ARTICLE

BONE-FUELED FIRES IN A TREELESS ENVIRONMENT: PRODUCTION, ARCHAEOLOGICAL SIGNATURE, AND TAPHONOMIC PROCESSES

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ABSTRACT

In areas without available wood, other fuel sources must be found. Backed by evidence of bone-fueled fires found in the 14,000-year-old component of the Swan Point site in the interior of Alaska, alternate fueled fires are explored and their unique characteristics described. There were four types of fires: a bone fire, a dung fire, a twig fire, and a fire with both bone and dung combined. Experimental fires fueled by bone, dung, twigs, or bone and dung combined are compared to the late Pleistocene burned features at the Swan Point archaeological site. The ability to discern and sample nonwood-fueled fires archaeologically is then discussed more generally. Taphonomic effects are studied in outdoor burn sites over time and in laboratory experiments designed to mimic freeze/thaw cycles and water percolation. Short term taphonomic changes produce residues which resemble those found at Swan Point.
Keywords: Swan Point, bone-fueled, hearth, dung, taphonomy, fire, experimental archaeology

INTRODUCTION

Modern humans use fire for warmth, cooking, waste disposal, illumination, protection from predators, and socialization. Today metal fire pits provide places for evening gatherings, relaxation, and socializing, even in large urban areas. Fire has always been an important but essential aspect of our survival and wellbeing, especially in marginal environments.

When building fires, wood is the most universal fuel. In modern societies, coal and petroleum-based products are also used. However, for most prehistoric societies, these options were not available, and wood was viewed as the most available fuel source. As people moved into treeless or tree-scarce environments, other sources of fuel were used. The most readily available were dung, animal fat and bone, used either as a substitute for wood or as a means of extending a scarce wood supply (cf. Bosch et al. 2012; Buonasera et al. 2015; Clark 1952; Crass et al. 2011; Darwent 2003; Dibble et al. 2009; Kedrowski et al. 2009; Kuzmin 2008; Marquer et al. 2010, 2012; Mentzer 2009; Schiegl et al. 2003; Soffer 1985; Thèry-Parisot 2002a, 2002b; Yravedra et al. 2017). Even in areas with available wood, such as the Aurignacian levels of Pataud in Dordogne, France, bones were used as fuel to a greater degree than wood (Thèry-Parisot 2002b; White et al. 2017).

Archaeologists are trained to look for wood-fueled hearths during excavation, with traditional signs of hearths being charcoal and ash, usually in a bowl-shaped depression or an area surrounded by stones with a reddening of the soil substrate. Scraps of burnt bone, broken lithics,

fire-cracked rock, and other items may occur. These items are usually considered trash tossed into the fire for disposal, not necessarily fuel.

Nontraditional hearths fueled by bone are more elusive and easily overlooked (Crass et al. 2011). Even hearths fueled with wood may have an ephemeral signature (Surovell 2022; Surovell and Waguespack 2007). Having recognized bone-fueled hearths from the earliest component at Swan Point in central Alaska (ca. 14,200 cal BP) (Fig. 1) (Bever 2006; Crass et al. 2011; Kedrowski et al. 2009; Reuther et al. 2023), we began a number of experimental fires to (1) demonstrate the taphonomic processes that affect bone-fueled hearths; (2) determine what signatures, if any, hearths fueled by bone, dung, and/or shrubs would produce; and (3) observe what advantages these alternative fuel sources may have in terms of heat, smoke, or odor production and the time requirement for tending the fire.

MATERIAL AND METHODS

Initial experimental bone-fueled fires were conducted under controlled conditions in a laboratory under a large fume hood and are described in detail elsewhere (Crass et al. 2011). As the burning experiments described here were conducted outside in natural uncontrolled environments, the observations and estimates of materials and products of the burns are predominately qualitative. However, we are able to report useful observations on how to identify bone-fueled hearths in the archaeological record and explain some of the taphonomic processes that reduce those hearths to the ephemeral signatures observed.

OUTDOOR BONE-FUELED FIRES

Wisconsin

In 2006, the first outdoor experimental fire fueled with approximately 60 gallons of dried red deer (*Cervus elaphus*) bones and ignited with braided, dried grass burned for six hours in northern Wisconsin (Fig. 2A). Bones were added to the fire as needed for six hours, after which the fire was allowed to naturally extinguish. The next morning the unburnt bones were removed (Fig. 2B) and the remaining bones were covered with a couple inches of sand to prevent attracting local carnivores (Fig. 2C).

Alaska

In 2009, three experimental bone-fueled fires were set at Shaw Creek Archaeological Research (SCAR) facility near Delta Junction, Alaska. Loess at least 10,000 years old was dug from a cut bank and used to form thick bases similar to the substrate found at Swan Point. Each fire was fueled by approximately 35 kilos of dried bone from either local wapiti (*Cervus canadensis*), bison (*Bison bison*), or yak (*Bos grunniens*). The fires were ignited using dried, braided, local grasses. Bones were periodically added to the top of the piles and the edges stirred for more complete combustion (Fig. 3A). The fires burned for seven hours, and the hearths were left untouched (Fig. 3B).

Four experimental fires were burned at SCAR in 2016 using bones only (approximately 15 kg bone), bone and dung (approximately 15 kg bone, <1 kg dung), dung only (approximately 2 kg), and twig. All were placed on loess pads as described above and dried, braided grass was used as kindling as needed. The bones were locally raised wapiti, bison, yak, or domestic beef and had been dried over winter in a garage. The dung was gathered from the wild Delta bison herd and dried. The twigs, smaller than 1.5 cm in diameter and 20 to 25 cm long, were gathered from dead shrubs and willow trees and placed in a pile reaching about 1.6 m high and 0.8 m wide. The twigs were not dried. The two experimental fires with bone burned for about four hours. The twig fire ran out of fuel after about three hours, and the dung fire smoldered and died out after about 2.5 hours.

