartz, and quartzite sandstone. Most of these effects occurred on sites that experienced moderate and heavy charring. Fracturing, spalling, sooting, discoloration or oxidation has been reported on mudstone, quartzite, rhyolite and vitric tuff (Buenger 2003; Deal 1995; Hemry 1995; Lentz and others 1996). Surface-collected vitric tuff artifacts from a high intensity fire were successfully sourced using X-ray fluorescence (Jackson and others 1994b), and were found to retain immunological data in the form of protein residues (Newman 1994).

Ground Stone

As discussed in the introduction, ground stone objects were used to pound, mash, crack, pulverize, grind or abrade minerals or plant and animal products. Little information regarding thermal effects to ground stone artifacts or the effects of fire on use-wear patterns is available in the literature (Adams 2002), although field observations and experiments indicate that objects manufactured of different materials will react differently to heating and cooling. For instance, Pilles (1984) reported sandstone manos that were severely cracked in wildfires, where basalt manos were only blackened. Lentz (1996) indicated that all five metates in a wildfire were affected by sooting, spalling, discoloration and/or adhesions, but the single mano was not altered. Portable mortars were rendered nearly unrecognizable due to extreme fracturing in one severe wildfire (Likins, personal communication, 1999), and in another, trough metates were broken in half (Jones and Euler 1986). Effects noted to pestles have included spalling, and blackening and discoloration to the point of obscuring material type identification (Deal 1995, 2001; Foster 1980; Tremaine and Jackson 1995). See figures 4-5 and 4-6 for illustrations of a



Figure 4-5—Granitic mano partially buried in soil within an area of intense ground charring from a wildland fire. Upper portion of mano is covered with a black, baked-on residue.

fire-affected mano and millingsone. Buenger's experiments showed sandstone blocks exhibiting color change and minor surface spalling at 200 °C (392 °F), with spalling becoming more extensive in the 400 to 500 °C (752 to 932 °F) temperature range (2003).

Outcrops and boulders containing mortars and milling features have been blackened, sooted, cracked, spalled, and exfoliated as a result of wildland fires (figs. 4-7, 4-8, 4-9) (Deal 1995, 2001). High fuel loading around boulders and rock walls has been reported to



Figure 4-6—Millingsone altered in a wildland fire; note discolored areas and potlidded milling surface.



Figure 4-7—White granitic bedrock mortar outcrop showing discoloration and spalling following a wildland fire. Spalling can be severe at rock outcrops where the fuels are heavy and allowed to radiate heat for extended lengths of time. This is graphically illustrated by the damage underneath the 24-inch dbh ponderosa pine that fell and smoldered on this bedrock mortar outcrop.



Figure 4-8—Note that the burning in the thicker butt-end of the log shown in figure 4-7 caused the most damage.

contribute to extensive damage (Blakensop and others 1999; Hester 1989). In one fire, major impacts on mortar outcrops resulted in the exfoliation of large sheets of rock from the intense heat (Deal 1995). Blackening of mortar rock outcrops often hampered positive identification of the material type, although soil in mortar cups protected the grinding features from damage (Deal 1995, 2001). Additional effects expected at bedrock milling features would probably be similar to those reported elsewhere for boulders and cliff faces (Blakensop and others 1999; Eisler and others 1978; Gaunt and others 1996; Hester 1989; Johnson and Lippincott 1989; Noxon and Marcus 1983; Roger 1999; Romme and others 1993; Switzer 1974). Rock faces at petroglyph and pictograph panels can also be extensively damaged by spalling in fires. Removing fuels near rock outcrops and rock art panels can help limit these types of effects.



Figure 4-9—(a) Heavy brush (manzanita) growing at the base of this granite face resulted in severe localized spalling. (b) Spalled fragments remaining attached to this granite face were easily removed by the touch of a finger.

