FIRE EFFECTS TO LITHIC ARTIFACTS

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INTRODUCTION

Lithic artifacts can be divided into broad classes, which overlap somewhat 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, gravers, 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, millingstones, manos, 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, are grouped separately from flaked and ground stone.

Scientific Values Associated with Lithic Artifacts

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, thus yielding information on material acquisiton, 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 flaked stone may yield information about tool function, and food processing and consumption. Some data resident in lithic artifacts may be useful in landscape reconstructions, fire histories and in 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 fires and to rehabilitate burnt areas following fires.

Fire suppression activities, rehabilitation activities, and recovery efforts affect lithic artifacts as they do other artifacts. Fireline and helispot construction can displace or break individual artifacts or lead to the complete destruction of lithic and ground stone scatters. Retardant, foam and water may cause stone artifacts to fracture, spall or potlid from rapid cooling. Retardant may corrode and contaminate some artifacts, particularly those of porous stone. Mop-up activities, such as digging out smoldering roots and stumps, and rehabilitation activities such as replanting, may displace and break artifacts. Long-term impacts include loss of provenience data due to landslides, erosion, wind movement of artifacts, deflation, blowdowns, burnt out stumpholes, frost heave and torrential downpours, which can wash artifacts into clusters resembling prehistoric work areas. These types of effects can make preservation and interpretation of archaeological resources exceedingly difficult.

Overall, relatively little is known or reported in the literature about thermal effects to 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 without collection of standardized data concerning the fire environment, fire history, fire behavior, temperature, burn intensity, or ground charring. This lack of information makes it difficult to compare or meaningfully summarize effects. The effects data that *is* available is heavily weighted to flaked stone (primarily to obsidian and chert). Reported fire effects to stone artifacts include breakage, spalling, crenulating, crazing, potlidding, pitting, microfracturing, bubbling, bloating, baking, smudging, discoloration, the addition of 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 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 1999; Gaunt et al. 1996; Linderman 1992; Deal 1999, 1999b). 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 the 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 associated macroscopic information, such as manufacturing technique. Likewise, few or no visible effects to artifacts may be present, but other microscopic data associated with these objects, such as plant protein, blood residue or hydration rinds, may be altered or destroyed. Some fire 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 (Blakensop et al.1999; Biswell 1989; Davis et al. 1992; Hester 1989; Likins 1999; Moskowitz 1998; Pilles 1982 and 1984; Racine and Racine 1979; Romme et al. 1993; Silvermoon 1987; Switzer 1974).

Another difficulty in assessing effects of fire to stone tools results from the fact that most reports lack explicit descriptions of the criteria used to measure effects. Even when the criteria are stated, results are frequently cited by others in misleading ways. For instance, one widely referenced source (Bennett and Kunzman 1985:1) states that "severe alteration of inorganic materials is not to be expected at temperatures below 400-500°C " (752-932°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, despite the fact that Bennett and Kunzman's 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 392°F (Silvermoon 1987), to 572°F (Hemry 1995:7; Lissoway and Propper 1988), to 752°F (Biswell 1989:220), to 752-932°F (Bennett and Kunzman 1985), to 800°F (Linderman 1992), to the more generous 932-1112°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 time. In fact, time and temperature seem to be inversely related for many types of effects: if the duration of heat is long enough, effects will occur at dramatically lower temperatures, similar to those which occur at more extreme temperatures in much 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 citations often lump all lithic items together, and often without discussions of "artifact-stored information" (Bennett and Kunzman 1985), such as obsidian hydration, pigments or protein residues. In these instances, effects statements are sometimes 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 to flaked stone has been segmented by toolstone type, with most research focused primarily on chert and obsidian.

Chert (including flint, jasper, chalcedony, and related silicates)

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 (Bayer 1979; Benson 1999; Eisler et al. 1978; Gaunt et al. 1996; Katz 1999; Lentz 1996a; Likins 1999; Lissoway and Propper 1998; Picha et al. 1991; Tremaine and Jackson 1995). These modifications have occurred in low to high intensity fires of varying duration, temperature, and severity of damage to the ground surface. In general, the longer and/or hotter the fire, the greater the reported damage.

