

# ARCBURN: LINKING FIELD-BASED AND EXPERIMENTAL METHODS TO QUANTIFY, PREDICT, AND MANAGE FIRE EFFECTS ON CULTURAL RESOURCES





## **ArcBurn: Linking Field-Based and Experimental Methods to Quantify, Predict, and Manage Fire Effects on Cultural Resources**

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*Front cover-Top: Fire spread during the Pino Fire, August 2014, Santa Fe National Forest. The ArcBurn project conducted in-field monitoring at archaeological rubble mound sites as part of the Southwest Jemez Collaborative Forest Landscape Restoration Project. Left: Rubble mound, post-fire. Center: Ceramic artifacts, post-fire. Right: Archaeologists assess fire effects on a rubble mound site. Photo credits: R. Loehman*

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## Abstract

Cultural resources are physical features, both natural and anthropogenic, associated with human activity. These unique and non-renewable resources include sites, structures, and objects possessing significance in history, architecture, archaeology, or human development (Fowler 1982). Wildfires can alter cultural resources through immediate effects such as destruction of structures and chemical and physical changes to artifacts that alter or destroy attributes important for determining artifact origin, age, cultural affiliation, or technology of production. Post-fire effects, most notably erosion, may also occur and cause destruction or translocation of artifacts and cultural sites. Damage to artifacts and sites constitutes a permanent loss of knowledge and information about the past. Fuels treatments have been shown to reduce fire severity, but effectiveness of risk mitigation operations is constrained by lack of information in three areas: 1) knowledge of the range of fire effects on the diversity of artifact types typical of many archaeological sites, 2) quantification of the magnitude and duration of heating that results in alteration or substantial damage, and 3) link between archaeological fire effects and operational fire models to aid managers in development of fuels treatments and characterization of risk. The “ArcBurn” project provides information critical to the integration of cultural resources and fire management decision processes.

## Background and purpose

The earliest documented, consistent human occupation of North America occurred after the end of the last glacial period, about 16,500-13,000 years before present (Bonatto and Salzano 1997). Wildfire emerged as a dominant process during the same period, commensurate with rapid climate changes and increased tree cover following deglaciation (Marlon, Bartlein et al. 2009). Prehistoric peoples likely used fire as a tool for maintaining open stands to facilitate travel, stimulating grass and shrub growth in hunting areas, clearing campsites, and managing crops (Barrett and Arno 1982; Vale 2002), although these human effects were likely limited in spatial extent (Allen 2002). Thus, many cultural landscapes have been subject to repeated wildfires, both during and after occupation. In recent decades, however, increases in wildfire frequency, severity, and extent have been noted, likely resulting from changes in climate and fuels (Flannigan, Stocks et al. 2000; Lenihan, Drapek et al. 2003; Westerling, Hidalgo et al. 2006; Littell, McKenzie et al. 2009). Shifts toward more frequent, larger, and more severe wildfires in

fire-prone landscapes are likely to continue with warming temperatures (Brown, Hall et al. 2004; Flannigan, Amiro et al. 2006; Lenihan, Bachelet et al. 2008; Loehman, Clark et al. 2011), resulting in fire patterns that are outside of the historical range. Fire behavior and fire patterns that are outside of the historical range of variation for cultural landscapes may expose cultural resources to greater heating intensities and longer heating durations that have previously occurred, causing historically unprecedented types and magnitude of alteration.

Cultural resources are physical features, both natural and anthropogenic, associated with human activity. These unique and non-renewable resources include sites, structures, and objects possessing significance in history, architecture, archaeology, or human development (Fowler 1982). Wildfires can alter cultural resources through immediate effects such as destruction of structures and chemical and physical changes to artifacts that alter or destroy attributes important for determining artifact origin, age, cultural affiliation, or technology of production (Romme, Floyd-Hanna et al. 1993; Buenger 2003). Such fire-induced changes affect the identification and interpretation of the archaeological record (Johnson 2004). Post-fire effects, most notably erosion, may also occur and cause destruction or translocation of artifacts and cultural sites (Floyd, Hanna et al. 2004). Because cultural resources are non-renewable, such damage to artifacts and sites constitutes a permanent loss of knowledge and information about the past (Lissoway and Propper 1990). The National Historic Preservation Act (NHPA 1966, Section 106) directs land managers to account for potential or actual wildfire damage to cultural resources.

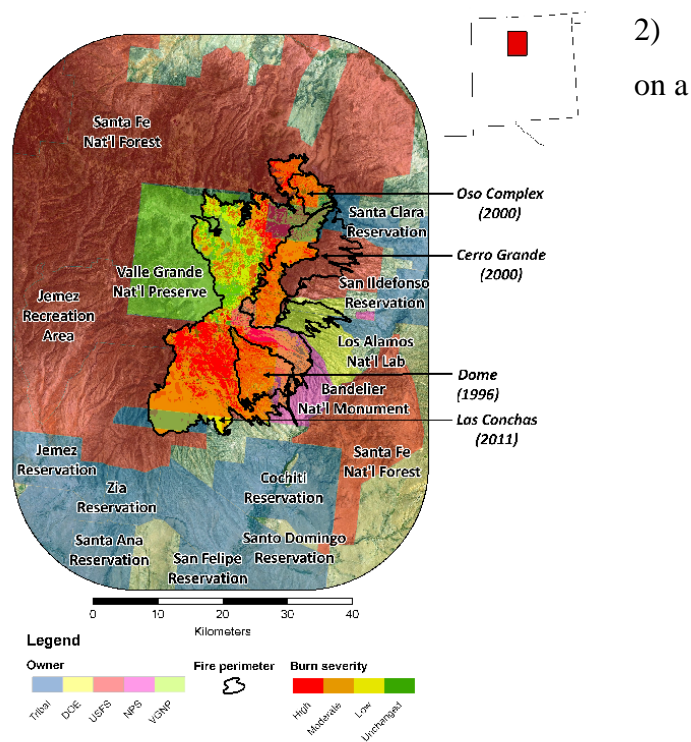
The ArcBurn project provides data on the heating intensities and durations associated with contemporary forest and woodland fuels, and resulting impacts to a suite of artifact types and classes. The project is a collaborative and trans-disciplinary project among fire scientists, forest ecologists, earth scientists, archaeologists, and fire managers that integrates cultural resources information into management decision processes via translation of experimental results into recommendations for fuel treatments and prescribed fire practices that reduce vulnerability of cultural resources to substantial fire effects. The project has four main components: 1) laboratory experiments to replicate southwestern pre- and post-suppression fire environments and the direct effects of fire exposure on four types of archaeological materials (ceramics,

## Study location and methods

## Study location

## Environmental setting

Our project is centered in the southwestern United States, in the Jemez Mountains of



**Figure 1. ArcBurn study region in the Jemez Mountains, New Mexico**

northern New Mexico (Figure 1). The Jemez Mountains lie along the western flank of the Rocky Mountains at the range's southern terminus. Elevations range from about 5,600 feet AMSL along the Jemez River near Cañon to the peaks of Redondo Peak (11,257 feet AMSL) and Chicoma Mountain (11,562 feet AMSL). The region consists of high, broad mesas separated by deep north-south trending canyons. The uppermost geology in the region is Quaternary and Tertiary Period volcanic deposits. Bandelier Tuff and Paliza Canyon Formations cover the mesa tops. These volcanic deposits are composed of tuff, pumice, and ash resulting from the various eruptions of the Valles Caldera between 1.6 and 1.8 million years ago. Canyons expose lower Abo (sandstones and shales), Yeso (sandstone), and Madera (limestone) formations. Vegetation in the Jemez Mountains consists mainly of piñon-juniper woodlands (up to 7,000 feet AMSL), ponderosa pine forest at middle elevations and northern areas (up to 9,000 feet AMSL), and mixed conifer forests of Douglas-fir and spruces in the northernmost, upper elevations (up to 10,000 feet AMSL). Additionally, there are riparian areas with willows and cottonwoods along the perennial streams and some areas of aspen groves at higher elevations.

### Wildfire activity

Tree-ring reconstructions of fire history in the Jemez Mountains suggest that prior to 1900 forests in the Jemez Mountains experienced frequent, low-intensity surface fires that occurred at mean intervals of about 5-10 years in ponderosa pine forests and 7 to 22 years in mesic mixed-conifer forests (Touchan et al. 1996). Major fire years were clearly associated with drought conditions, with the most extensive fire activity in ponderosa pine forests occurring in dry years that followed within one to a few years after wet years, during which continuous fuels would have accumulated (Swetnam and Baisan 1996). After 1893 widespread fires generally ceased, coinciding with the onset of intensive livestock grazing across northern New Mexico (Touchan et al. 1996).

A number of large wildfires have burned across the Jemez Mountains in the past five decades, occurring with low to high severity in multiple forest types (Figure 1). These include the 1977 La Mesa fire (15,270 acres), the 1996 Dome Fire (over 16,500 acres), the 2000 Cerro Grande fire (42,600 acres), the 2010 South Fork fire (16,960 acres), the 2011 Las Conchas fire (156,000 acres), and the 2013 Thompson Ridge Fire (23,903 acres) (Tillery and Haas 2016). Recent fire size and severity have been attributed to changes in stand structure and fuels over the past century, including the formation of dog-hair thickets, decreased understory cover, and increased fuel loading and continuity (Covington and Moore, 1994) due to a combination of natural factors such as good seed crop years and anthropogenic factors such as grazing and fire suppression. Wildfire suppression costs have increased as the number and severity of fires has increased. The ten-year average for wildfire suppression costs between 2005 and 2014 was more than double the ten-year average between 1985 and 1994 using constant 2014 dollars (NIFC 2015). The 2011 Las Conchas Fire destroyed 63 homes, cost \$48 million to suppress, caused massive flooding, destroyed archaeological sites, forced the shutdown of Albuquerque's drinking water intake, and devastated the traditional homelands of Santa Clara Pueblo (EPSCoR 2012).