Thermal shock, reportedly from as little heat as that generated by sunlight, and particularly when coupled with the freezing of water in cracks and pores of rock, can lead to fracturing, exfoliating and degrading of granite, basalt and limestone (Schiffer 1987). Based on field observations and experiments, Blackwelder (1927) concluded that in many forested areas of the western United States, fire was the primary agent of fracturing, spalling, and weathering in boulders and rock outcrops, rather than diurnal changes in temperature. Blackwelder defined fire weathering features at boulders and outcrops as resembling curved wedges, plates or scales, 1 to 5 cm (0.4-2 in) thick, which often taper to a thin edge (1927). Based on experiments, Blackwelder (1927) reported many igneous rocks (basalt, andesite, porphyry) will withstand rapid heating and cooling up to 200 °C (392 °F) without any damage, but will begin breaking and fracturing when cooled after being heated to higher temperatures, while granites and quartzites tolerate slow temperature changes to as high as 800 °C (1472 °F).

Pollen, phytoliths, starches, ochre and other pigments, and protein residues from plants and the blood of small mammals have been detected on ground stone (Johnson 1993; Mikkelsen 1985; Traylor and others 1983; Yohe and others 1991). These remains can be used to infer tool function, as well as the time of year a site was occupied. Fire and fire retardant can be expected to negatively impact these data types, although Tremaine and Jackson (1995) retrieved a granitic handstone from the surface of a severely burned site that yielded positive residue reactions for cat and acorn. Several other ground stone objects from this fire tested positive for acorn, deer, and rabbit (Newman 1994). Animal proteins can survive temperatures to at least 800 °C (1472 °F) (Thoms 1995). Pollen is destroyed at temperatures over 300 °C (572 °F) (see Lentz and others 1996; Romme and others 1993; Timmons 1996).

Thermal Effects on Rock Used as Heating or Cooking Stones

Stone slabs were sometimes placed over fires or hearths and used for cooking. The slabs were often shaped, and sometimes prepared by the application of oil onto the cooking surface (Adams 2002). With use, cooking slabs became oxidized and blackened; with repeated heating and cooling, some slabs became friable and sloughed off on the underside (Adams 2002). Adams (2002) reports that the oil-saturated surfaces are sometimes the only part of these cooking stones recovered in archaeological sites. Stone pot rests used to support cooking vessels in fires and hearths also became blackened and fractured from heat (Adams 2002).

Occasionally, ground stone was used as cooking stones in stone-boiling, which often led to discoloring, cracking or fracturing (although some pieces may have already been broken and only served a second career as a cooking stone; Johnson 1993). Conditions for stone-boiling are similar to burning situations in wildland or prescribed fires where fuels are heavy, the duration of heat is extended, and cold water, foam or retardant is dropped on heated stone. Post-fire studies in Mesa Verde National Park (Corbeil 2002) have shown that surfaces on porous rock like sandstone are vulnerable to damage from retardant and gel; phosphates in retardant can penetrate the rock and crystallize, turning the surface into a fine powder, and gel can dry and peel grains off of rock surfaces. In addition, retardant and gel entrap or absorb water, which can contribute to spalling. Distinguishing stone that has been fractured by wildland or prescribed fires from those previously fractured during stone-boiling or cooking hearths has proved problematic (Lentz and others 1996; Tremaine and Jackson 1995). Several researchers have suggested ways to differentiate between cultural heating and natural burning based on fracture patterns, location within particular fuel loading situations, analysis of organic residue, or luminescence analysis of mineral constituents (Hemry 1995; Kritzer 1995; Picha and others 1991; Rapp and others 1999; Seabloom and others 1991).

Experiments with rock types used in stone-boiling, roasting and oven pits, hearths, and sweat lodges have produced information concerning how various stone behaves when subjected to heat (Brink and others 1986; Kritzer 1995; McDowell-Loudan 1983; Pierce 1983, 1984; Wilson and DeLyria 1999;). Topping (1999) found that granitic rocks used to line fire pits “cracked along the axis parallel to the fire,” while those embedded in the soil did not crack. Of the rocks that cracked, those with multiple breaks were “subjected to the most violent temperature shock,” whereas those “subjected to the least amount of temperature shock” were only cracked roughly “in half” (1999). Blackwelder (1927) reported that a 2.7 kg (6 lbs) cobble of andesite, rapidly heated to 200 °C (392 °F) in an electric furnace, then rapidly cooled nine separate times, suffered no visible effects. A greywacke river pebble 7.6 cm (3 in) thick had “thin slabs split off along almost imperceptible planes of stratification” while still in the oven at 350 °C (662 °F) (Blackwelder 1927). Heating a piece of fine-grained granite slowly for 2 hours to a temperature of 880 °C (1616 °F), and then cooling it slowly for 10 hours, resulted in a darkening of its pink shade, and a single small crack on the surface (Blackwelder 1927).