Unequal or rapid heating and cooling of chert causes fracturing and breakage from thermal shock (Luedtke 1992:91-92), with thin flakes less susceptible than bulkier cores and cobbles (Bennett and Kunzman 1985:14; Picha et al. 1991; Perkins 1985:25). Fine-grained cherts become altered at lower temperatures and suffer more thermal shock than coarse-grained ones (Mandeville 1971:41). Chert protected from direct heat, even if insulated by as little as 1-2cm of sand or other material, is generally less susceptible to thermal shock than unprotected pieces (cf. Perkins 1985:21-22; Flenniken and Garrison 1975:127). After direct contact with flames some chert will become calcinated to the point of being easily crushed (Weymouth and Williamson 1951).

Chert from different sources fracture at different temperatures, although most reportedly fracture within a fairly tight range of 662°F to 770°F (Luedtke 1992:91-92; Purdy 1974; Rick 1978), and others not until 990°F is reached (Schindler et al. 1982:528). At temperatures between 662°F and 752°F, chert can become distorted, brittle and explosive in as little as 20 minutes (Luedtke 1992:97). Some chert will explode if raised to these temperatures rapidly, but not when temperatures are elevated slowly (Purdy 1974:41-42; Luedtke 1992:91-92). Impurities in chert can result in alterations at temperatures as low as 302°F, or as high as 1202°F, with recrystallization causing the material to coarsen, appear foliated, and take on a sugary appearance (Luedtke 1992:27).

Chert was often deliberately heated during the manufacture of tools. Replicative studies of possible heat-treating techniques have provided substantial data applicable to thermal effects in fires (Bleed and Meier 1980; Rich 1978; Griffiths et al. 1987; Luedtke 1992). Each chert has a temperature range below which there will be no improvements 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 (cf. 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 (Rich 1978; Griffiths et al. 1987). The temperature range that improves flaking characteristics for most chert is from 482°F and 842°F, with the length of exposure to heat varying from 30 minutes to as long as 72 hours (Luedtke 1992:92).

The most obvious changes to heat-treated cherts are in color and internal luster. External color change can make visual source determinations difficult or impossible (Perkins 1985:26), 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*, a change that is not visible until a flake is removed after heat treatment. Temperatures at which color and luster are altered vary by chert source, with color changes noted between 464°F and as high as 1472°F, and luster between 250°F and 752°F (Purdy 1974; Purdy and Brooks 1971; Mandeville1971:49; Picha et al. 1991; Perkins 1985:23-24).

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 1992:94-97; Rogers and Francis 1988). When heated, the external surfaces of cherts tend to become optically dull. Bennett and Kunzman (1985:7) found this occurred at temperatures of 1112°F to 1472°F. Perkins (1985:28-30) suggested that the presence of lustrous and relict dull flake scars on the same piece is a good indication that the object had been deliberately heat-treated, and not subsequently altered in a fire. Complete artifacts that display all visually dull surfaces, particularly when combined with potlidding and crazing, are likely to have been subjected to a post-manufacturing fire.

Other data associated with chert artifacts can be extracted through protein residue analysis, source determination through macroscopic fossil content and trace element analysis, and dating via thermoluminescence or electron spin resonance spectroscopy (Luedtke 1992:109-137; Julig 1994; 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.

Obsidian

Obsidian is one of the most data-rich toolstones, as it is can be chemically sourced to the volcanic flow of origin and is datable by measuring the thickness of its hydration band. Once one accounts for certain variables such as the obsidian source, soil moistures, soil pH, and temperatures (all of which appear to affect absorption rate), 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 1990*)*.