WEATHERING EXPERIMENTS

A large white-tailed deer (*Odocoileus virginianus*) bone burn was conducted in 2014 in Wisconsin to produce burned residue for weathering experiments. Dried bones from at least six deer were burned on a layer of dried bison dung on top of a layer of washed sand. The sand substrate produced a residue which looks similar to that found at Swan Point (see Fig. 4; Kedrowski et al. 2009); >10,000-year-old loess was not readily available. The bones burned over a period of at least eight hours and the subsequent remains were removed, exposing four residues labeled black, greasy, crusty, and ash.

The weathering experiments were designed to determine if various natural weather conditions could cause the fatty acid methyl esters (FAMEs) to degrade over time. The freeze/thaw experiment replicates, in part, changes in FAMEs, which might occur due to recurring seasonal freezing and thawing over 14,000 years. The percolation experiment replicates, in part, the inundation of the underlying soils with rain and snow melt over 14,000

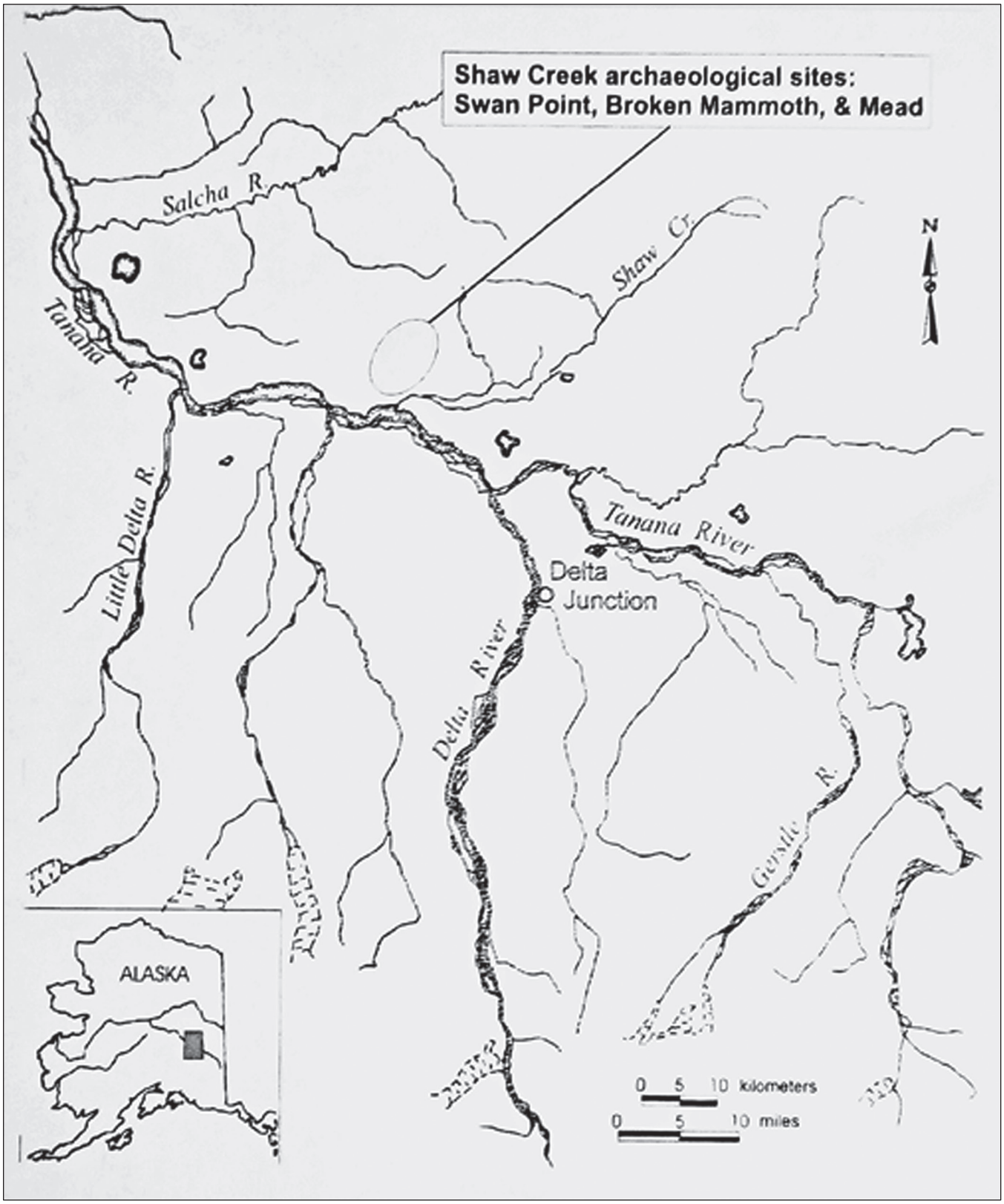

Figure 1. Map of Alaska with location of Shaw Creek archaeological sites. Shaw Creek Archaeological Research (SCAR) is also within the shaded area. (Adapted from Holmes 2001.)

Figure 2. (A) 2005 experimental outdoor red deer bone-fueled hearth (in Wisconsin); (B) the remains of the hearth the following morning; (C) the remains after the removal of the partially burned bones; (D) cross-section of the bisected remains of hearth in 2013.

years. Although these experiments were designed as part of a FAME project, some observations were made that are pertinent to this paper.

Freeze/thaw Experiment

The crusty residue was subjected to multiple cycles of freezing and thawing. Small pieces of residue were placed in petri dishes; distilled water was added to half the dishes. Both sets of dishes were placed in a freezer for a minimum of 24 hours and then removed and left at room temperature for a minimum of 24 hours. One wet and one dry petri dish were removed from the rotation every 10 cycles for almost three years. The removed samples were dried and stored in glass vials at room temperature for analysis in the FAME project.

Percolation Experiment

Four glass funnels were lined with a cellulose paper filter to prevent sand from flowing out. Enough washed sand was placed on the filter to provide a level surface approximately midway up the funnel. A piece of each residue (black, greasy, crusty, and ash) was placed in separate conical funnels and covered with approximately 5 cm of sand. The funnels were placed in ring stands over beakers and 500 ml separatory funnels were suspended over the conical funnels (Fig. 4). Distilled water (500 ml) was dripped into each conical funnel most days for over four years, allowing alternating periods of dampness and dryness.