Wilson and DeLyria (1999) determined that andesite and basalt rocks were more durable than quartzite in replicative studies with camas ovens/roasting pits.

During three successive firings, several rocks exploded within the first hour at temperatures between 150 °C and 425 °C (302 °F and 797 °F). Most damage to the rock occurred during the initial firing, with each successive firing resulting in additional damage. Rocks in the oven were fractured by spalling off thin flat potlids, or by breaking into blocky chunks, with block breakage more common to quartzite than to igneous rocks, probably due to bedding planes in quartzite.

How certain rock reacted to different rates of heating and cooling was undoubtedly well known by people in the past, as particular types of stone were selected for different thermal applications. Pierce (1983, 1984) found that quartzite cooking stones heated quickly, boiled water quickly, fractured often when heated, but rarely fractured when placed in water. Sandstone also heated rapidly, did not fracture when heated, but “became so friable that large quantities of sand were dislodged from the exterior of the stone” (Pierce 1983), and the more often sandstone was heated, the more it crumbled. Vesicular basalt took longer to heat, requiring twice the fuel of either quartzite or sandstone, but retained heat longer than either stone (Pierce 1984). Basalt tended to fracture when heated, more often than when cooled rapidly. Due to these different capacities for the storage and transfer of heat, as well as the friability of various rock types when heated, Pierce concluded that certain stones would more likely be selected for stone-boiling foods, while others, such as sandstone, were more suitable for hearth stones (1983).

Other Stone Artifacts

Vessels, cooking pots, lamps, clubs, atlatl weights, net weights, loom weights, digging stick weights, pump drill weights, plummet, bolas, pipes, gamestones, chunky stones, charmstones, pendants, ornaments, balls, beads, earspools, lip plugs, rings, bracelets, gorgets and effigy figurines are found in various archaeological contexts throughout North America. Relatively little research has been conducted on thermal effects on these objects, although it can be expected that they would be affected much like ground stone, as they were often fashioned of the same materials. In addition, plant, animal and mineral residues on any of these could be affected by fire.

Some additional stone material types used to make the above objects include agate, alabaster, aragonite, argillite, azurite, calcite, catlinite, chalk, fluorite, galena, gypsum, hematite, jasper, jade, kaolinite, magnesite, malachite, selenite, serpentine, slate, steatite and turquoise. Of these, agate and jasper, which are varieties of chert, can be expected to react to fires in the same manner described previously for chert. Steatite can be heated to high temperatures; it stores heat and

releases it slowly, making it a good choice for cooking stones and cooking vessels. Steatite has been successfully sourced using instrumental neutron activation analysis (Truncer and others 1998), the accuracy of which might be impacted by high temperature fires. Catlinite, kaolinite, and chalk, used to make pipes or cooking vessels, have limited effects at low temperatures, often only discoloring and hardening. Little is known about the effects of fire on artifacts made of the other material types, although physical constants have been recorded for some with respect to thermal expansion, density at high temperatures, thermal conductivity and diffusivity, weight loss from heating, melting and transformation temperatures, heat fusion, and heat capacity (Birch and others 1942; Dane 1942). Some of these materials turn color when heated. For instance, azurite and malachite turn black when heated, slate often whitens, gypsum becomes cloudy and opaque, magnesite turns a pinkish-brown or cream color (and was deliberately heated in the past to make beads more colorful), and turquoise turns white (Miles 1963; Mottana and others 1977). Magnesite bubbles and releases gases prior to decomposing at 1000 °C (1832 °F), and calcite “dissociates” at 1000 °C (1832 °F) (Mottana and others 1977).