Hydration is frequently rendered unmeasurable after wildland fires. Obsidian located in portions of fires that are lightly fueled more likely to retain hydration than those burnt under moderate or heavy fuels (see Origer 1996; Linderman 1992; Deal 1999; Benson 1999; Green et al. 1997). Obsidian located on the ground surface is more likely to be altered by fires, although Skinner et al. {1997) reported that hydration was erased to soil depths of at least 6cm. The percentage of obsidian with measurable bands recovered from wildland fires varies widely, from a low of only 9% (Skinner et al. 1997:17), to 35% (Trembour 1990; Pilles 1984:12), to 51-64% (Skinner et al. 1996), to as high as 71% (Jackson et al. 1994 for surface and near-surface obsidian). Preliminary results of lab and prescribed fire experiments indicate that extended exposure to heat, even at very low temperatures can alter hydration bands (c.f. Linderman 1992; Deal 1999; Solomon 1999). Hydration bands can become too diffused to accurately measure after 2 hours at 392°F and after one hour at 572°F (Solomon 1999). Hydration bands have been erased completely after 4 hours at 153°F, after 12 hours at 392°F, and after one hour at 752°F and 810°F (Solomon 1999; Skinner et al. 1997).

In order to control for potential variations in effects by obsidian source, and variations which could be present in different samples from the same source, Skinner et al. (1997:10) used a single flake of obsidian cut into 6 pieces, with each piece heated for one hour at temperatures of 212°F to 1112°F, in 212° increments. At 212°F, the hydration bands were still distinct. At 392°F, band width had increased slightly, but was still visible and measurable. At 572°F, the band was difficult to measure, due to diffuse and indistinct diffusion fronts. At 752°F, the diffusion front was gone, the band was not measurable, but a slight bluish tint marked where the band was. At 932°F and 1080°F, there was no sign of a hydration band. Skinner et al. (1997:10) concluded that, in dating obsidian, problems in interpretation may occur in cases of lower temperature exposures, when the band width is not completely erased and the hydration age may be misread to indicate an artifact 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 Stevenson et al. (1989:194).

Obsidian from distinct volcanic flows have unique chemical compositions, allowing researchers to determine the source of obsidian tools and debris left on sites in prehistoric contexts. Few studies have analyzed potential fire effects to obsidian sourcing, but several that have used X-ray fluorescence have been successful in obtaining source information even from surface samples subject to intense fires (Davis et al. 1992:26; Keefe et al. 1998; Skinner et al. 1997; Skinner et al. 1995; Steffen 1999; Tremaine and Jackson 1995). However, Shackley and Dillian (1999) reported potential problems with sourcing thermally altered obsidian artifacts from New Mexico and Arizona, noting that bonding of melted sand to the surface of the obsidian could create sourcing errors. Skinner et al. (1997:17) noted problems in using X-ray fluorescence techniques with obsidians from central Oregon, which had a dark patina believed to be a silica-based encrustation. Anderson and Origer (1997:18) reported that the exterior surface of some obsidian was altered enough to make sourcing via *macro*scopic attributes difficult one year after a wildland fire. Some of the apparent inconsistencies and wide temperature ranges for effects reported in the literature may be the result of different source materials reacting differently to thermal environments.

Visual effects also occur to obsidian at varying temperatures and at differing lengths of exposure to heat (see Deal 1999b). Obsidian has been reported to fracture, crack, craze, potlid, exfoliate, shatter, oxidize, bloat, melt, suffer pitting and bubbling of surfaces, become smudged, discolored, or covered with residue, or be rendered essentially unrecognizable (Anderson and Origer 1997; Bayer 1979; Davis et al. 1992; Deal 1999; Eisler et al. 1978; Hull 1991; Johnson and Lippincott 1980; Kelly and Mayberry 1979:606; Lentz 1996a; Likins 1999; Lissoway and Propper 1988; Nakazawa 1999; Origer 1996; Pilles 1984; Rogers and Francis 1988; Skinner et al. 1997; Steffen 1999, 1999a; Steffen et al. 1997; Stevenson et al. 1985; Traylor et al. 1983; Trembour 1979). Gaunt and Lentz (1996) report that the extent of adhesions increased as fire intensity increased, with the greatest quantity of adhesions on surface lithics (Lentz 1996a:71). Obsidian has melted at 1400°F (Trembour 1979:84), or suffered extreme vesiculation between 1292°F and 1400°F which turned obsidian into a frothy mass (Steffen 1999). Extreme vesiculation has been noted in a backfire, a prescribed fire, and a campfire (Steffen 1999). Some of the most severe fire effects have been noted at quarry sites and source areas, such as that reported from the Dome Fire in New Mexico (Steffen 1999, 1999a).