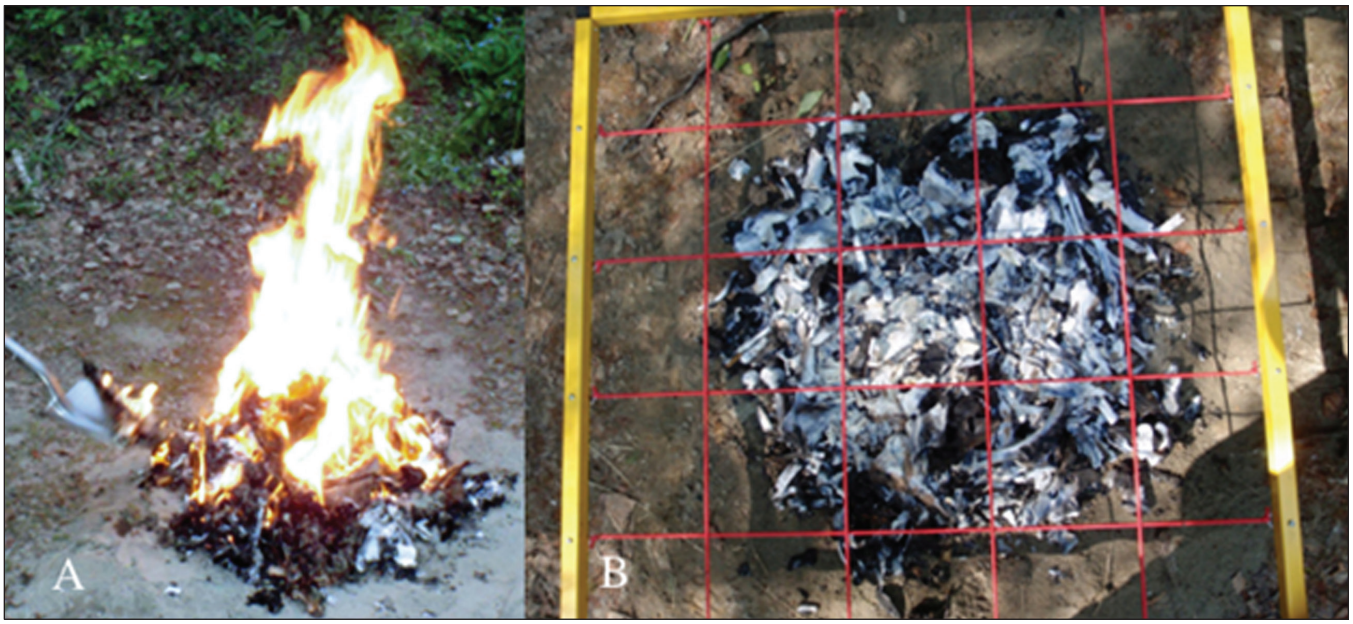

Figure 3. (A) Stirring the bones during the 2009 experimental outdoor burn (Alaska); (B) remains of the burn the following morning, showing more complete combustion of the bone compared to 2B.

Figure 4. Percolation experiment setup.

RESULTS

OUTDOOR BONE-FUELED FIRES

Wisconsin

Wood-fueled fires burn from the bottom up, but bone fires burn from the top down. The rendered grease from the top drips down, providing fuel to burn the lower bones. The main taphonomic processes in Wisconsin were weather, weed growth, and disturbances from dogs and chickens. After eight years, the burn area resembled the rest of the yard except for a low, unremarkable mound. Half of the mound was excavated, revealing scant evidence of the fire (Fig. 2D). Tiny pieces of calcined and burnt bone, bone ash, and a matrix of sand were the only visible evidence. The classic markers for a wood hearth were absent—no charcoal or reddened substrate.

Alaska

Most of the bones from the 2009 experiments were completely consumed, with only a few of the last bones appearing either unburnt or minimally charred. These largely intact bones could attract carnivores (Fig. 3B). After one year, the burnt bones attracted small animals which scattered fragments and knuckles from long bones (Fig. 5). One hearth had evidence of digging within the bone pile (Fig. 6). The distribution of bones was plotted (Fig. 7).

Bones were spread as far as four or more meters from the edges of the hearths. Since the burns are in a cul-de-sac, the spread of bone fragments was most likely due to movement by smaller animals (i.e., rodents, fox, lynx, etc.) and not due to trampling by large animals. The accumulation of leaves and weeds prevented further plotting of the movement of bone fragments in subsequent years.

Since the fires were relatively protected, many of the larger bones changed little from one year to the next. However, six years after the burn, Crass accidentally stepped on a large bone fragment which turned into bone ash. Further investigation revealed the slightest bit of

Figure 5. Examples of bone fragments from 2009 burn (Alaska) moved by animals. Focal distance is the same in all photographs.

Figure 6. Evidence of animal digging and disturbance in the 2009 experimental bone hearth.

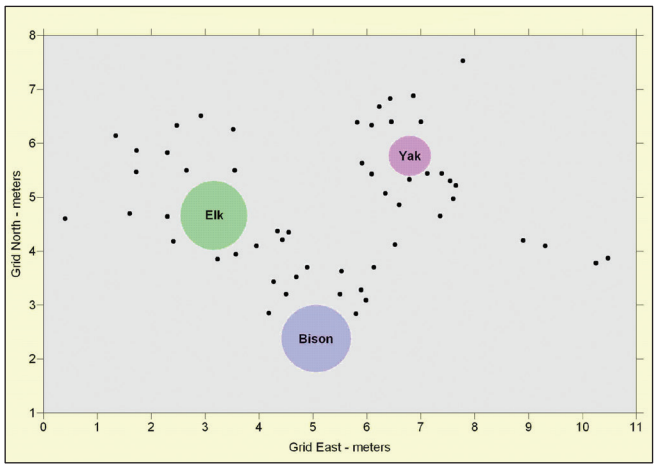

Figure 7. Bone displacement by animals of the 2009 hearths one year after the burn.

pressure on the burnt bone pieces easily reduced them to bone ash (Fig. 8).