### Prehistoric human occupation

Peoples have moved about and lived within the Jemez landscape for the past 10,000 years. Early archaeological sites are dominated by large and small scatters of lithic (worked stone) artifacts, including obsidian and chert artifacts (Anschuetz 1996, Wolfman 1994). The Puebloan era – characterized by the development of structures and a cultural evolution in architecture, artistic



expression, and water conservation - began about 2,000 years before present day. From about A.D. 600-1175 populations were low, with archaeological sites in the form of pit houses or small surface dwellings. Population size increased dramatically from about A.D. 1175 to A.D. 1325, associated with the establishment of several small villages (“pueblos”) and numerous small structures (“field houses”) (Anschuetz 1996, Elliott 1991, Leibmann et al. 2016). The majority of known Puebloan sites in the Jemez Mountains - consisting of field houses and various-sized pueblos - date to the period between A.D. 1325 and A.D. 1700. Field houses, rock art, and artifact scatters are often found associated with large pueblo ruins. In the Jemez Mountains, sites above 8400’ are dominated by large and small scatters of obsidian or chert artifacts or extensive obsidian quarries. Between 6,000’ and 8,400’ the majority of prehistoric Puebloan-era archaeological sites are comprised of stone masonry architectural features related to domestic habitation or agricultural pursuits. Architectural types include large and small pueblos, small field structures, and agricultural terraces and grid gardens. These sites also have rich assemblages of pottery, obsidian, and chert artifacts. Our focus on ceramic, obsidian, and chert artifact materials and architectural stone targets the most abundant components of the Jemez archaeological record.

### Land management

The Jemez Mountain region has diverse land management including US Forest Service lands (Santa Fe National Forest), National Park Service (Valles Caldera National Preserve and Bandelier National Monument), Los Alamos National Laboratory, and tribal lands including those of the Jemez, Santa Clara, Ohkay Owingeh, Santo Domingo, San Ildefonso, Santa Ana, San Felipe, Cochiti and Zia Pueblos. In addition, because this region is the ancestral and current home and is sacred to numerous Native American tribes, it contains features and sites still in use as traditional cultural properties.

### Laboratory-based simulations of fire environments

We developed a suite of controlled experiments that simulated a range of fuel and fire environments typical of culturally significant areas of the Jemez Mountains. Simulations were conducted at the US Forest Service Rocky Mountain Research Station Fire Sciences Laboratory in Missoula, MT. We simulated three fire environments: 1) **Crown fire**, dominated by radiant heating without direct flame contact; 2) **Surface fire**, a combination of radiant and convective

heating with direct flame contact, and 3) **Ground fire**, the slow, low-temperature, flameless (smoldering) form of combustion such as occurs with persistent combustion of biomass behind the flaming front of wildfires or within slash piles, masticated fuels, or other fuel-rich and oxygen-poor fire environments. We developed multiple “doses” for each fire environment based on factorial combinations of duration and temperature (crown fire simulations), fuel load and below-fuel surface moisture (surface fire simulations), or fuelbed depth and below-fuel surface moisture (ground fire simulations). Various levels of heat output (energy) were produced by these doses and measured using thermocouples attached to artifact samples.

### Archaeological materials

Artifact samples (Table 1) included ceramics, obsidian, chert, and architectural stone (“masonry”), all local to and locally sourced from the Jemez Mountains. Chert, masonry, and non-artifact obsidian samples were collected under permit authorizations issued by the Valles Caldera Trust, Santa Fe National Forest, and the National Park Service, and ceramics were unprovenienced sherds from collections at Bandelier National Monument and the Maxwell Museum of Anthropology at the University of New Mexico. We included a collection of archaeological flakes drawn from past excavations in the Dome area of the Santa Fe National Forest and from surface collections within the Valles Caldera National Preserve to test for fire effects on obsidian hydration (OH) dating potential. Obsidian can be used to date sites, but it is well-documented (Lloyd et al. 2002) that heat exposure from fires damages OH dating potential by “drying out” the hydration bands and “resetting” the OH clock. We tested several classes and/or sizes for each of the artifact types to assess whether class, surface area, or size affected fire sensitivity or likelihood of alteration. All artifacts were weighed, measured, and scanned prior to and after testing, and extensive additional pre- and post-heating measurements of key characteristics related to artifact type, manufacture, and form were recorded.

Table 1. Artifact types and classes used in laboratory experiments

Artifact Type	Artifact Class				
Ceramics	Carbon paint n=102	Mineral paint n=102	Glaze paint n=102	Plain utility n=102	Textured utility n=102
Obsidian	Unmodified nodules (small and large) for one obsidian type (Cerro del Medio); n=204		Non-artifact flakes (small and large) for two obsidian types (Cerro del Medio and Cerro Toledo); n=612		Obsidian hydration specimens: Archaeological flakes (varied sizes) for two obsidian types (Cerro del Medio and Cerro Toledo); n=72
Chert	No classes; n=102				
Masonry	No classes; n=102				

**Ceramics** included sherds (pieces of pottery vessels) classed as five separate ware types common in the Jemez Mountains and that are representative of archaeological assemblages in the southwestern U.S. Ceramic classes included three decorated types (carbon, mineral, and glaze paints) and two utility wares (plain and textured). **Obsidian** included nodules (raw stone specimens not modified by people), non-archaeological flakes (knapped from nodules to sizes consistent with archaeological assemblages), and archaeological flakes. Obsidian flakes from two geological source areas in the Jemez Mountains (Cerro del Medio and Cerro Toledo units) were used to investigate potential differences in fire effects among obsidian types. For experiments on obsidian nodules, only Cerro del Medio nodules were included. Because of limited access to suitable archaeological specimens obsidian hydration alteration was assessed only for dry-bed smoldering experiments. **Chert** samples were non-archaeological flakes knapped from nodules collected from the Cerro Pedernal source unit. Flakes were consistent in size and color with specimens found in Jemez Mountains archaeological assemblages. **Masonry** samples were welded volcanic tuff stones sourced from a stockpile of archaeological specimens from disturbed contexts at Bandelier National Monument, and non-archaeological stones of similar size, shape, and geologic origin collected from a proximate area to the archaeological samples.

### Crown fire simulations

We used an Olympic raku kiln with a top hat design (electric heating coils embedded in the lid) to replicate heating intensities and durations characteristic of crown fires (Butler et al. 2010, Frankman et al. 2012). We used time and temperature factors of 600°C and 900°C and 60

seconds and 90 seconds for a total of four doses. We tested six samples per class (e.g., six glaze paint ceramics, six plain utility ceramics, etc. – Table 1) in two or more replicated simulations per dose. Ambient and upper and lower surface temperatures of samples were measured using K-type thermocouples (28 gauge wire) routed to a LabJack U6-Pro data logger (Figure 2).



**Figure 2. Simulated crown fire environment. Olympic raku kiln with a top hat design (left); Obsidian flakes with thermocouples in place (top right); Ceramics with thermocouples in place (bottom right)**

### Surface fire simulations

We built an 8' x 3' x 1.5' open flame bed consisting of a welded L-shaped metal bracket frame with galvanized mesh surround, a ceramic board underlayment, and quartz sand bed. We included three fuel factors - a low (0.5kg/m<sup>2</sup> or ~2.2 tons/acre), moderate (1.0 kg/m<sup>2</sup> or ~ 4.5 tons/acre) and high (1.5 kg/m<sup>2</sup> or ~6.7 tons/acre) fuel load - and two sand bed moisture levels (moist, at 2% to 4% moisture by volume, and dry, at 9% to 11% moisture by volume), for a total of six doses. Obsidian, chert, or ceramic artifact samples were placed on the sand beds



underneath the fuel layer, at the soil-fuel interface. Masonry samples were placed on sand beds atop litter fuels. Fuels were ponderosa pine needles air-dried to 30-40% moisture. Fuel type and range of loadings are characteristic of the surface fuels found in the study region in areas of high concentration of cultural materials. We tested nine samples per class in three replicated simulations per dose. Ambient and upper and lower surface temperatures of samples were measured using K-type thermocouples (28 gauge wire) routed to a LabJack U6-Pro data logger (Figure 3).



**Figure 3. Simulated surface fire environment. Ceramics and masonry on sand bed before fuels and thermocouples are in place (top left); Surface fire bed, ignition (top right); Surface fire bed, after flaming front (bottom left); Flames incident on masonry samples (bottom right).**

### Ground fire simulations

We constructed benchtop burn buckets from galvanized metal tubs, with galvanized mesh surrounds filled with quartz sand (“sand bed”). We included low (2cm or ~6.7 tons/acre) and

high (6cm or ~19.4 tons/acre) fuelbed depths and two sand bed moisture levels (moist, at 2% to 4% moisture by volume, and dry, at 9% to 11% moisture by volume) for a total of four doses. Artifact samples were placed on the sand beds underneath the fuel layer, at the soil-fuel interface. Fuels were pre-dried bulk peat moss at depths characteristic of duff depths found in the study region in areas of high concentration of cultural materials. We tested six samples per class in three replicated simulations per dose. For obsidian hydration experiments we tested six samples of each obsidian source type in three replicated simulations per fuel load (low and high), for dry sand bed conditions only. Ambient and upper and lower surface temperatures of samples were measured using K-type thermocouples (28 gauge wire) routed to a LabJack U6-Pro data logger (Figure 4).



**Figure 4. Simulated ground fire environment. Masonry with thermocouples in place, on duff bed (left); Obsidian, ceramics, and masonry with thermocouples in place, before fuels are in place (right).**

### Analysis of archaeological materials

We developed a classification matrix for detecting and attributing fire-caused alteration of archaeological materials (Table 2). This matrix broadly defines the ways in which fire may alter archaeological materials (Appendix 1) such that a loss of information (LOI) results, and more specifically assigns observed fire alteration for each of the project artifact types to one or more of the LOI categories. Archaeological samples were analyzed by professional archaeologists for loss of information in the following categories: **Identification:** is the object less recognizable or

no longer recognizable as an artifact? **Form:** Is the artifact shape or form altered? **Material:** Is the base chemical or mineral structure of the artifact altered? **Technology:** Is information lost on how and where the artifact was manufactured? **Provenance:** Do fire effects interfere with identification of material sources? **Chronometry:** Do fire effects alter the relative or absolute chronometric dating potential of the artifact? **Cultural Affiliation:** Do fire effects alter characteristics that allow for identification of affiliation? **Persistence:** Is the artifact in a form that is durable following fire? For each experimental sample the presence or absence and degree of alteration was assessed.