Since the temperatures and duration of heat at which effects are noted to obsidian vary widely, it has been suggested that some component of the field fire environment (such as wood ash, soil chemistries or soil moistures), or the obsidian source material itself, are mitigating or contributing to observed changes (c.f. Steffan 1999; Trembour 1979; Nakazawa 1999; and Deal 1999).

As an aside, Deal (1999:13-18) has suggested that obsidian hydration data can be used as an indicator of the absence of heavy fuel loads or large fires in past landscape conditions. Many areas of the country bear evidence, based on fire-scarred trees and ethnographic descriptions of repeated Native American burning, of frequent fire return intervals which exceed those expected from lightning (cf. Agee 1993; Anderson 1993, 1999; Anderson and Moratto 1996; Barrett 1980; Blackburn and Anderson 1993; DeVivo 1990; Lewis 1973; MacLeery 1994; Pyne 1982; Olson 1995, 1999; Van Lear and Waldrop 1989; Yarnell 1998). In areas with frequent , periodic fires, fuels would be reduced to the point that areas burnt at fairly low temperatures with very restricted fire residence times (Deal 1999). In these areas, the mere *presence* of numerous hydration readings from surface obsidian can help support fire history reconstructions at the local and even regional landscape level (Deal 1999).

Hydration dates have the additional benefit of potentially extending fire history data well beyond the limit of several centuries inherent in dating fires from tree cores. It is ironic that in many cases, and for several artifact classes including stone tools, frequent past burning helped preserve certain types of data resident in artifacts, while at those same sites, because of higher fuel loading, today's wildland fires and prescribed burns are impacting and destroying the same data.

Several researchers have suggested that past fire events are discernible on obsidian in the form of re-established hydration bands (Trembour 1979, 1990; Linderman 199:22-24; Green 1999). Some obsidian 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; Origer, personal communication), suggesting the possibility that they had 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. 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. Steffen (1999) 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.

All this begs one to ask whether or not obsidian hydration data is useless, particularly if it should prove that fire-destroyed obsidian hydration bands later rehydrate. Surely, if one were to recognize that a site, or a portion of a site, had been subjected to a fire in the past, it could help explain why other data (pigments, protein residues, organic material) were missing. In northeastern California, researchers 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 then are using this data to reconstruct landscape-level fire histories (Green 1999).

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 (et al. 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 et al. (1995) for similar results from another moderate to severe wildland fire). Blood residue analysis has also been successful on basalt artifacts burnt at high intensities (Tremaine and Jackson 1995; Newman 1994). Pilles (1984:12) noted that thermoluminescence dates from basalt could be as much as 24% younger (more recent) than expected due to fires.

In lab experiments, Blackwelder (1927:137) reported that 12 periods of rapid heating and cooling of a small piece of basalt resulted in no effects, although a similar piece, which was heated to 572°F with no visible effects, fractured after being rapidly cooled in cold water only twice. Another specimen was heated to 572°F for 30 minutes, with no visible changes, but when the temperature was raised to 617°F, the basalt lost "a few thin flakes... from the sides" (Blackwelder 1927:137). After rapid heating to temperatures of 707°F for 30 minutes, a fourth sample "broke violently into a considerable number of pieces while still in the oven" (Blackwelder 1927:137). A block of basalt (presumably a cube about 3 inches to a side) was heated to 302°F, with no visible changes. The temperature was then raised to 752°F, and after 10 minutes, flakes began to spall off, continuing "until the block was almost wholly reduced to fragments". Another 3-inch basalt cube was placed in a furnace at 1112°F, resulting in "small scales" breaking off after 3 minutes, and continuing for another 10 minutes (Blackwelder 1927:137). Blackwelder's experiments suggest that basalt may be extremely susceptible to thermal damage in fires.