A second set of experimental fires in 2016 with bone, bone-and-dung, dung, and twig did not produce visible hearth remains similar to those produced by a traditional wood fire. Bone fires are grease fires, and the irregularities and permeability of the hearth floor may cause grease to pool in low areas. The soil below the extinguished fire is only warm, even after hours of burning. When bones and bone ash are pushed aside the ground surface is warm but not uncomfortably hot to touch. With wood fires the ground surface is hot long after the fire is out because of the long-known insulating properties of ash (Seton 1910). Bone-fueled fires do not form an insulating ash layer (Crass et al. 2011) and thus do not heat the substrate as much as wood fires. The limited heating of the substrate by a bone-fueled fire produces little discernible reddening of the soil. Although charred pieces of bone are found, there is no wood charcoal since no wood was used in the fire. Bone ash, either from completely burnt bones or from the degradation of partially burnt bones, will occur and various sections of burnt residue will be seen. In a newly burned fire, this residue will occur in a noncontiguous

Figure 8. (A) Little pressure transforms burnt bone into ash and dust; (B) remains of the 2009 bone burn (Fig 3B) after seven years of weathering and animal disturbance.

erratic shape due to bone placement, pooling of the liquid fat, and irregularities in the matrix.

Dung fires produce an abundance of ash but leave little mark on the substrate. Dung fires tend to smolder rather than burn hot like a wood fire. Unless the ash is blown away, the flames quickly die down, smolder, and ultimately extinguish themselves without completely exhausting the fuel. However, if you mix bone and dung, the ash produced by the dung insulates the fire and absorbs some of the liquid fat. The substrate becomes warmer and produces a thicker layer of burnt residue. The bone-only and bone-and-dung fires used the same amount of bone by volume, and bone was added to both fires throughout the burn. Dung was also added to the bone-and-dung fire periodically.

The twig fire was burned as a comparison and to determine the feasibility of using scrub tundra vegetation or shrubs as a fuel source prior to forestation (Hoffecker et al. 2014). The gathering of a 1.6 by 0.8-m pile of shrubbery twigs took a group of six students approximately 20 minutes, and the fuel was consumed in three hours and 15 minutes. The twigs were added a few at a time until all were burned. The result was little evidence of a small fire the next morning. There was some reddening of only the very superficial substrate (Fig. 9A), but most of the ash and charcoal had blown away overnight. The twig fire left scant indication of its existence even 24 hours later. (Cross-sections of the bone and the bone-and-dung fire can also be seen in Figs. 9B and 9C).

WEATHERING EXPERIMENTS

Samples of the residues produced experimentally are morphologically and chemically indistinguishable from the archaeological specimens from the lowest levels at Swan Point. Cross-sectioning of the residue produced by the 2014 experimental burn exhibited four distinct types of residues:

A. **Black.** The loose sand located around the edges of the hearth frequently acquired a thin veneer of the bone grease soot, much like lamp black on the surface of cooking vessels or stones in a hearth ring. Under magnification, this charred, organic coating is very thin, appearing varnish-like (Figs. 10B and 10C).
B. **Greasy.** Rendered bone grease soaking into the substrate before being consumed in the fire acts as a mastic, cementing the substrate into a coherent mass (Fig. 10A). Deposits of this greasy residue often occur either below or to the outside of the crusty residue. Because this part of the hearth residue is minimally altered bone grease, the greasy residue is prone to biological degradation as well as mammal and insect feeding and would likely be removed from the archaeological hearth feature.
C. **Crusty.** The charred and partially burnt bone grease acts as cement, binding the sand grains together in a durable, thick layer (Fig. 10A). Unlike the varnish-like coating of the black residue, the crusty residue is very thick and fills the space between sand grains. This crusty residue corresponds to the archaeologically

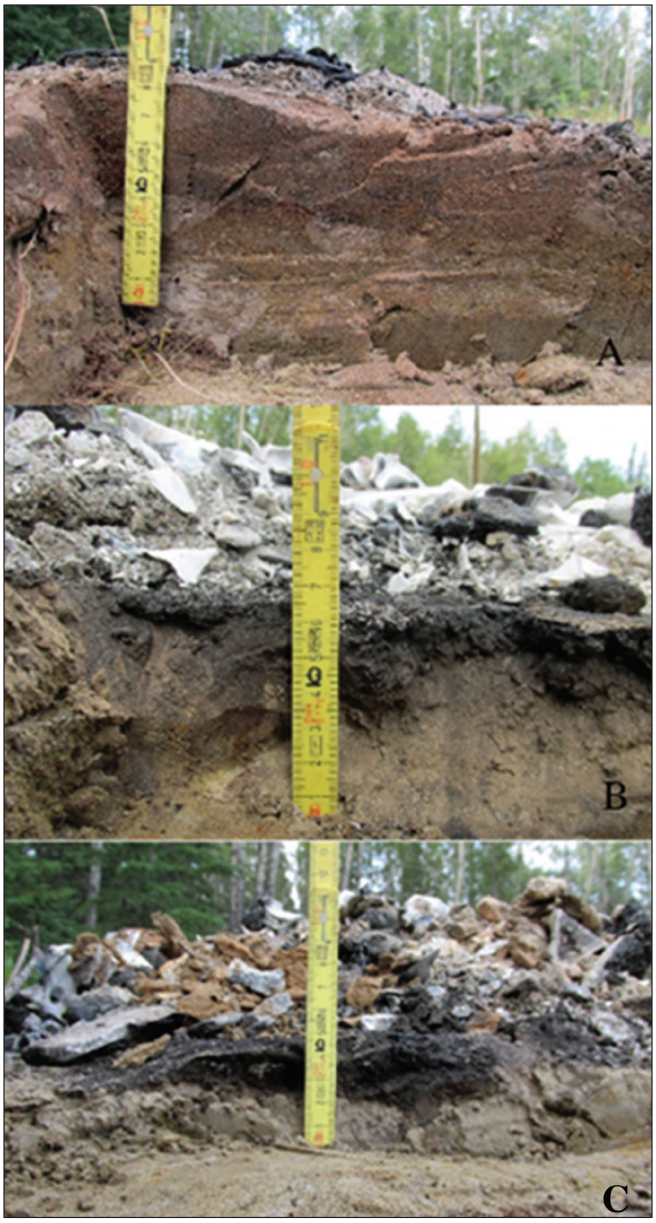

Figure 9. Cross sections of (A) twig fire, (B) bone-only fire, and (C) bone and dung fire.