Analysis of **ceramics** targeted potential fire effects on characteristics related to form and identification (spalling, fracture, melting, residue, loss of paint), material and technology (surface or paint color change, changes in core pattern and temper), provenance, chronometry, and cultural affiliation (changes in core pattern and temper, changes in surface and paint colors, obscuring of surfaces from residue and blackening, cracking/crazing, melting of glaze paint) and persistence (fracture). Observations for **obsidian** included coarse macroscopic alterations (fire fracture, cracking of objects, sooting, sheen, and vesiculation) and fine macroscopic alterations (surface crazing and fine subsurface bubbles) to flakes and nodules, and microscopic alterations to obsidian hydration layers in the archaeological artifacts. To assess loss of information, post-heating analysis targeted alterations to the form and integrity of nodules and flakes (fracture, vesiculation), changes to the glass body in flakes (fracture, vesiculation, bubbles, color change), changes to flake surface or near-surface that serve as evidence of heat exposure (crazing, sheen, bubbles, vesiculation), and alteration of obsidian hydration information in the archaeological specimens. Specimen analyses for fire fracture and obsidian hydration alteration are reported here. **Chert** samples were assessed for residue, surface sheen, color change, cracking, surface crazing, and fracturing. **Masonry** samples were assessed for residue, color change, spalling, fracture, and cracking.

We further assessed whether fire effects to artifact samples were “substantial” (see also “significant impact” in Sturdevant 2009). We define substantial effects as changes of sufficient severity to alter or diminish information potential at three levels: 1) for individual fire effects, 2)



for each sample or assemblage of tested artifacts, 3) for each experimental fire environment and dose. For each potential fire effect listed above and in Table 2, archaeologists evaluated whether a substantial alteration had occurred.

Table 2. Classification matrix for detecting and attributing fire-caused alteration of archaeological materials (for definitions of fire alteration see Appendix 1).

<b>Loss of information</b>	<b>Ceramics</b>	<b>Obsidian</b>	<b>Chert</b>	<b>Masonry</b>
Identification: Is the object less recognizable or no longer recognizable as an artifact?	Spalling and fracture; residue deposits; melting	Vesiculation, fracture	Spalling, fracture	Fracture
Form: Is the artifact shape or form altered?	Fracture; melting; loss of paint	Vesiculation, fracture	Spalling, fracture	Fracture, cracking, spalling
Material: Is the base chemical or mineral structure of the artifact altered?	Alterations to core; temper	Glass color change, sheen, vesiculation	Color change, crazing	Color change
Technology: Is information lost on how or where the artifact was manufactured?	Change in temper; surface or core color; core pattern; obscured surfaces	Loss of flake form, alteration of flake platforms and dorsal scars	Spalling, fracture	Fracture, spalling
Provenance: Do fire effects interfere with identification of material sources?	Change in temper; core color	Vesiculation, glass color change	Color change	
Chronometry: Does fire alter the relative or absolute chronometric dating potential of the artifact?	Change in paint or surface color, loss of paint; obscured surfaces; crazing; melting of glaze paint; core color or pattern change	Fracture, vesiculation, obsidian hydration alteration	Spalling, fracture	Fracture, cracking, spalling
Cultural Affiliation: Do fire effects alter characteristics that allow for identification of affiliation?	Change in paint or surface color, loss of paint; obscured surfaces	Fracture, vesiculation	Spalling, fracture	Fracture, cracking, spalling
Persistence: Is the artifact in a form that is durable following fire?	Fracture	Fracture, vesiculation	Fracture	Fracture, cracking, spalling



Samples with one or more instances of substantial alteration (e.g., sherd color change sufficient to interfere with identification, fracturing of obsidian nodules leading to mis-identification of resulting flakes) were assessed to have been substantially altered by a particular experimental test. When 50% or more of samples within an artifact type and class (e.g., mineral painted ceramics, obsidian nodules) were substantially altered, we determined that a particular experimental fire environment and dose had caused an unacceptable level of alteration for a particular artifact type and class (Table 5). Some observed fire effects on individual experimental samples were not deemed “substantial” when considered in terms of loss of information - for example, the obscuring effects of some surface residues may not interfere with documentation of key artifact characteristics, such as ceramic decoration or chert source. Our assessment of relevance or non-relevance for information loss provides a stronger basis for prioritizing preservation measures and treatment actions.

### **Archaeological fire severity modeling**

We analyzed the relationship of archaeological fire severity (degree of alteration to sites and artifacts), derived from existing post-fire assessments, to topographic, climatic, vegetation, and fire weather variables to identify characteristics of sites and site settings that are associated with observed archaeological fire effects. We used a classification algorithm in Random Forests (Breiman 2001) to identify important predictors and implemented the RandomForest (Liaw and Wiener 2002) and caret package (Kuhn 2008) in R (R Development Core Team 2010) to produce predictions free from overfitting. We also compared satellite derived indices of fire severity (BARC) with site level observations of archaeological fire severity using Chi-square and conditional probabilities, to assess whether BARC fire severity characterizations reasonably represent fire impacts to a given site. These analyses improve our capacity to identify and prioritize archeological sites for post fire surveys and treatment and determine which sites are most at risk of negative impacts from future fire.

### **Characterization of post-fire debris flow hazard**

We applied a predictive model to estimate the likelihood and magnitude of post-fire debris flows following two recent fires, the Las Conchas and Thompson Ridge, in the Jemez Mountains. This method estimates risk of post fire debris flows (probability of debris flow x debris flow volume) using information on burn severity, topography, and soil properties under a range of precipitation

conditions (Cannon et al., 2010). The model is intended to capture the response of watersheds to short duration, relatively rare (<2-10 years) convective storm events. We produced probability and debris flow maps for watersheds within and surrounding the Valles Caldera National Preserve, where both the 2011 Las Conchas fire and 2013 Thompson Ridge fire burned.

### **Fire behavior modeling**

We used the First Order Fire Effects Model (FOFEM) to replicate the exposure doses (duration and energy intensity) produced by our laboratory fire experiments and those predicted for the predominant fuels types within the culturally significant areas of the Jemez Mountains (Table 3). FOFEM is an application that integrates a number of separate models to predict the effects of prescribed burning and wildfires (Reinhardt and Dickinson 2010) and is commonly used in pre-burn planning to predict the consumption of forest (vegetative) fuels, smoke emissions, tree mortality and soil heating. We represented fuels within the study region as Fuel Loading Models (FLMs), derived from the LANDFIRE program (LANDFIRE 2008) for the Jemez Mountains. The Fuel Loading Model surface fuel classification system characterizes wildland surface fuel as classes of fuel beds that have similar fuel loadings and produce similar emissions and soil surface heating when burned using computer simulations (Lutes et al. 2009). FLMs provide a simple and consistent way for managers to describe onsite fuel for input into fire behavior and effects software (Sikkink et al. 2009). The models contain representative loading for each fuel component (e.g., woody and non-woody) and characterize fuel loading across all vegetation and ecological types. We included the three FLMs most predominant in the region – FLM 11: no duff, light litter (0.04 kg/m<sup>2</sup> or .18 tons/acre); FLM 21: light duff (0.74 kg/m<sup>2</sup> or 3.3 tons/acre), light litter (0.26 kg/m<sup>2</sup> or 1.16; and FLM 31: moderate duff (1.64 kg/m<sup>2</sup> or 7.31 tons/acre), moderate litter (0.42 kg/m<sup>2</sup> or 1.87 tons/acre).

Table 3. Duration and intensity (exposure doses) replicated by the First Order Fire Effects Model (FOFEM) for laboratory fire experiments and predominant fuels types, represented as fuel loading models\* (FLMs) within the Jemez Mountains.

Fire environment	Duration (minutes)	Intensity (kw/m <sup>2</sup> )
<b><i>Radiant heating</i></b>		
600 °C	1	32.96
600 °C	1.5	32.96
900 °C	1	107.4
900 °C	1.5	107.4
<b><i>Surface fire (flaming combustion)</i></b>		
0.5 kg/m <sup>2</sup> (2.2 tons/acre) litter fuel	1	36
1.0 kg/m <sup>2</sup> (4.5 tons/acre) litter fuel	1	73
1.5 kg/m <sup>2</sup> (6.7 tons/acre) litter fuel	1	109
FLM 11	1	13
FLM 31	1	131.6
FLM 21	1	102
<b><i>Ground fire (smoldering combustion)</i></b>		
2cm depth (6.7 tons/acre) duff fuel, 100% consumption	33	11
2cm depth (6.7 tons/acre) duff fuel, 60% consumption	25	4.5
6cm depth (19.4 tons/acre) duff fuel, 100% consumption	100	11
6cm depth (19.4 tons/acre) duff fuel, 60% consumption	25	4.5
FLM 31, 100% consumption	37	11
FLM 31, 60% consumption	29	4.7
FLM 21, 100% consumption	17	11
FLM 21, 60% consumption	14	6.1

\* FLM 11: no duff, light litter (0.04 kg/m<sup>2</sup> or 0.18 tons/acre); FLM 21: light duff (0.74 kg/m<sup>2</sup> or 3.3 tons/acre), light litter (0.26 kg/m<sup>2</sup> or 1.16 tons/acre); FLM 31: moderate duff (1.64 kg/m<sup>2</sup> or 7.31 tons/acre), moderate litter (0.42 kg/m<sup>2</sup> or 1.87 tons/acre)

## Key findings

### Key Finding #1: Fire type, duration, and intensity matter: Experimental fire environments and doses caused a range of archaeological fire effects