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

Very little data is available on other kinds of flaked toolstone, other than chert and obsidian. Quartz is an excellent thermal conductor and expands first in one direction, then another, which adds stress to the rock leading to fractures (cf. Luedke 1992:96). Thermal expansion in quartz crystals, compared as a percent increase from the volume recorded at 68°F, is recorded as a 0.36% increase at 182°F, 0.78% at 392°F, 1.9% at 752°F and 4.5% at 1112°F (Dane 1942:34). Quartz undergoes changes in crystalline structure at 1064°F, and liquifies at 3133°F (Luedtke 1992:96-97). In lab experiments, Bennett and Kunzman (1987:8) detected no weight loss to cryptocrystalline quartz at temperatures of less than 932°F, and Purdy (1974:44) found only 0.01% weight loss in a quartz crystal after 24 hours at 662°F. In areas with moderate to severe ground charring within one fire, milky and crystalline quartz was often covered with a black, shiny residue on all surfaces except that in contact with the ground, making it extremely difficult to identify material type during post-fire archaeological investigations (Deal 1995; 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, sooting, discoloration or oxidation has been reported on mudstone, rhyolite and viric tuff (Hemry 1995:4; Lentz 1996:70; Deal 1995). Surface-collected vitric tuff from a high intensity fire was successfully sourced using X-ray fluorescence (Jackson et al. 1994), and were found to retain immunological data (Newman 1994).

GROUND STONE

Little information regarding thermal effects to ground stone artifacts is available in the literature, although field observations and experiments indicate that objects manufactured of different materials will react differently to heating and cooling. For instance, Pilles (1984:10) 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 the presence of adhesions, but the single mano was not altered. Portable mortars were rendered nearly unrecognizable due to extreme fracturing in one severe wildfire (Likins 1999), and in another, trough metates were broken in half (Jones and Euler 1986:246). Effects noted to pestles included blackening and discoloration to the point of obscuring material type identification and spalling by heating (Deal 1995; Foster 1980; Tremaine and Jackson 1995).

Outcrops and boulders containing mortars and milling features have been blackened, sooted, cracked, spalled and exfoliated as a result of wildland fires (Deal 1995, 2001). In one fire, major impacts at several sites resulted in the exfoliation of large sheets of rock off a mortar outcrop from the intense heat (Deal 1995). Blackening of mortar rock outcrops often hampered postive identification of the material type, although s soil in the mortars may have protected the grinding areas from damage (Deal 1995, 2001). Additional effects that could be expected at bedrock milling features would probably be similar to those reported elsewhere for boulders and cliff faces (cf. Blakensop et al. 1999; Eisler et al. 1978; Gaunt et al. 1996, Hester 1989; Johnson and Lippincott 1989; Noxon and Marcus 1983; Switzer 1974, Roger 1999; Romme et al. 1993:2). Fuel loading around boulders and rock walls has been reported to contribute to extensive damage (Blakensop et al. 1999; Hester 1989).

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 rock such as granite, basalt and limestone (Schiffer 1987:154). Based on field observations and experiments, Blackwelder (1927) concluded that for many forested areas in 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 defines fire weathering features at boulders and outcrops as resembling curved wedges, plates or scales, 1 to 5cm thick, which often taper to a thin edge (1927:135). Based on experiments, Blackwelder reported that most igneous rock (basalt, andesite, porphyry) will withstand rapid heating and cooling up to 392°F without any damage, but would begin breaking and fracturing when cooled after being heated to higher temperatures, while granites and quartzites tolerate slow temperature changes to as much as 1472°F (1927:138).

Pollen, phytolyths, starches, ochre and other pigments, and protein residues from plants and the blood of small mammals have been detected on ground stone (Yohe et al. 1991; Traylor et al. 1983:7; Johnson 1993; Mikkelsen 1985). These remains can be used to infer tool function, as well as the time of year a site was occupied. Although it is expected that fire, and probably fire retardant, could negatively impact these data types (for instance, pollen is destroyed at temperatures over 572°F; cf. Romme et al.1993:28; Lentz 1996:63), Tremaine and Jackson (1995) retrieved a granitic handstone from the surface of a severely burned site which yielded positive residue reactions for cat and acorn. Several other ground stone objects from the Cleveland Fire tested positive for acorn, deer and rabbit (Newman 1994).