recovered hearth residue at Swan Point (Kedrowski et al. 2009:Fig. 4) and resembles the sea mammal oil indurated matrix seen in Inuit houses on the North Slope (Slaughter 1982).

D. **Ash.** The small pieces of highly calcined bone and the ash from the burnt dung make up the fourth category of residue. This material is extremely light weight and highly friable. The likelihood of ash preservation is small because a light breeze would easily blow the ash off any surface. When exposed to intermittent wetting and drying in a natural environment, the small, calcined bone fragments degrade and turn to dust.

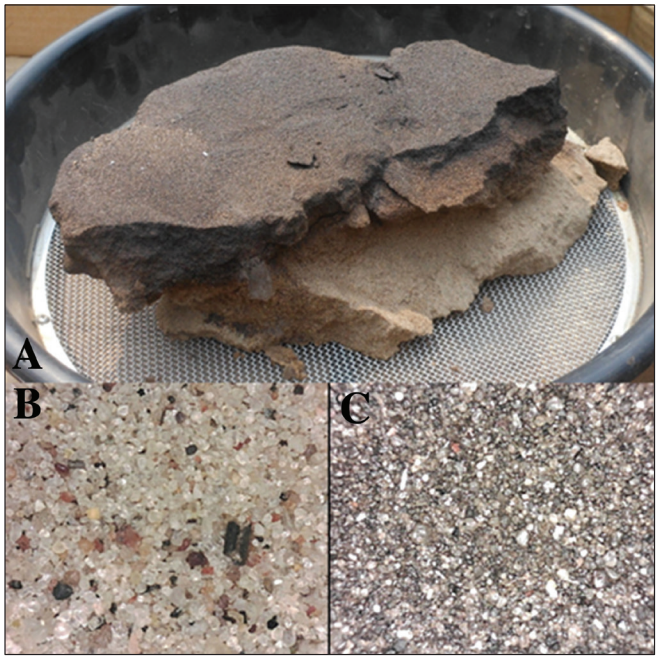

Figure 10. (A) A large chunk of dark, crusty residue over lighter, greasy residue from the 2014 bone-fueled burn. The ash and black residue were removed from the tub prior to the removal of this consolidated portion; (B) comparison of clean sand with (C) sand covered with black residue.

While the purpose of the weathering experiments was to observe any degradation of the fatty acid methyl esters (FAMEs) in the residues, two experiments provided insight into the degradation of hearth remains. The first was a freeze/thaw and the second a percolation experiment.

Freeze/thaw Experiment

Residues were subjected to long-term freeze/thaw cycles both as wet and dry specimens. The wet samples are initially soft and friable when first thawed but return to their original firm state upon drying. If the residue is not disturbed, the shape and texture remain. If the sample is disturbed within the petri dish, the dried sample falls apart and resembles a dark soil without visual or tactile evidence of the crusty residue.

Percolation Experiment

Funnels containing the black and the ash residues quickly exhibited some mixing of the residues with the sand. The funnel with the black residue became a uniform dark brown/gray color (Fig. 11A).

Upon excavation of the funnel contents, the black residue formed a thin surface crust and migrated upward. Discoloration was observed as an amorphous

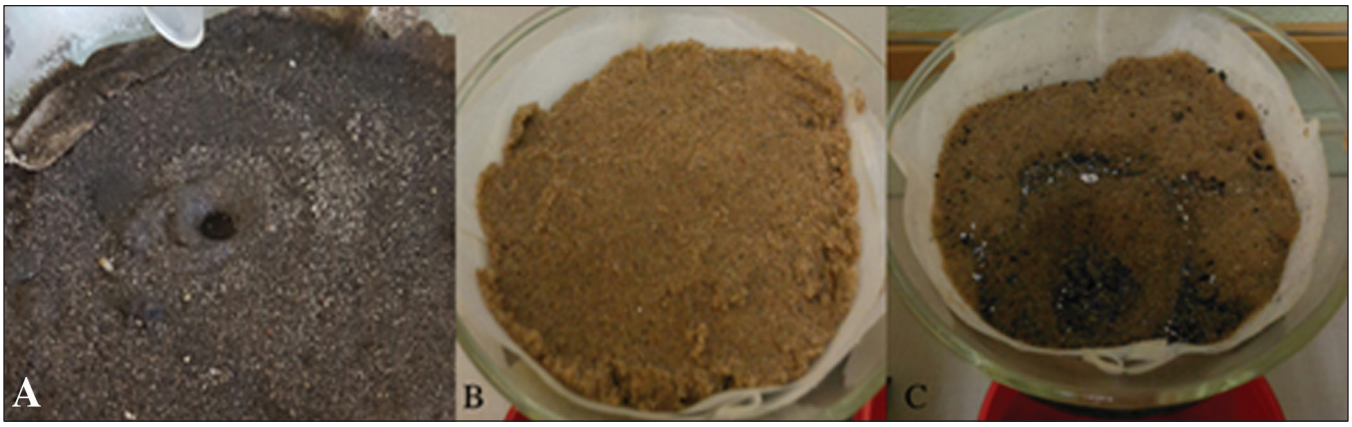

Figure 11. (A) The effect of percolation on the black residue buried in clean sand; (B) ash residue buried in clean sand before percolation; (C) the effect of percolation on the ash residue.

homogenization moving downward, similar to a rodent burrow in appearance. The funnel with the ash residue and small pieces of calcined bone had some of the ash and calcined bone migrate to the surface (Fig. 11B and 11C). The ash residue migrated upward, forming a homogeneous layer and leaving the lower sand unchanged. The greasy residue had a small slightly friable area compacted near the surface and migrated both upward and downward. The initial water percolated through this residue was quite odiferous. Over time, the odor disappeared and was thought to be from mold or bacterial growth. The crusty residue resembled the remains found at Swan Point (Fig. 12).