Coal is a sedimentary rock, vulnerable to fire and readily combustible. In some areas in the past, coal was ground and polished into a variety of shapes including bear teeth, elk teeth, bird heads, bird claws, animal effigies, gorgets, beads, ornaments, pendants and discoids (Cowin 1999; Fogelman 1991; Fundaburk and Foreman 1957; Graybill 1981; Griffin 1966; Redmond and McCullough 1996; Turnbow 1992). Cannel coal is highly volatile, ignites easily, burns with a luminous flame, and was once used as a substitute for candles (Bates and Jackson 1984; Yarnell 1998). Lignite, a soft brownish-black coal that becomes pasty when heated, and jet, a dense, black lignite that can be highly polished, were used as inlay on shell (Miles 1963), or made into animal forms. In the ground, coal veins ignited during wildfires can smolder for years after ignition (Wettstaed and LaPoint 1990), and several coal mines have been burning for more than a century (Maclean 1999; Pyne 1997).

Minerals such as mica and copper were also used prehistorically. Sheet mica was cut and crafted into spectacular shapes, such as bird talons, serpents, hands and bear claws, and was overlain decoratively on a variety of ornaments (Jennings 1974; Prufer 1964; Peschken 1998). Some mica objects were decorated with incising and painting; fire can smudge and destroy pigments on these delicate objects. When heated, mica loses water, becoming more friable and less flexible. Although little else is known about fire effects to mica, the thermal expansion of muscovite mica has been measured at increasing temperatures. Compared to its

size at 20 °C (68 °F), it expands 0.03 percent at 100 °C (212 °F), with expansion to 0.15 percent at 200 °C (392 °F); 0.37 percent at 400 °C (752 °F); 0.66 percent at 600 °C (1112 °F); 1.3 percent at 800 °C (1472 °F); and 1.55 percent at 1000 °C (1832 °F) (Dane 1942). Expansion can lead to exfoliation of mica.

Native copper melts at 1082 °C (1979.6 °F) (Mottana and others 1977). Copper was quarried prehistorically, and in some regions, fire and cold water may have been used to separate copper from the surrounding rock overburden (Quimby 1960), after which it was cold-worked and heated prior to shaping (Farquhar and others 1998; Jennings 1974). Copper nuggets were hammered into thin sheets, which were beaten together to make thicker objects, and shaped by abrading (Lewis and Kneberg 1958) into awls, punches, chisels, flakers, harpoons, spear points, knives, adze bits, panpipes, bells, plaques, rings, effigies, breastplates, beads, ear spools, headdresses and hair ornaments. Copper was also used to overlay wooden and shell objects such as gorgets, pendants and ear spools. Thin sheets were sometimes embossed by pressing the copper over a carved wooden die, painted, or decorated with feathers or fabric (Burroughs 1998; Fundaburk and Foreman 1957; Lewis and Kneberg 1958; Prufer 1964). Fire can be expected to distort, obscure or destroy decorative elements on copper.

Corrosion and oxidation often provide a protective surface on copper at archaeological sites, unless heating cracks the corrosive film and allows it to grow inward (Schiffer 1987). As temperatures increase, corrosion rates increase, with wood ash accelerating corrosion (Schiffer 1987). Copper used in modern applications discolors with a dark red or black oxide that thickens under higher heating conditions and with longer heat exposures (NFPA 1998). Prior to melting, copper blisters, exhibits surface distortions, and forms blobs and drops on its surface (NFPA 1998). After melting, the copper re-solidifies, forming irregularly shaped and sized globules that are often tapered or pointed (NFPA 1998). Several techniques have recently been used to source copper, including neutron activation (Julig and others 1992), X-ray fluorescence (Wager and others 1998), and thermal ionization mass spectrometry (Woodhead and others 1998). It is probable that fire would affect the accuracy of these analytical techniques.

Native American objects made with smelting and casting techniques adopted from French, English, and Spanish colonists include lead, pewter and brass pipes; silver bow guards and other silver work; and steatite and catlinite pipes inlaid with pewter and lead. These would be thermally altered in fires in the same manner as materials described in the chapter on historic artifacts (chapter 6). These objects date from the late 1600s through the present (Furst and Furst 1982).