Fire environment (crown, surface, or ground), and dose, as determined by combinations of duration and temperature (crown fire simulations), fuel load and below-fuel surface moisture (surface fire simulations), or fuelbed depth and below-fuel surface moisture (ground fire simulations) produced a range of archaeological fire effects (Table 4). These fire effects were consistent within experimental fire environments, artifact types, and sample and treatment replicates - for example, fire fracture in chert and cracking in masonry were produced only in

simulated crown fires, and residue and color changes occurred in both surface and ground fires (but not simulated crown fires). For **ceramics** we observed color change (darkening on the surfaces, Figure 5) in all three fire environments. The most substantial alterations (i.e., changes that caused loss of information) were produced in surface fire experiments, as the result of direct flame contact; these included color change, residue deposits, cracking, and melting. Crown fire experiments produced the fewest substantial effects across ceramics classes. For **obsidian**, fire fracture occurred with greatest frequency in crown fire environments. Obsidian fire fracture, which results from thermal stresses from rapid heating and is affected by object mass, occurred in both large and small nodules but more frequently in larger nodules. Overall, larger nodules were more sensitive and had a highly likelihood of producing larger numbers of non-artifact fragments that could be misconstrued as artifacts. Fire fracture occurred in a small proportion of large flakes but no small flakes showed fire fracture. While fire fracture was nearly non-existent in the ground fire environments, alteration of obsidian hydration bands occurred in high percentages in the ground fire environments. These contrasting outcomes demonstrate the need to consider the kind of fire effect targeted and not just the artifact type under consideration. Further, hydration outcomes differed among the obsidian sources, with Cerro Toledo archaeological flakes having greater sensitivity to thermal alteration (between 94% [2cm fuel depth] and 100% [6cm fuel depth] loss) than Cerro del Medio archaeological flakes (between 38% [2cm fuel depth] and 100% [6cm fuel depth] loss). More complex outcomes (e.g., deepening of hydration) were observed for some hydration bands greater than 3.5 microns in depth, suggesting that heat alteration of adsorbed water in glass may be either non-linear or concentration-dependent. For **chert**, color change, residue, and surface sheen were the principal fire effects (Figure 6). These alterations occurred in the surface and ground fire environments but not with simulated crown fires, although crown fire experiments caused fracturing of samples at the highest temperatures, regardless of duration of heating. For **masonry**, residue deposits and color changes were the most prevalent fire effect (Figure 7) – occurring in most crown fire experiments and all surface and ground fire experimental doses. Cracking occurred only in high-temperature crown fire experiments and one ground fire (smoldering) experiment.

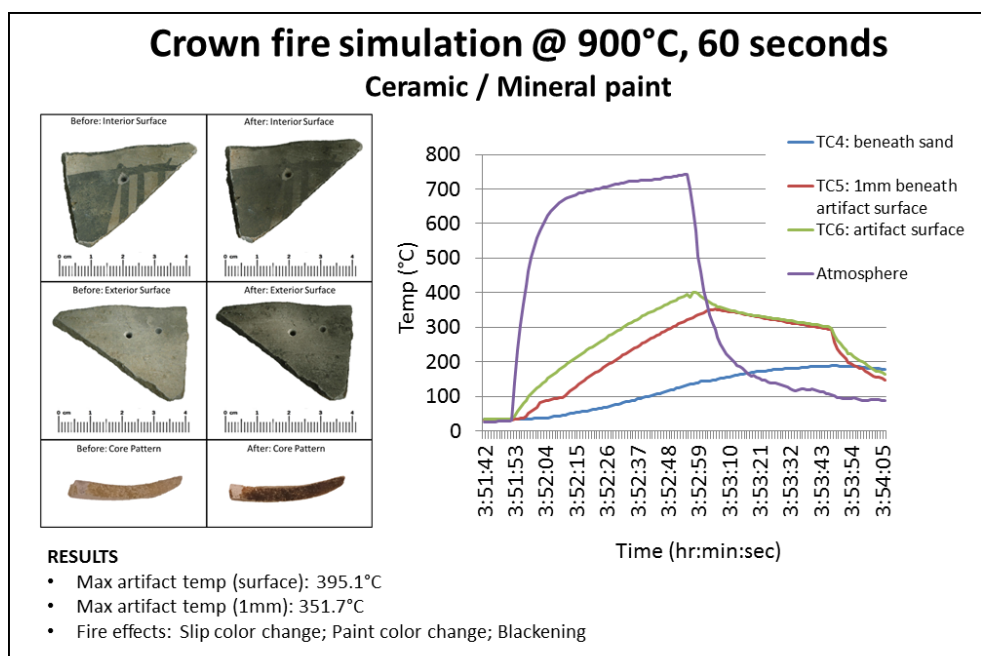


Table 4. Observed\* archaeological fire effects for ceramics, chert, obsidian and masonry for experimental fire environments and doses.

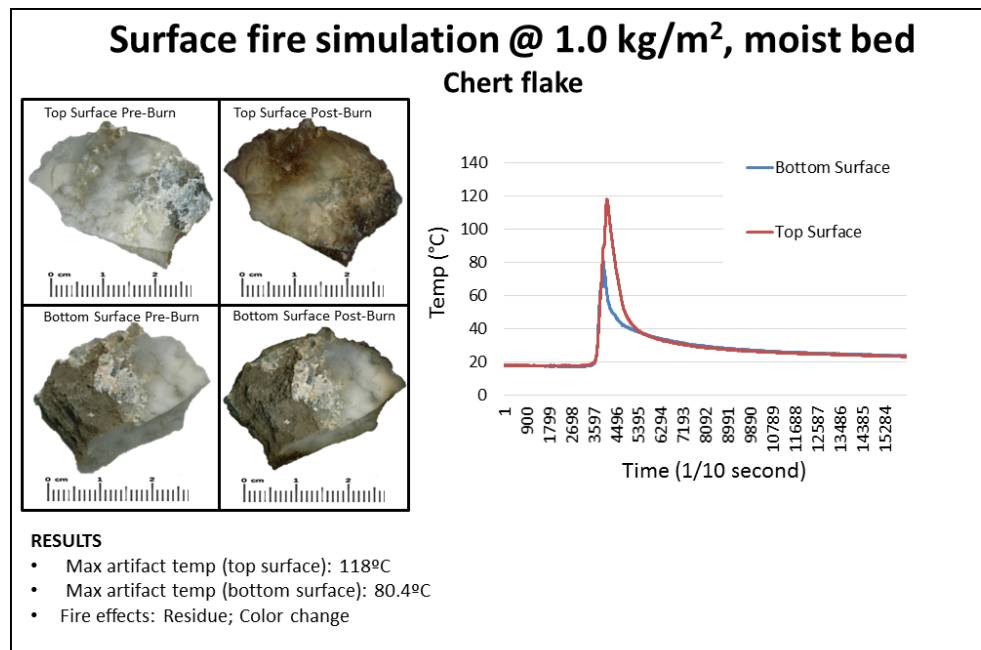
	<b>Ceramics</b>	<b>Chert</b>	<b>Obsidian**</b>	<b>Masonry</b>
<b><i>Crown fire environment (kiln tests)</i></b>				
600 °C, 60 sec.	Color change	None	Fracture: None	Color change
600 °C, 90 sec.	Color change	None	Fracture: nodules	Color change
900 °C, 60 sec.	Color change	Fracture	Fracture: nodules, flakes	Color change, cracking
900 °C, 90 sec.	Color change	Fracture	Fracture: nodules, flakes	Color change, cracking
<b><i>Surface fire environment (open flame beds)</i></b>				
0.5 kg/m <sup>2</sup> fuel, dry bed	Residue, color change	Residue	Fracture: nodules	Residue, color change
0.5 kg/m <sup>2</sup> fuel, moist bed	Residue, color change	Residue, color change	Fracture: None	Residue, color change
1.0 kg/m <sup>2</sup> fuel, dry bed	Residue, color change	Residue, color change, surface sheen	Fracture: nodules, flakes	Residue, color change
1.0 kg/m <sup>2</sup> fuel, moist bed	Residue, color change	Residue, color change, surface sheen	Fracture: nodules, flakes	Residue, color change
1.5 kg/m <sup>2</sup> fuel, dry bed	Residue, color change, melting, cracking	Residue, color change, surface sheen	Fracture: nodules	Residue, color change
1.5 kg/m <sup>2</sup> fuel, moist bed	Residue, color change, melting	Residue, surface sheen	Fracture: nodules	Residue, color change
<b><i>Ground fire environment (benchtop burn buckets/smoldering)</i></b>				
2cm fuel depth, dry bed	Residue, color change	Residue, color change	Fracture: None OH alteration	Residue, color change
2cm fuel depth, moist bed	Residue, color change	Residue, color change	Fracture: None	Residue, color change, cracking
6cm fuel depth, dry bed	Residue, color change	Residue, color change, surface sheen	Fracture: flake OH alteration	Residue, color change
6cm fuel depth, moist bed	Residue, color change	Residue, color change, surface sheen	Fracture: None	Residue, color change

\*Effects are noted when exhibited by one or more samples within artifact types

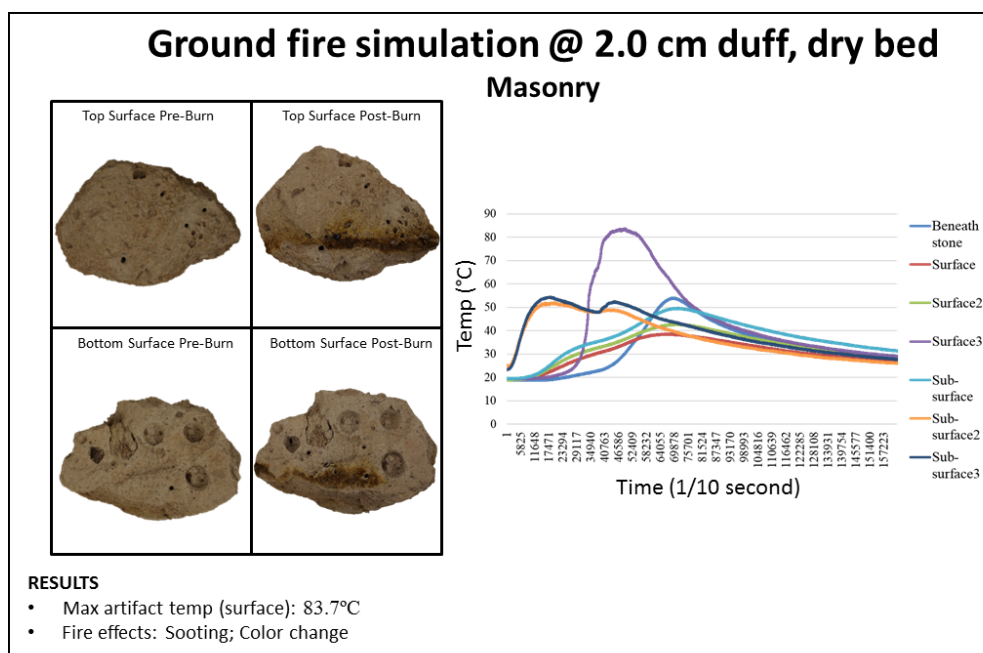
\*\*For obsidian, only fire fracture and hydration alteration are included.