The original solid piece was partly eroded by the percolation, and some bits had broken down and were no longer coherent. What remained was a solid piece of crusty residue.

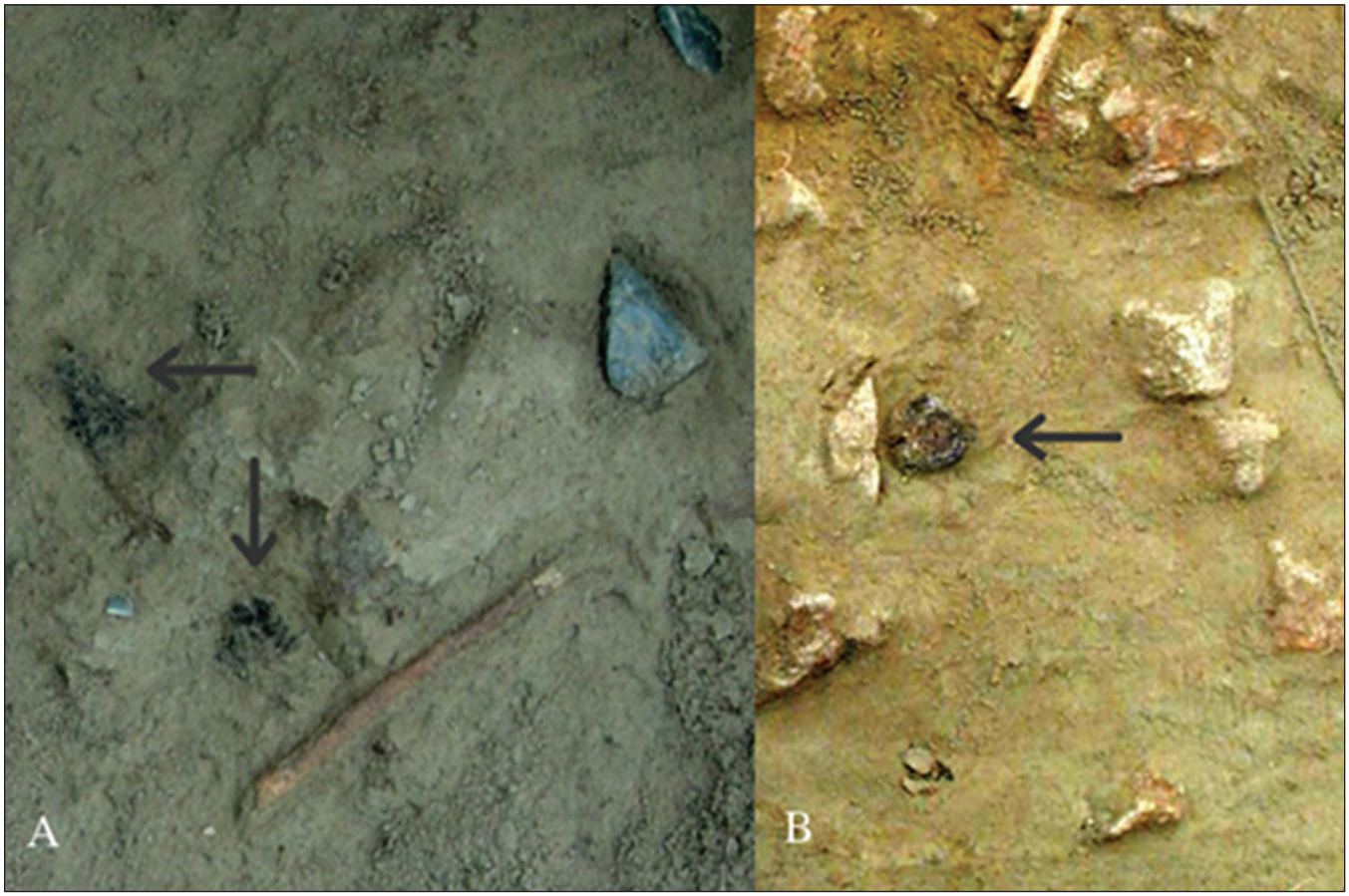

Figure 12. Examples of the in situ crusty residues from 14,000-year-old bone-fueled hearths at Swan Point.

DISCUSSION

EXPERIMENTAL HEARTH SIGNATURES

Wood-fueled fires are well described and experienced but show variability depending on the type of wood used. For this paper, the only wood used is willow (*Salix*) twigs gathered from the SCAR property. Twig fires require constant feeding. Twigs were added one or two at a time to a small, closely contained fire, producing noticeable warmth and a fair amount of smoke. One person had to keep continually adding twigs. A greater number of twigs could have been added, but the fire would have lasted a very short period. An immense volume of twigs would be needed for a fire to last throughout the night, quickly denuding the area of woody vegetation if only shrubs and scrub were available (c.f. Henry 2017; MacLeod 1925).

Dung fires, once actively burning, provide heat and light. Dung alone tends to smolder and produce abundant smoke and ash. The ash accumulation can extinguish a dung fire unless the ash is removed, requiring close tending to produce optimal heat and/or light. Undried or damp dung will smolder and not produce a flame. Dampness will make the dung unacceptable as a fire starter or fuel.