Thermal effects to rock used as heating or cooking stones

Occasionally, ground stone was used as cooking stones in stone-boiling, which often led to their being discolored, cracked or fractured (although they may have already been broken and only served a second career as a cooking stone; Johnson 1993:343). Conditions for stone-boiling are similar to burning situations in wildland or prescribed fires, where fuels are heavy and the duration of heat is extended, and where cold water, foam or retardant is dropped on heated stone. Distinguishing stone that has been fractured by wildland or prescribed fires from that previously fractured in stone-boiling or in cooking hearths has proved problematic (Lentz 1966:62-63; Tremaine and Jackson 1995), although several researchers have suggested ways to differentiate the two based on fracture patterns, location within particular fuel loading situations, analysis of organic residue, or luminescence analysis of mineral constituents (Hemry 1995:42; Kritzer 1995; Picha et al. 1991:23,24; Rapp et al. 1999; Seabloom et al. 1991:1).

Experiments with rock types used in stone-boiling and in roasting and oven pits, hearths, and sweat lodges have produced information concerning how various stone will behave when subjected to heat (Kritzer 1995; McDowell-Loudan 1983; Pierce 1984, 1983; Wilson and DeLyria 1999; Brink et al. 1986). Topping (1999:6) 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" (1999:6). Blackwelder (1927:137) reported that a six pound cobble of andesite rapidly heated to 392°F in an electric furnace, then rapidly cooled nine separate times, suffered no visible effects. A greywacke river pebble 3 inches thick had "thin slabs split off along almost imperceptible planes of stratification" while still in the oven at 662°F (Blackwelder 1927:137). Heating a piece of fine-grained granite slowly for two hours to a temperature of 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 1927:137).

Wilson and DeLyria (1999) determined that andesite and basalt rocks were more durable than quartzite in replicative studies with camas oven/roasting pits. During three three successive firings, several rocks exploded within the first hour, with temperatures between 302° and 797°F. Most damage to the rock occurred during the initial firing, but damage continued with each successive firing. 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.

Pierce (1983, 1984) found that quartzite cooking stones heated quickly, boiled water quickly, fractured often when heated, but fractured only rarely when placed in water. Sandstone also heated rapidly, although more sandstone was needed to bring water to a boil than quartzite. Although sandstone did not fracture while being heated, it "became so friable that large quantities of sand were dislodged from the exterior of the stone" (Pierce 1983:4), 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 sandstone or quartzite

(Pierce 1984:4, 9). Basalt tended to fracture 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 (1983:4). 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.

OTHER STONE ARTIFACTS

Vessels, cooking pots, lamps, clubs, atlatl weights, net weights, loom weights, digging stick weights, pump drill weights, plummets, bolas, pipes, gamestones, chunkey 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 to 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 includes argillite, serpentine, magnesite, hematite, turquoise, agate, jasper, jade, fluorite, selenite, azurite, gypsum, alabaster, aragonite, malachite, calcite, chalk, catlinite, kaolinite, quartz, galena and meteoric iron. Little is known about the effects of fire to artifacts made of these materials, although physical constants have been recorded for some with respect to thermal expansion, density at high temperature, thermal conductivity and diffusivity, weight loss from heating, melting and transformation temperatures, heat fusion, and heat capacity (Birch et al. 1942; Dane 1942:30-34). 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 turquoise turns white (Miles 1963:128, 148; Mottana et al. 1977). Magnesite bubbles and releases gases prior to decomposing at 1832°F; calcite "dissociates" at 1832°F (Mottana et al. 1977). Catlinite, kaolinite, chalk, steatite, used to make pipes or cooking vessels, survive well at low temperatures, often only discoloring and hardening these items. Steatite has been successfully sourced using instrumental neutron activation analysis (Truncer et al. 1998), the accuracy of which might be impacted by high temperature fires.

One type of stone used to make objects in some areas is particularly vulnerable to fire, as it is readily combustible. 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 discoidals (Cowin 1999; Fogelman 1991; Fundaburk and Foreman 1957:21; 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 1983:72; Yarnell 1998:13). Lignite, a soft brownish-black coal which becomes pasty when heated, and jet, a dense, black lignite that can be highly polished, were used as inlay on shell (Miles 1963:188-189), or made into animal forms. Coal veins ignited in wildfires can smolder for months after ignition (Wettstaed and LaPoint 1990).