**Figure 5. Fire effects and exposure dose associated with a crown fire simulation experiment, mineral painted ceramic artifact.**



**Figure 6. Fire effects and exposure dose associated with a surface fire simulation experiment, chert artifact.**



**Figure 7. Fire effects and exposure dose associated with a ground fire simulation experiment, masonry artifact.**

**Key finding #2: Not all fire effects are “substantial” (i.e., result in a loss of information)**

Archaeologists identify significant or substantial direct effects of fire as those that alter or diminish the information potential of artifacts and cultural features (Table 2). For individual specimens, some observed fire effects on experimental samples were not deemed “substantial” when considered in terms of loss of information. For example, sooting on artifacts may not persist indefinitely (i.e., the effects are reversible or diminish over time), or the obscuring effects of some surface residues may not interfere with documentation of key artifact characteristics such as chert source. Sooting and additive sheen on obsidian were observed frequently in the experimental results, but are not significant in terms of loss of information. Other changes are permanent but of low relevance, such as oxidation and color change in masonry. Our assessment of relevance or non-relevance for information loss provides a stronger basis for prioritizing preservation measures and treatment actions. We assessed substantial alteration or loss of information across an assemblage of tested artifacts (rather than those observable on individual artifacts) when 50% or more of samples were affected (Table 5). Using this criteria, substantial effects for ceramic assemblages occurred across all three fire environments, but for obsidian, chert, and masonry substantial effects occurred only in the higher dose crown fire environments.

Obsidian hydration alteration, which was tested only in dry-bed ground fire environments, was substantial at both fuel levels.

Table 5. Substantial\* loss of information (LOI) assessed for ceramics, chert, obsidian and masonry for experimental fire environments and doses. A substantial effect is one that causes loss of information (LOI) in one or more categories (Table 2). Experimental fire environments are assessed to have caused substantial effects when at least **half of the samples** for each dose were affected in a manner that caused LOI. Numbers in bold are the percent of samples tested, for each dose, for which we assessed a substantial loss of information in one or more categories.

Ceramics: CP = carbon paint, MP = mineral paint, GP = glaze paint, PU = plain utility, TU = textured utility. Obsidian: Flk = flakes, Nod = nodules, OH = obsidian hydration alteration

	Ceramics					Obsidian*			Chert	Masonry
	CP	MP	GP	PU	TU	Flk	Nod	OH		
<i>Crown fire environment (kiln tests)</i>										
600 °C, 60 sec.	33.3	33.3	16.7	33.3	66.7	0	0	--	0	0
600 °C, 90 sec.	33.3	33.3	66.7	0	33.3	0	25	--	0	0
900 °C, 60 sec.	33.3	66.7	33.3	50	50	5.6	83.3	--	16.7	50
900 °C, 90 sec.	100	100	100	50	83.3	22.2	66.7	--	66.7	50
<i>Surface fire environment (open flame beds)</i>										
0.5 kg/m <sup>2</sup> fuel, dry bed	77.8	100	55.6	66.7	55.6	0	5.6	--	0	0
0.5 kg/m <sup>2</sup> fuel, moist bed	22.2	66.7	33.3	22.2	33.3	0	0	--	0	0
1.0 kg/m <sup>2</sup> fuel, dry bed	100	100	88.9	88.9	77.8	1.9	27.8	--	0	0
1.0 kg/m <sup>2</sup> fuel, moist bed	77.8	88.9	44.4	33.3	55.6	3.7	5.6	--	0	0
1.5 kg/m <sup>2</sup> fuel, dry bed	88.9	100	88.9	77.8	77.8	0	27.8	--	0	0
1.5 kg/m <sup>2</sup> fuel, moist bed	66.7	88.9	33.3	44.4	77.8	0	38.9	--	0	0
<i>Ground fire environment (benchtop burn buckets/smoldering)</i>										
2cm fuel depth, dry bed	100	66.7	66.7	33.3	83.3	0	0	82.3	0	0
2cm fuel depth, moist bed	66.7	83.3	16.7	16.7	33.3	0	0	--	0	16.7
6cm fuel depth, dry bed	100	100	100	100	83.3	2.8	0	100	0	0
6cm fuel depth, moist bed	100	66.7	33.3	66.7	83.3	0	0	--	0	0

\* For obsidian, only fire fracture and hydration alteration included; hydration alteration experiments included only ground fire environments.

**Key finding #3: Satellite derived indices of fire severity (BARC) correspond well with site level observations of archaeological fire severity for some but not all fire severity classes.**

Satellite and field based severity classifications corresponded well (>65% probability of similar classification) for sites located in areas with BARC=Low and BARC=High severity. However, there was less agreement between field and satellite based classifications for sites in BARC=unburned and BARC=Moderate areas. Over 59% (205 of 346 sites) of sites located in a BARC=unburned areas had some observed burn effects in field surveys. Within sites classified



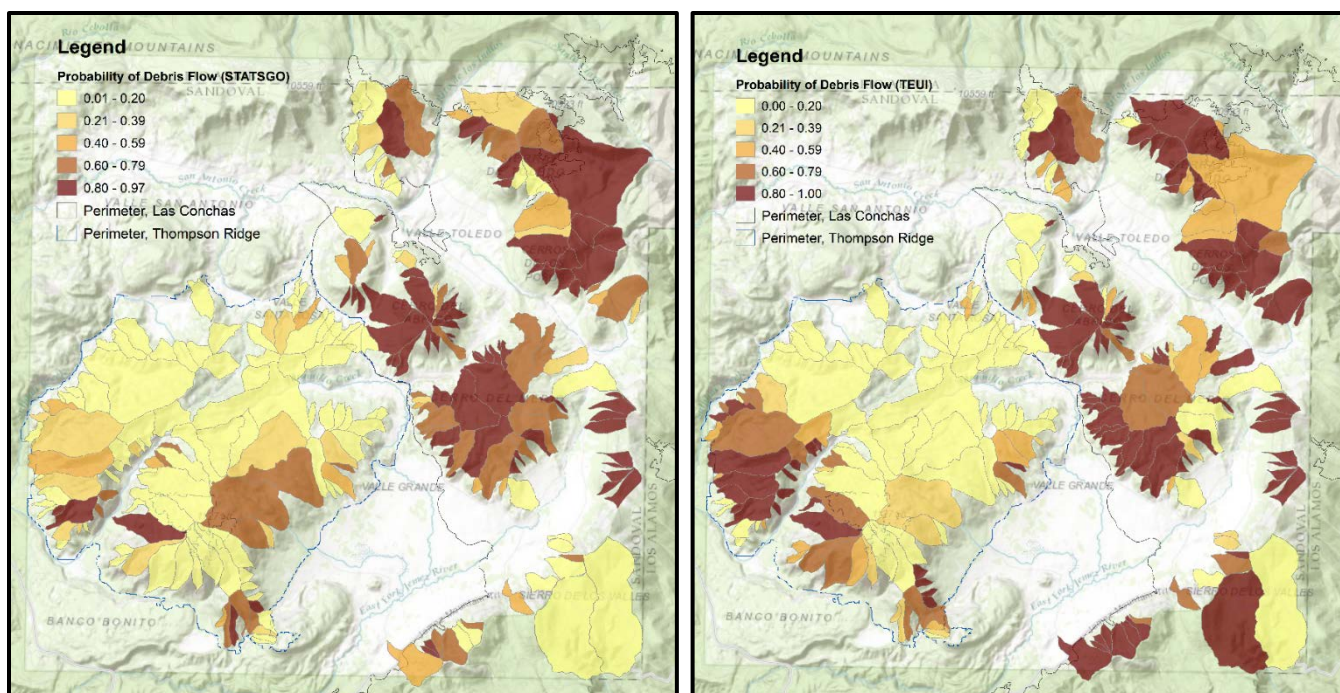
as moderately burned by BARC (n=119), field based assessment were equally likely to assign low, moderate and high burned designations (45, 40, and 30 observations, respectively).

**Key finding #4: The likelihood of observing fire impacts to archeological sites depends on site level vegetation and topographic characteristics**

For observations of fire effects made at the site level, climate variables appeared most important for individual tree accuracy but vegetation and topographic variables were best able to partition the data into effect/no effect classes. For observations made on objects within sites, vegetation and topography variables were most important for model accuracy and LANDFIRE Existing Vegetation Type (EVT) and again topographic variables were the best classifiers. For both site and within-site analyses, elevation was persistently an important variable. In general, sites with lower slope-cosine-aspect (southern, flat areas over northern steep areas), higher Heat Load Index (HLI, southwest facing slopes) and at lower elevations were more likely to experience fire effects. Sites within fires that occurred during hotter years (higher minimum temperatures, higher Burning Index [BI]) were also more likely to be classified as having a fire effect. We also found a tendency to see more fire effects in areas where fuel loads are relatively low and fuels support slow moving fires (e.g. models 101, 142, 161, 181 and 183), than in areas where fire spread is expected to be moderate or high (e.g. models 121,122, and 145). An exception to this is model 147 which indicates a very high fuel load with a high rate of spread. This exception aside, this trend is an indication that residence time of fire may have an influence on likelihood of observing fire impacts.