A bone-fueled fire is primarily a grease fire and burns extremely hot, with the heat dissipating out into the surrounding area. Once underway, the fire is almost smoke free and has a mild odor of grilled meat. The fire will burn until the grease is exhausted. Bones need to be added about every half hour. Periodically stirring and repositioning partially burnt bones to the top of the pile extends the length of time the fire will burn. The addition of dung to the fire extends the length of time between feeding with more bones. The dung acts as a sponge and absorbs the grease that drips to the bottom, thereby allowing the fire to burn at the base as well as the top of the bone pile. The dung also makes the fire more efficient because less grease is lost by soaking into the underlying matrix or running downslope. After the flames die down, a bone and dung fire smolders and maintains heat, even in the rain.

Since the fire is extremely hot, all the bones do not have to be dry. Once a fire is established, fresh bones burn as readily as dry ones. Freshly killed wapiti lower legs were added to an experimental bone fire and burned completely. Dried bones are needed to start the fire. The only requirement is the bones must contain fat. Bone trash from butchery or meals would be perfect fuel, as would scavenged bones considered unusable for food or tools. Bones are useless as fuel if they have been exposed long enough for weather and insects to remove all fat and connective tissue leaving only a mineral matrix. Some partially buried ancient bones contain enough fat to burn. Even today, partial carcasses and assorted bones are widely available on the landscape in Interior Alaska. Experience quickly teaches which ones are useful as fuel.

Bone fires produce incredible heat and light and could easily keep one warm through an Arctic night. Of the fires discussed, a bone fire is the least affected by light rain or snow and is the last to go out in heavy precipitation. One Alaska burn was done in March 2010 when the temperature was below 0° F with approximately 2.5 feet of snow. The packed snow was cleared to the ground, forcing us to stand in the resulting pit. The fire was built in the center, and we stood with the wind at our backs. Once the fire was going, heat waves were readily visible. The wind caused the heat to create ripples in the snow on the windward side of the pit. Several hours later, as the sun set, our supply of bones was depleted. As the fire died down, we realized we were cold. The warmth generated by the fire had allowed us subconsciously to remove our hats, scarves and gloves, and open our coats. With a windbreak or any type of simple shelter, a bone-fueled fire can keep you warm in frigid cold. In contrast, one can stand next to the twig fire on a cool summer evening and not feel warmed.

ARCHAEOLOGICAL BONE-FUELED HEARTHS AT SWAN POINT

The year we excavated the burnt bone residue at Swan Point was an unusually hot and dry summer. The substrate was firm and dry, which readily allowed color variations and stains to be seen. The small buttons and drops of heat-hardened greasy residue were easily discernable and collected (Fig. 12), leading us to experimentation which proved these findings to be the remains of bone-fueled fires (Crass et al. 2011; Kedrowski et al. 2009). Since then, we have not been so fortunate. The following summers were cooler with more rain and the underlying permafrost thaws more each year. The excavation units have been moist to muddy, and therefore color changes are more difficult to see. Even with diligent searching, few samples were recovered.

The effect of soil moisture has been seen with the experimental burns at SCAR. Each year the burns are observed, and samples are periodically taken. The hard crusty residue disappeared one very wet year, leaving

a dark, greasy smear. The collected samples readily fell apart, resulting in a darkly stained matrix with a slightly greasy feel. This could easily be overlooked in an excavation. The following year was drier, and the residues were again hard and crusty, holding their shape when sampled. Similar effects were seen with the freeze/thaw experiments in the laboratory.

Because of these observations, we developed a protocol for removing potential moist bone-fueled fire residue samples. Any sample that appears greasy, but not crusty, is removed in a block. The matrix is removed from the area until the sample is pedestaled. A small metal cookie sheet or other firm, flat item with a keen edge is used to cut the matrix beneath the sample. The potential residue is removed in one piece with as little disturbance as possible. The sample is firmly wrapped in foil, placed in a sturdy container, and dried slowly. When safely at the lab the foil can be loosened a bit to allow better drying but at a slow rate. The residue sample will dry to the identifiable crusty state with excess matrix falling away.

The percolation experiment demonstrated how water quickly transforms the four residues. The black residue and the ash are unlikely to remain in their original locations, making the recognition of bone-fueled hearths more difficult, especially in sandy or other well-drained soils.

COMPARISON TO OTHER WORK WITH BONE-FUELED FIRES

The archaeological literature on bone as fuel can be divided into two basic categories: determining the reasons burnt bones are found (c.f. Beresford-Jones et al. 2010; Cain 2005; Chase 1999; Clark and Ligouis 2010; Costa 2016; Villa et al. 2002; Villa et al. 2004; Yravedra et al. 2017) and experimental studies with bone-fueled fires (c.f. Aldeias 2017; Buonasera et al. 2019; Costamagno et al. 1999; Costamagno et al. 2002; Costamagno et al. 2009; Costamagno et al. 2010; Mallol et al. 2013; Mentzer 2009; Pérez et al. 2017; Spenneman et al. 1989; Stiner et al. 1995; Théry-Parisot et al. 2005; Théry-Parisot and Costamagno 2005; Vaneeckhout et al. 2013; Yravedra et al. 2005; Yravedra and Uzquiano 2013).

Reasons for finding burnt bones at archaeological sites are well established: disposal of butchery waste, cooking, fuel source, accidental inclusion, redeposition during hearth cleanup, or a hearth built over buried bones. The significant questions addressed by these authors are distinguishing one cause from another archaeologically and demonstrating if bones were used as a primary fuel source. The experimental bone-fueled fires attempt to determine if bones can be a primary fuel source and what visible markers would remain.

This is the first study of bone-fueled fires without any wood. Most researchers used some wood or wood byproducts, such as pinecones, in their experiments. The amount varies, with 75% bone and 25% wood being the highest ratio listed in published literature (Costamagno et al. 1999; Mentzer 2009; Théry-Parisot 2002a; Vaneeckhout et al. 2013; Yravedra and Uzquiano 2013). Our experiments were designed to reproduce and understand the firm, dark, crusty specimens discovered in the 14,000-year-old level at Swan Point. These samples resembled the seal oil indurated matrix seen in Inuit archaeological sites (Slaughter 1982; pers. observation, Wales, Alaska 2001). The hypothesis was the samples were heated Arctic megafauna fat mixed with loess. The archaeological environment was herb/shrub tundra with abundant sedges and grasses (Bigelow and Powers 2001), otherwise described by Guthrie (2001) as mammoth steppe. Wood was not an available fuel source. Heizer (1963) described many early ethnographic reports of woodless fires, so bone-only fires were possible.