Implications for Cultural Resource Protection and Fire Planning

The key factors that seem to affect the nature and extent of fire damage to archaeological resources, including lithic artifacts, are fire intensity, duration of heat, and penetration of heat into soil (Traylor and others 1983). Research shows that as temperatures increase, so do effects, and that effects increase as the length of time exposed to heat increases; if exposure time is long enough, effects can occur to stone tools even at reduced temperatures. Buenger's fire simulations show that the two most important components of the fire environment resulting in thermal effects to surface artifacts are fuel loads and wind velocity (2003). Increased fuel loads offer longer heating times, and increasing winds bend the flames closer to the ground where surface artifacts are located. Insulation from heat, even with a few centimeters of soil or incompletely consumed fuel, is often adequate in reducing impacts (Anderson and Origer 1997; Buenger 2003; Lissoway and Propper 1988; Picha and others 1991; Pilles 1984; Seabloom and others 1991). The mass of lithic artifacts is another factor determining the nature of thermal effects. More massive artifacts are more susceptible to fracture from thermal shock than thin ones, due to uneven heating and cooling (Bennett and Kunzmann 1985; Luedtke 1992; Perkins 1985).

Surface artifacts generally suffer the most damage in fires, although many will often retain data potentials, even on sites burned numerous times in the past, or that have recently been subjected to wildfires or prescribed burns. Some lithic and ground stone scatters, as well as other types of archaeological sites, are strictly limited to surface contexts, due to shallow soils or depositional history. These sites are obviously more threatened by fire than those with deep subsurface deposits. Since even shallow soils offer some protection to artifacts, one can conclude that subsurface materials will generally retain the most data potential following wildfires. However, the surface of a site at any given point in time can change as a result of numerous agents, including deflation, erosion, deposition, windthrown trees, animal burrowing and human activities. These alterations in site stratigraphy are often not obvious, even when the site is excavated. In areas of the country where bioturbation and windthrown trees commonly mix soil deposits, the material on the surface has often been found to reflect the full temporal range of site occupation, providing a snapshot of the site's chronology (Jackson 1999; Jackson and others 1994a).

Prescribed burning will result in some predictable loss of various types of data associated with stone artifacts. Losses can be anticipated to be the greatest for prescribed burns planned in areas that have not had prior fuels management projects. However, if

fuels can be reduced on sites prior to burning—either through hand removal of downed fuels or hand thinning (Siefkin 2002), or by mechanical means when appropriate (see Jackson 1993; Jackson and others 1994a)—data loss will be reduced. Collecting surface samples prior to burning would secure the data possibly impacted by the prescribed burn. However, in many areas, fuels are now so dense that the presence and nature of surface artifactual materials are unknown. Burn prescriptions can also be designed to reduce potential effects. For example, a head fire might cause fewer effects to artifactual materials on the ground surface than a cooler, slower-moving backing fire, due to the increased fire residence time of the latter (Smith 2002).

Since fire suppression and exclusion began, many areas of the country have lost numerous fire cycles. These lost fire cycles represent a tremendous fuel buildup, with a resultant increase in fire intensity, burn times, and fire severity (USDA 1995), and increased threats to cultural resources (Benson 1999; Blakensop and others 1999; Gaunt and others 1996; Hester 1989; Kelly 1981; Kelly and Mayberry 1980; Lentz and others 1996; Lissoway and Propper 1988; Pilles 1984; Siefkin 2002; Wettstaed and LaPoint

1990). Since fire suppression activities usually result in the greatest disturbance and data loss on sites, it is imperative that we work toward removing fuels proactively to reduce these effects. It is ironic that in many cases, and for several artifact classes including stone tools, frequent past burning may have helped preserve certain types of data resident in artifacts, while today's wildland fires and prescribed burns are impacting and destroying the same data, because of higher fuel loading.

Future studies need to explicitly state what criteria are being used to determine effects, and what is not being analyzed. Attempts should be made to standardize data related to effects, including fire environment and fire severity, as well as alterations to artifacts. Prescribed fire experiments need more stringent methods for monitoring and reporting burn temperatures, relative humidities, fuel and soil moistures, fuel loading, fire intensity, fire severity, ground charring, and the length of time that various surface and buried artifacts are subject to heat. Effects that now appear inconsistent or contradictory might be found to align more closely, if we can understand how the variables present in the fire environment affect lithic artifacts and other cultural resources.