**Key finding #5: Probability and volume of debris flow is greatest for post-Las Conchas landscape**

Debris flow probabilities ranged from 0.7% to 97% (mean 45%) and tended to be greater for watersheds affected by the Las Conchas fire than those within the Thompson Ridge fire. Debris flow probability tended to be greater for smaller high elevation watersheds. Predicted debris flow volume ranged from 21m<sup>3</sup> to 40,932 m<sup>3</sup> (mean 2781.63m<sup>3</sup>) with larger watersheds having a tendency for greater predicted volume of debris flow (Figure 8).



**Figure 8. Comparison of debris flow probabilities under a 10-year, 30-minute rainfall of 24mm using distinct soils datasets.**

## Management implications

Our focus on ceramics, obsidian, chert, and masonry resources targets the most abundant components of Jemez Mountains archaeological assemblages and includes materials that are also found in the archaeological record elsewhere in North America. The degree to which the following management implications are relevant to other regions will be determined by the similarity of environmental conditions, archaeological assemblages, and management concerns and priorities.

## Archaeological fire effects

Fire environment and fuel type and amount cause a range of archaeological fire effects and in some cases result in substantial alteration – fire effects that diminish or destroy the information potential of artifacts. Our results demonstrate that different artifact types have different responses (tolerances or sensitivity) to fire. Managers may be able to adjust fuel treatments and fire management options based on the specific tolerances of artifacts; however, because artifacts are often clustered together within sites, treatment decisions may need to be based on the most

sensitive type(s) of artifact in assemblages. Specific to each artifact type included in our analysis, our results suggest the following treatment recommendations:

**Ceramics:** Substantial alteration of ceramics occurred across all of the fire environments. To minimize substantial alteration of ceramics site treatments can first target surface fuels that promote direct flame contact with surface artifacts. If direct flame contact can be minimized, the next level of protection would be to reduce the potential for smoldering near sherds through reduction of duff fuels. Carbon and mineral painted wares were more sensitive to thermal alteration than glaze or utility wares; thus, consideration of the specific types of ceramics present is critical.

**Obsidian:** Radiant heating doses typical of crown fires are likely to cause fracture in surface assemblages of obsidian. Open flame environments and resulting direct flame contact may also cause fracture. Artifact size, shape, and source material likely affect sensitivity to fire fracture. Ground fire environments with deeper fuels are demonstrated to cause more substantial alteration to the chronometric potential held in obsidian hydration bands, although this may differ depending on obsidian source material. Removal or dispersal of fuel jackpots or any heat source that can produce high radiant heat loads are a high priority for protection of obsidian artifacts. Prescribed burning to maintain lesser ground-fuels in forested environments may provide this lessening of fuels.

**Chert:** Radiant heating doses typical of crown fires are likely to cause color changes in surface chert artifacts, but not to a degree that would obscure sample origin (i.e., provenance). High-intensity crown fires or radiant heat loads may cause cracking or fracturing; thus, removal or dispersal of fuel jackpots or any heat source that can produce high radiant heat loads are a high priority for protection of chert artifacts.

**Masonry:** Radiant heating doses typical of crown fires can cause cracking in masonry, potentially compromising the stability and persistence of standing walls and architectural features. Removal or dispersal of fuel jackpots or any heat source that can produce high radiant heat loads are a high priority for protection of masonry features.

## **Fuel treatments for archaeological site protection at sites with masonry features**

We developed guidelines for proactive fuels removal and thinning within boundaries of archaeological sites with masonry features (i.e., “rubble mounds,” piles of stone from walls or buildings that have fallen), prior to prescribed burning and in areas with likelihood of high severity wildfire. These guidelines minimize the risk of unwanted (“substantial”) fire effects to the archaeological assemblages included in this project. Suggested treatments minimize energy output, heating duration, and flame contact in a manner consistent with our study results.

Generally, recommendations are to manually remove or reduce down and dead surface fuels and thin the forest canopy to fuel loads and arrangement consistent with pre-suppression levels and aligned with historical fire regimes and vegetation types. These fuel treatments are specific for the vegetation community within which archaeological sites with masonry features or rubble mounds are located (e.g. ponderosa pine forest versus piñon-juniper woodland). These measures may not be practical or warranted at large artifact scatter sites. Specifically:

### **For rubble mound sites in ponderosa pine and mixed conifer**

- Remove dead/down logs that are on the site, especially those in direct contact with architectural features – this will minimize the duration and intensity of exposure (reduce smoldering).
- Cutting should be done with chain saws; no mechanical ground disturbing equipment. Directionally fell trees away from architectural features.
- On architectural features, cut all trees less than 16 inches diameter at breast height (DBH); use professional judgment on 16 to 24 inches DBH trees; leave most trees greater than 24 inches DBH (which would survive a fire). This minimizes potential for localized crowning and high radiant heat pulses within site boundaries.
- On artifact scatters around architectural features thin trees to a 20 foot spacing; favor leaving larger trees (>16” DBH).
- Consider potential for post-fire mortality of large-diameter trees that can fall into sites or cause damage from root upheaval – these may require raking or other clearing of surface fuels to prevent mortality from excessive bole scorch.
- Consider whether stumps are present in or near wall alignments or architectural features. If these stumps are fully consumed they may topple walls or undermine site stability when large root masses burn out. Stumps may be cut flush to ground level and covered with mineral soil to protect from burnout.

- Prune trees up to 4 feet above ground level to remove ladder fuels.
- Slash: Generally, no slash piles should be left within site boundaries. Slash should be removed outside the site boundary at a far enough distance to minimize radiant heating of site features and artifacts. Small amounts of slash can be scattered (but not piled) within site boundaries.
- Place logs on contour, away from site features or areas of artifacts. Remove branches so logs will be in contact with ground surface and decompose more quickly.

**For rubble mound sites in piñon-juniper woodlands:**

- Minimally treat live fuels, paying special attention to potential vectors of fire spread (i.e., potential for fire to spread onto an archaeological site)
- Cutting should be done with chain saws; no mechanical ground disturbing equipment. Directionally fell trees away from architectural features.
- Around architectural features, cut trees so that canopies are at a 10 foot spacing (distance from outer crowns).
- Slash: Scatter all slash; do not make large piles. Place slash over rills, head cuts, erosional areas, and sheeting outside of the site boundary. Small amounts of slash can be strategically placed in head cuts inside the site boundary as directed by an archaeological monitor.

We developed guidelines for **best ignition practices** that apply across sites (including non-architectural sites) in all vegetation types, including:

- Larger ignition buffers around archaeological sites, which will allow fire to spread through sites without adding extra ignition via torching.
- Tailored ignition patterns that reduce fuel hazards around sites, but mitigate the potential for high severity fire areas that occur with terrain or fuels jackpot.
- Strategic ignition patterns to control fire behavior on approach to and within archaeological sites, to minimize tree mortality.
- Within archaeological site boundaries, consider whether fire can carry across the site from ignition points outside of the site boundary. If spreading fire is not likely within the site due to sparse and discontinuous fuels and/or the presence of barriers to fire spread (rock walls or mounds) do not use a drop torch to burn out shrubs, stumps, logs, or other fuels within the site, as these areas of high-intensity fire can damage cultural resources.

## Archaeological fire severity modeling

Our analysis shows that BARC maps can reflect the probability of observing coincident fire severity levels during field surveys where BARC maps indicate low or high burn severity.

However, there were much lower probabilities of finding coincident severity in field surveys for



areas classified as unburned or moderately burned by BARC. Our findings imply that BARC maps provide a fairly good estimate of conditions within sites for areas recognized as burned in image analysis but may not capture all impacts to archeological sites, especially where BARC does not detect fire impacts to vegetation.

Prediction for fire impacts: Overall, trends from this analysis indicate site exposure and/or residence time of fire influences the likelihood of observing fire impacts. Where vegetation and topography appear to be important predictors of burn severity there are significant implications for traditional forest management (e.g. fire suppression) that lead to increased live and dead fuels (Birch et al., 2015). Proactive removal of fuels on or adjacent to sites is suggested to reduce the direct effects of fire-related changes to artifacts (Johnson 2004). In some cases, removal of a sample of surface artifacts like obsidian and ceramics may be the best strategy for preserving artifacts for future analysis (Johnson 2004). Predictions of where and how likely severe fires occur can help managers determine where and how aggressively to suppress fires and manage fuels (Holden et al. 2009). For instance, management strategies might focus on fuel reduction in areas with vegetation and topographic positions associated with high probability of fire effects (Birch et al., 2015). For areas with low probability of fire effects, it may be more advantageous allow high severity burns where they are ecologically sound (e.g. north-facing slopes, Birch et al., 2015).

### **Characterization of post-fire debris flow hazard**

Post-fire debris flow and sedimentation represent huge threats to the integrity of watersheds and archeological sites contained within them. Typically areas at greatest risk are those downslope of fire scars in areas where the slope and drainage channels become less steep (Johnson 2004). Our results identify several areas of potential concern. Burn severity as well as slope and topographic ruggedness are important predictors of post fire debris flow probability and, thereby, at-risk archeological sites. Application of models to predict post fire debris flow risk can help managers identify sites of high priority for recovery or stabilization. These models can also be applied to unburned landscapes under various precipitation and burn conditions to identify high priority sites prior to wildfire (e.g. Tillery and Haas 2016).