Our experiments have shown that bone fires do not need wood or shrubs for ignition. Braided dried grass or dung make excellent fire starters. Other available items such as feathers or worn grass insoles are possibilities.

A second consideration is the amount of bone consumed and the duration of the fire. Much of the published research used a relatively small amount of bone: less than one to 125 g (Pérez et al. 2017; Yravedra et al. 2005; Yravedra and Uzquiano 2013), between one and 10 kg (Mentzer 2009; Théry-Parisot 2002a), and more than 10 kg (Costamagno et al. 2010; Vaneeckhout et al. 2013). Some fires lasted less than one hour and many died out within two. Since most of the experiments had varying ratios of bone to wood, there is often a range of burn times. Vaneeckhout et al. (2013) described burns lasting approximately three hours. Costamagno et al. (2010) split each fire into two distinct burning phases lasting 2 and 2.5 hours for a total of 4.5 hours with a cooling period between burns.

All our experiments used large amounts of bone, ranging from 10 to 40 or more kilos. Burn times varied, with short burns of two to three hours and long burns of up to seven hours. A significant difference is seen in the bone fragmentation and production of the four residues:

the longer the burn, the greater the bone fragmentation and residue production. Bone grease is more completely used by stirring the fire which enhances the consumption and fragmentation of the bone. This supports the observation of Costamagno et al. (2010) that fire maintenance is a prime determining factor in the experimental outcome. Fires lasting less than one hour are not expected to show the full range of effects.

Much work has been done regarding the best skeletal elements to use for fuel (Cain 2005; Costamagno et al. 1999; Théry-Parisot et al. 2005; Théry-Parisot and Costamagno 2005; Villa et al. 2002; Villa et al. 2004). We have burned all skeletal elements, fresh, dried, and frozen as well as decomposing and maggot-infested. All bone has been used including cancellous and compact, intact and complete, sawed by a butcher, and scavenged from kill sites. The only requirement is that the bones need to be dry to start the initial fire. Failed bones are ones left on the ground surface so long all the grease and connective tissue have been removed by weather, insects, and microorganisms.

TAPHONOMY

The final consideration is the taphonomic changes observed from outdoor hearths as well as the laboratory-designed experiments to mimic freeze/thaw cycles and water percolation. Nearly two decades of observing the remains of bone-fueled hearths have contributed to the understanding of how a large pile of burnt and calcined bones, bone ash, and organic residues can be transformed into a scattering of small bits of organic residue in 14,000 years. Animals, insects, and microorganisms begin the transformation by spreading, degrading, and trampling the burnt bone. Disruption can also be caused by rodents burrowing into the hearth remains. In 2019, we observed a young vixen routinely hunting among the hearths, digging up and devouring small rodents, supporting Aldeis' (2017) hypothesis of carnivores interacting with hearth features.

Archaeologically, Lanoë et al. (2019) described the disruption of buried hearth areas by rodent burrows at Swan Point and other Early-Middle Tanana sites. They proposed hearth remains such as ash or bone may be the attractant. Plants also contribute to the degradation. Within six years, the larger pieces of bone will turn to dust with gentle pressure, so any traffic in the area quickly breaks down the remaining bone bits. The organic residue is easily smeared during wet periods and if disturbed, breaks down and disappears into the matrix. Since bone fires do not heat deeply into the substrate, a classic hearth floor is absent. Therefore, on an archaeological site, one should not assume burnt bones were dumped somewhere just because a baked sediment is not evident (Schiegl et al. 2003).

The massive deer bone burn in the laboratory led to the discovery of four types of residues: black, greasy, crusty, and ash. The percolation experiments have shown that over four years with more than 1000 washings of distilled water, both the buried ash plus small, calcined bone pieces and the black residue migrated to the surface. The migration allows other taphonomic processes, such as wind, an opportunity to remove additional evidence of a burn. All the observations of actual and laboratory accelerated temporal changes are miniscule, however significant when compared to 14,000 years of taphonomic processes.

CONCLUSION

Bone-fueled fires leave a characteristic archaeological signature distinct from fires employing either exclusively wood, or wood extended by other organic materials, such as bone or dung. The hearth signature is not as prominent as that left by wood fires and may easily be overlooked. However, with careful excavation and sample collection of sites in areas and/or time periods where wood was scarce, the remains of bone-fueled fires can be found.

Bone-fueled fires are easily maintained, especially with the addition of dung, and can provide light, protection from predators, and sufficient heat to warm a shelter and prepare meat. Fuel was readily available from game procured by hunting as well as bones gathered from scavenging carcass remains. Other fuel would include dried grasses, twigs, and dung. Undoubtedly, fires were kept burning with whatever fuel was easily obtained or plentiful.

Experimental fires fueled with copious quantities of bones produced four distinct types of residues; however, only the cemented sediments (i.e., crusty residue) are likely to be preserved and encountered on archaeological sites. Unfortunately, the crusty residue can be missed during excavation. When moist, the crusty residue becomes very soft and indistinguishable from other organic-rich inclusions. The residue returns to its crusty state if carefully collected and dried.

In summary, in situ evidence of what ultimately was shown to be the remains of bone-fueled fires in the 14,000-year-old component at Swan Point was found.

Bone-fueled fires can be made using only materials found in a treeless environment. Residues, similar to those found at Swan Point, have been reproduced experimentally. A protocol is proposed for identifying and collecting residues from bone-fueled hearths at archaeological sites. This study shows how, over time, the remains of a bone-fueled fire can be taphonomically changed to what has been found after 14,000 years. These results provide an incentive for future studies.

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