Minerals such as copper and mica 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 (Prufer 1964; Jennings 1974:232-237; 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 68°F, it expands 0.03% at 182°F, with expansion to 0.15% at 392°F, 0.37% at 752°F, 0.66% at 1112°F and 1.3% at 1472°F (Dane 1942:34). Expansion can lead to cracking and fracturing of rock, and probable exfoliation of mica.

Native copper melts at 1980°F (Mottana et al. 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 1960:52), after which it was cold-worked and heated prior to shaping (Farquhar et al. 1998; Jennings 1974:144-

145, 233). Copper nuggets were hammered into thin sheets, which were beaten together to make thicker objects, and shaped by abrading (Lewis and Kneberg 1958:107-108) 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 earspools. Thin sheets were sometimes embossed by pressing the copper over a carved wooden die, and then painted, or decorated with feathers or fabric (Burroughs 1998; Lewis and Kneberg 1958:108; Fundaburk and Foreman 1957:10,160-163; Prufer 1964). Fire can be expected to distort, obscure or destroy decorative elements on copper.

Corrosion and oxidation often provides a protective surface on copper at archaeological sites, unless heating cracks the corrosive film and allows it to grow inward (Schiffer 1987:191-195). As temperatures increase, corrosion rates increase, with wood ash accelerating corrosion (Schiffer 1987:192). Copper used in modern applications discolors to a dark red or black that thickens under higher heating conditions (NFPA 1998:27). Prior to melting, copper blisters, exhibits surface distortions, and forms blobs and drops on its surface (NFPA 1998:110). After melting, the copper resolidifies, forming irregularly shaped and sized globules which are often tapered or pointed (NFPA 1998:110). Several techniques have recently been used to source copper, including neutron activation (Julig et al. 1992), X-ray fluorescence (Wager et al. 1998) and thermal ionization mass spectrometry (Woodland et al. 1998). It is probable that fire would affect the accuracy of these analytical techniques.

IMPLICATIONS FOR CULTURAL RESOURCE PROTECTION AND FIRE PLANNING

The key factors which seem to affect the the nature and extent of fire damage to archaeological resources are fire intensity, duration of heat, and penetration of heat into soil (Traylor et al. 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. Insulation from heat, even with a few centimeters of soil, is often adequate in reducing impacts (Anderson and Origer 1997; Lissoway and Propper 1988; Picha et al. 199; Pilles 1984; Seabloom et al. 1991).

So far, it is evident that the surface of sites generally suffer the most damage in fires. 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 windtrown trees commonly mix soil deposits, the material on the surface has often been found to reflect the full range of dates of use on the site, providing a snapshot of the site's chronology (Jackson 1999; Jackson et al. 1994: III B 4-12).

Still, surface artifacts often retain data potentials, even on sites that have burnt numerous times in the past, or that have recently been subjected to wildfires or prescribed burns, depending on local fire history, fuel loading in recent fires and how these fuels burnt, and the type and amount of ground charring. These data have value depending on the local and regional research interests. Archaeologists need to be much more informed about the fire environment, fire behavior, fire intensity and fire severity, in order to assess what data is likely to be affected by fire, what is likely to remain, and what is cost effective to retrieve. As our understanding of fire effects increases, these data losses will become more predictable and comprehensible. Certainly, archaeologists need to continue to analyze artifacts, features and constituents from the surface of burnt-over sites if we want to expedite our understanding of fire effects to cultural resources.

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 which 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 1999), or by mechanical means when appropriate (see Jackson 1993; Jackson et. al 1994), the data loss will be reduced. Collecting surface samples prior to burning would secure the data that could be 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 1999).

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 1995:3-73-99), and increased threats to cultural resources (Benson 1999; Blakensop et al. 1999; Gaunt et al. 1996; Hester 1989; Kelly 1981; Kelly and Mayberry 1979; Lentz et al.1996; Lissoway and Propper 1988; Pilles 1984; Siefkin 1999; 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.

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, fire severity, as well as alterations to artifacts. Prescribed fire experiments need more stringent methods for monitoring and reporting on 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 these variables affect cultural resources, including stone tools.

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