## Relationship to other recent findings and ongoing work

Our work adds key experimental finding to the recently released guide *Wildland fire in ecosystems: effects of fire on cultural resources and archaeology* (Ryan et al 2012). Our results add to the ongoing dialog about how cultural resources are affected by fire. For example, as noted by Rude and Jones (Rude and Jones 2012), blackening is the most common fire effect on pottery. Several studies note that blackened sherds are still identifiable as to type (Picha et al. 1991, Ruscavage-Barz 1999). In opposition, this research suggests that type identification can be affected by the darkening of surfaces. Subtle differences in surface color can be part of ceramic type identification and the ability to compare the pre-burn color to post-burn surfaces showed substantial change in the surface colors. For obsidian, this is the first systematic study of fire fracture. Dissemination of descriptive information to identify fire fracture, and to understand the conditions under which it occurs, will aid archaeologists in minimizing the effect on sites and in avoiding mistaken identification of non-artifact pieces. For analyses of obsidian hydration alteration, this work builds on the compilation of studies provided in Loyd et al. (2002) by comparing effects across explicitly identified obsidian source materials. This project also complements and extends recent work to understand fire, climate, and human interactions in the Jemez Mountains (Swetnam et al. 2016). Our project provides key insight into how to preserve important data sources that feed explorations into past fire, climate, and human interactions.

## Future work needed

We recommend additional experimental work focused in five areas: 1) Exploration of fire effects on thermoluminescence (TL) dating, a technique used to determine the age of ceramics and known to be affected by fire exposure. Additional experimentation on archaeological ceramics samples could to address questions such as *How does fire (and different fire environments) influence the dating potential of ceramics? For subsurface artifacts, how does depth of burial affect dating potential?* 2) Investigations of obsidian fire effects across multiple geochemical sources from diverse regions, and evaluation of archaeological artifacts representing a wide range of prehistoric ages to assess whether significantly deeper hydration bands (i.e., occurring on older artifacts) respond differently to heat than shallower hydration bands (i.e., found on younger artifacts); 3) Determination of fire effects on additional artifact types and materials, including rhyolitic and basalt materials, groundstones, faunal bone, and historical artifacts such

as glass, metal, and porcelain (for example, building on the work of Sturdevant 2009); 4) Impacts of repeated fires of varying severity, and 5) Persistence of archaeological fire effects such as sooting, residue, and color change, and long-term and cumulative impacts of effects such as cracking and spalling on durability of archaeological materials. Further, we recommend comprehensive and long-term monitoring of fuel treatment effectiveness for reducing substantial alteration to cultural resources.

## Acknowledgements

We gratefully acknowledge the support, intellectual contributions, and efforts of Ronald Loehman (University of New Mexico), Rory Gauthier (National Park Service), Dennis Carril (US Forest Service, Santa Fe National Forest), Tom Swetnam (University of Arizona), Mike Bremer (US Forest Service, Santa Fe National Forest), and Dan Jimenez, Cyle Wold, Sarah Flannery, Daniel Congdon, and Faith Ann Heinsch (US Forest Service, Rocky Mountain Research Station Fire Sciences Lab), and of our ArcBurn advisory board, Mark Altaha, Mike Bremer, Garry Cantley, Michelle Ensey, Linn Gassaway, Dan Hall, Margaret Hangan, Lisa Hanson, Jeremy Kulisheck, Joe Lally, Ron Maldonado, Norm Nelson, Jason Nez, Harding Polk, Will Reed, and Marla Rodgers. This work would not have been possible without them. Any use of trade names is for descriptive purposes only and does not imply endorsement by the US Government.

## Deliverables

### Project website

<http://www.forestguild.org/Arcburn>

### Publications

Kneifel, Rebekah. 2015. *Radiant heat effects on ceramic artifacts from the American southwest: from experimental results to site treatment guidelines*. Master's Thesis, University of Montana, Department of Anthropology, May 2015.

Contributions to: Lally, J. 2015. *DON'T BLAME IT ALL ON OXYGEN: A response to Swenson*. Pottery Southwest, publication of the Albuquerque Archaeological Society.

ArcBurn results reported in Parmenter, R.R. (compiler). 2015. *Summary Report for 2010-2014 Southwest Jemez Mountains Collaborative Forest Landscape Restoration Project (CFLRP) Monitoring Program: Natural and Cultural Resources Sections*. Valles Caldera National Preserve, Jemez Springs, New Mexico, USA. 33 pp., available here: <http://www.nmconservation.org/swjm/cflrp-monitoring-report-2010%E2%80%932014>

### **Conference presentations (outside of organized ArcBurn special sessions)**

Kneifel, R., R. Loehman, C. Constan, and J. Reardon. 2015. *Radiant Heat Damage to Southwest Ceramic Artifacts: Turning Experimental Results into a Mitigation Guide*. Montana Archaeology Society 57<sup>th</sup> Annual Meeting, Pray, MT, April 2-5.

Kneifel, R., R. Loehman, C. Constan, J. Reardon. 2015. *Fuel Treatment Guidelines to Reduce Wildfire Damages to Ceramic Artifacts in the American Southwest*. General Session, Practices and Products of Cultural Resource Management in North America. Society for American Archaeology 80<sup>th</sup> Annual Meeting, San Francisco, CA, April 15-19.

Loehman, R. 2014. *In the Line of Fire: Risk Mitigation and Protection of Cultural Resources in Fire-Prone Environments*. Special Session (invited), Wildland Fire Risk Assessment and Decision Making. Presented by PI R. Loehman, Association for Fire Ecology Large Wildland Fires Conference, Missoula, MT, 2014.

Steffen A. 2015. Panel presentation: Forum organized by the Union of Concerned Scientists: “Resilience, Archaeology and Global Warming: What We Can Learn from Past Human Responses to Climate Change That Can Help Us Today”, 80<sup>th</sup> Annual Meeting of the Society for American Archaeology, San Francisco, April 2015.

Steffen, A. and R. Loehman. 2015. *ArcBurn: Measuring Fire Vulnerability in Southwestern Landscapes*. Symposium, Fire and Humans in Resilient Ecosystems in the American Southwest. Society for American Archaeology 80<sup>th</sup> Annual Meeting, San Francisco CA April 15-19.

Steffen, A. and R. Loehman. 2014. *Landscape Fire in the Western US: Threats to America's Past in a Time of Changing Futures*. IUCN World Parks Congress (invited). Sydney, Australia, November 12.

Loehman, Rachel A., and Anastasia Steffen. 2012 *ArcBurn: Linking field-based and experimental methods to quantify, predict, and manage fire effects on cultural resources*. Poster presented at the 5<sup>th</sup> International Fire Ecology and Management Congress, Portland, OR, December 3-7.

### **Organized conference sessions and presentations**

1. New Mexico Archeological Council Fall 2015 Conference, November 14, 2015, Albuquerque, NM: Fire And Archaeology in the Southwest  
**Archaeological Fire Effects (ArcBurn)**, Session organized by Ana Steffen and Amalia Kenward
  - Ana Steffen & Rachel Loehman - *ArcBurn: Quantifying Cultural Resources Fire Vulnerability in Southwestern Forests*

- Connie Constan, Rachel Loehman, and Jennifer Dyer - *Wildfire Effects to Archaeological Ceramics in the Jemez Mountains*
  - Zander Evans - *Connecting Forest Management, Fire, and Cultural Resources*
  - Megan Friggens - *Modeling Archaeological Fire Effects and Post-fire Erosion*
2. Association for Fire Ecology 6<sup>th</sup> International Fire Ecology and Management Congress, November 16-20, San Antonio, TX  
**Bridging gaps between fire ecology and archaeology: A millennial perspective on managing cultural-ecological landscapes**, Special session organized by Rachel Loehman
- Rachel Loehman, Chris Roos, and Tom Swetnam - *Fire and fire surrogates in cultural-ecological landscapes of the prehistoric Southwest*
  - Nicolas V. Kessler\* and Ronald H. Towner - *Long-term land-use and environmental change in Cebolla Canyon of western New Mexico*
  - Anna Patterson- Klimaszewk, Scott Mensing, and Linn Gassaway - *Potential Native American impacts on the forest structure, Sequoia National Forest, California*
  - Thomas Hanson - *Dynamic Entanglements on the Fringe: Fire, Community, and Ecological Change in Lowland Bolivia*
  - Rich Guyette - *Embracing 'smart ignitions' in the combustion dynamics of ecosystems*
  - Anastasia Steffen and Rachel Loehman - *ArcBurn: Measuring and Managing Fire Vulnerability of Southwestern Cultural Landscapes*
  - Jun Kinoshita, Linn Gassaway, and William Reed - *History of Archaeologists on the Fire Line*
  - Jennifer Dyer - *Restoring Fire at the Landscape Scale to Protect Sacred Sites*
  - Jay Sturdevant - *Historic Archeology, Climate Change, and Wildland Fire: A Midwestern Perspective on Future Threats to Resource Preservation*
  - Rachel Loehman, Connie Constan, and Jennifer Dyer - *Trial by fire: Do fuel treatments work to mitigate wildfire damages to cultural resources?*
  - Dennis Carrill - *Managing the Pino Fire for Resource Benefit: Insights on fire management and archaeological resources*
  - Megan Friggens, Rachel Loehman, and Connie Constan - *A GIS-based model for predicting wildfire-caused damages to archaeological sites and artifacts*
  - Rebekah Kneifel, Zander Evans, and Jen Dyer - *Fuel Treatment Guidelines for Reducing Wildfire Damages to Cultural Resources in the American Southwest*
  - Panel discussion - *Bridging gaps between fire ecology and archaeology in theory and practice*
3. Association for Fire Ecology 3rd Southwest Fire Ecology Conference, November 28 – December 2, 2016 Tucson, AZ  
**Coexistence: cultural resources, fuels treatments, fire management**, Special session organized by Zander Evans
- Will Reed - *Heritage Guidance for BAER*
  - Rachel Loehman - *Linking field-based and experimental methods to quantify, predict, and manage fire effects on cultural resources*
  - Connie Constan - *Management considerations and wildfire effects on archaeological materials in the Jemez Mountains*



- Jen Dyer - *Partnering with Tribes to Protect Cultural Resources in an Era of Megafires*
- Megan Friggens - *Fire and Cultural Resources: a method for assessing potential impacts of wildfire on archeological sites*
- Ana Steffen - *Managing lithic scatters and fire: If they are made of stone, why treat them like glass?*

### **Training/outreach/workshops**

*ArcBurn: Monitoring and measuring fire effects on cultural resources.* Fact sheet and briefing paper, Santa Fe National Forest. In conjunction with monitoring activities on the Pino wildfire, August-September 2014.

*ArcBurn Resource Library.* Online resource library hosted by FRAMES.

[www.frames.gov/arcburn](http://www.frames.gov/arcburn)

Constan, C., J. Civitello, and A. Steffen. 2015. *ArcBurn*. East Jemez Resource Council, Española Ranger District, January 28.

Constan, C. 2015. *Protecting Cultural Resources in Fire-Prone Landscapes*. Las Cumbres, newsletter of the Santa Fe National Forest (v.4, no.1).

Constan, C. 2016 *Fire effects on ceramics*. RT-130 Fire Refresher. Jemez Ranger District. April 5, 2016.

Constan, C. 2016 *Pino fire effects*. Fire Management Officers meeting. Carson/Santa Fe National Forests. April 18, 2016.

Constan, C. *ArcBurn*. 2015. Site Lines, newsletter of the Santa Fe National Forest Site Stewards (v.13, no.1). [www.sfnfsitestewards.org/news/news\\_2015\\_01.pdf](http://www.sfnfsitestewards.org/news/news_2015_01.pdf)

Evans, A. 2016. *Prescribed fire and cultural resources*. Discussion at the New Mexico Prescribed Fire Council Meeting. Socorro, NM, April 6.

Farella, J. 2013. *Legacy wood: how to recognize an important archeological resource*. webinar: <https://forestguild.mitel-nhwc.com/join/fbbswfv>

Kneifel, R. 2014. *Fuel Treatment Guidelines to Reduce Wildfire Damages to Ceramic Artifacts in the American Southwest*. Brown Bag Lecture. University of Montana Anthropology Department, Missoula, MT, October 31.

Kneifel, R. 2015. *ArcBurn Project: Missoula Fire Sciences Lab*. Archaeology Month public outreach at Fort Missoula, Missoula, MT, April 11.

Loehman, R. 2016. *Smoke from a Distant Fire: Human-Wildfire Interactions in Prehistoric Forests of the Southwestern US*. Webinar: <https://forestguild.mitel-nhwc.com/join/vsrwxxw>

ArcBurn: Quantify, predict, and manage fire effects on cultural resources

Nez, J.. 2015. *A Diné Perspective on Cultural resources and fire management*. webinar:  
<https://forestguild.mitel-nhwc.com/join/jrczrvp>

Steffen, A. Congressional Briefing on Climate Change and At-Risk National Landmarks, organized by Union of Concerned Scientists. Panel presentation and discussion, Hart Senate Building, Washington, D.C., May 20, 2014.  
<http://www.eesi.org/briefings/view/052014landmarks>

Steffen, A. 2016. *Archaeology, Fire and ArcBurn: Developing Tools to Query the Past, and Cope with the Future of Landscape Fire*. Presentation in Workshop: Global Environmental Change Threats to Heritage and Long Term Observing Networks of the Past: The Arctic Case and Beyond, World Conservation Congress, Honolulu, September 4, 2016

### **Media**

Ana Steffen was interviewed by Sarah Jane Keller, May 18, 2016, which resulted in an article on Smithsonian.com <http://www.smithsonianmag.com/science-nature/why-archaeologists-are-setting-spiritually-important-early-american-sites-fire-180959259>

Ana Steffen was interviewed by Patricia Brown of The New York Times for an article on vulnerability of archaeological artifacts to climate changes and fire, September 23, 2015.

Rachel Loehman and Connie Constan were guests on the “Great Outdoors NM” radio show on AM 810 and FM 99.9 KSWV Que Suave, August 28, 2014. They discussed the Pino Fire and the ArcBurn instrumentation that was occurring.

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## Appendix 1. Definitions of thermal effects on archaeological materials

Effect	Archaeological materials affected	Definition	Reference(s)
Additive sheen	Obsidian	A surface coating caused by organic build-up. Often has a characteristic "gun-metal" or smooth, burnished appearance.	Steffen 2005, 2002; Buenger 2003
Altered sheen	Chert, obsidian	A surface alteration that is silvery and reflective in appearance, often with a crinkly texture. In obsidian, may be due to shallow, tiny bubbles just below the artifact surface.	Steffen 2005, 2002; Nakazawa 1998, 2002
Blackening	Ceramics	Surface darkening due to exposure to heat or smoke (similar to fire clouding), or the presence of a reducing atmosphere.	Rice 1987
Color change	Ceramics, chert, masonry, obsidian	An observable change from the original, pre-fire color. Generally due to an alteration in the mineral composition of a specimen during exposure to heat.	Ryan et al. 2012
Core pattern change	Ceramics	Alteration of core pattern from heat exposure. Each ceramic profile has a "core pattern" of contrasting oxidized and reduced bands which range from one solid color throughout the core to multiple stripes of two or more colors.	Van Hoose 2006; Rice 1987
Crazing	Ceramics, chert	Fine, non-linear or latticed surface cracks.	Buenger 2003; Rice 1987
	Obsidian	A network or array of shallow cracking on object surfaces occurring only very near the surface; does not extend into the body of the object. Obsidian crazing can be very fine to somewhat coarse. The patterning of crazing often can appear as a delicate network or as somewhat parallel curved lines. Obsidian crazing can be readily distinguished from radial lines because the latter does not form interlocked shapes or closed polygons.	Steffen 2005, 2002; Nakazawa 1998, 2002; Trembour 1979, 1990
Cracking	Ceramics, chert, masonry, obsidian	Shallow crevices that typically penetrate deeper than the surface. For ceramics, cracks may penetrate	Buenger 2003; Steffen 2005, 2002;

Effect	Archaeological materials affected	Definition	Reference(s)
		beyond the slip and into the paste. In obsidian, surface cracking is a secondary state of surface crazing, caused by stretching of a finely crazed surface when expansion of the glass occurs with bubbling, vesiculation, or other plastic deformation.	Nakazawa 1998, 2002
Fracture	Ceramics, chert, masonry	Breakage into multiple pieces, and/or the presence of fractures or fissures that penetrate deeply into a specimen.	Buenger 2003
	Obsidian	Breakage caused by thermal stress. Can appear similar to intentional knapping reduction but initiates from within the item rather than at a margin or edge as in externally applied force. Fracture surfaces can express rings or waves of force but are lacking bulbs of percussion. Other fracture markings may be shared with conchoidal fractures from knapping, such as gullwings and hackles, but certain characteristics, including mist and parabolas, are distinctive of fire fracture surfaces.	Steffen 2005, 2002; Tsirk 1996
Hardness change	Ceramics	Resistance of the surface to deformation, based on the Mohs Hardness Scale.	Rice 1987
Hydration alteration (microscopic)	Obsidian	Hydration bands on obsidian surfaces (observed under magnification) are used by archaeologists to measure the relative age of obsidian artifacts, with deeper bands indicating greater age and shallower bands demonstrating lesser age. The depth of hydration can increase with heating, often with concomitant blurring of the boundary line, or the band can be lost entirely.	Trembour 1979, 1990; Origer in Solomon 2002; Skinner et al. 1997
Matte finish	Obsidian	A dulling of one or more surfaces. This may look like "weathering" or a lusterless patina.	Steffen 2005, 2002; Bennett & Kunzmann 1985; Nakazawa 1998, 2002



<b>Effect</b>	<b>Archaeological materials affected</b>	<b>Definition</b>	<b>Reference(s)</b>
Melding/ fusion	Obsidian	Joining of glass pieces, often those created by fire fracture.	Steffen 2005
Oxidation	Ceramics	Molecular reaction of clay to oxygen and heat. Observed in pigment used for surface treatment, can include a change in color from the original pigment (black to red) or the combustion of the pigment entirely.	Buenger 2003; Rice 1987
Paint, slip, or surface color change or loss	Ceramics	Any observable color change of a specimen from the original pre-fire color.	Buenger 2003
Residue	Ceramics, chert, masonry, obsidian	An oily surface deposit, difficult to wash off.	
Sooting	Ceramics, chert, masonry, obsidian	Black carbon powder from smoke, can generally be rinsed off.	
Spalling or potlid fracturing	Ceramics, chert, masonry, obsidian	The exfoliation of a portion of the original surface of a specimen due to differential heating and pressure release.	Buenger 2003
Subsurface bubbles	Obsidian	Individual (discrete) bubbles that develop below the subsurface, but without the abundance, density, and interconnectedness of vesiculation. These incipient bubbles can be sparse or plentiful, and have been observed to be influenced by compositional or textural characteristics of the glass. Usually there is little to no appreciable object deformation because the internal bubbles are not developed sufficiently to compromise the shape of the glass matrix.	Steffen 2005, 2002; Nakazawa 1998, 2002
Temper alteration	Ceramics	Chemical, molecular, or surficial alteration of the non-plastic, geologic or organic material inclusions within clay.	Rice 1987
Vesiculation	Obsidian	Formation of abundant and interconnected bubbles throughout the interior or near surface. Causes deformation that can result in an increase in object volume or size. Specimens can be either completely or partially vesiculated.	Trembour 1979, 1990; Steffen 2002, 2005; Nakazawa 1998, 2002; Shackley and Dillian 2002

<b>Effect</b>	<b>Archaeological materials affected</b>	<b>Definition</b>	<b>Reference(s)</b>
Vitrification/ melting	Chert	Melting and fusion of glassy minerals within clay during high-temperature firing of pottery (above 1000°C), resulting in loss of porosity; the process in which a substance melts and turns to glass.	Ryan et al. 2012; Rice 1987