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THERMALLY MODIFIED ROCK: THE EXPERIMENTAL STUDY OF "FIRE-CRACKED" BYPRODUCTS OF HOT ROCK COOKING

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ABSTRACT

Despite its ubiquity in residential middens at many North American archaeological sites, thermally modified rock (TMR) is among the least studied elements of the archaeological record. TMR assemblages, however, may provide key insights into routine cooking practices, patterns of refuse disposal, and midden formation processes. This article outlines the results of experimental research aimed at understanding the conditions by which TMR assemblages were created in residential settlements in the Pacific Northwest. We present baseline data addressing the thermal properties of the hearth, the rate and circumstances of cobble fracturing, the extent to which different kinds of cobbles break when exposed to heat for varying durations, and the effectiveness of hot cobbles at achieving cooking temperatures.

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INTRODUCTION

Thermally modified rock (TMR)—rock that has been cracked, discolored, or otherwise physically altered as a result of exposure to intense heating and cooling processes—is among the most ubiquitous and abundant culturally modified material in many North American archaeological sites.[1] TMR is also among the least studied elements of the archaeological record, particularly that comprising intentionally discarded rubbish. Methods for the analysis of TMR are rarely systematic and have not been afforded the same disciplinary scrutiny as that applied for the study of lithic, ceramic, zooarchaeological, and paleoethnobotanical assemblages. This is surprising, if only for the fact that TMR is often a byproduct of cooking via convection and thus potentially salient to archaeological questions centering on regional- and household-level foodways.

TMR is typically better preserved than archaeofaunal and macrobotanical specimens in most archaeological contexts. As such, TMR may be a more reliable dataset in studies addressing, for example, variable labor contributions to food processing activities. However, we see three conceptual and methodological impediments to the productive use of TMR for addressing anthropologically substantive questions concerning past behavior. First, TMR is seldom deemed to have the interpretive potential of other artifact classes (Wedel, 1986) that comprise the aggregate residue of household activities (e.g., wood charcoal, unidentifiable fragments of animal bone, byproducts of lithic technology, small ceramic sherds). Important exceptions to this statement can be found in archaeological site reports throughout North America and especially in the southern plains and Texas. Nevertheless, there persists an unwillingness to parse the thorny histories and varied origins of TMR in archaeological sites (Petraglia, 2002). That is, although heated rocks can be integral to cooking activities, TMR can also be linked to roasting pits, residential heating, sweat lodge activities, the production of ceramic temper, and the purposeful or accidental burning of residential architecture (Frison, 1983; Lovick, 1983).

Second, the methods applied to the observation and documentation of TMR are highly variable and often unsystematic (Homsey, 2009; Lovick, 1983; McDowell-Loudan, 1983; Petraglia, 2002). TMR is not consistently regarded as an artifact or find, and the design of many site survey and excavation forms reflect its conceptual relegation to background matrix or a compositional attribute of cultural strata rarely afforded the same scrutiny as, for example, soil color. As

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[1] Archaeologists have applied various descriptive terms to rocks that exhibit evidence of exposure to intense heat and subsequent cooling processes. "Fire-cracked" or "fire-altered" are commonly used descriptors, and "fire-broken" (Brink and Dawe, 2003) and "thermally altered" (Brink and Dawe, 2003; Petraglia, 2002) have been suggested. Here, we argue for the use of "thermally modified" as a descriptor of rocks that exhibit physical transformations that can be linked to exposure to intense thermal changes, including but not limited to cracking, crazing, discoloration, and/or pocking.

such, TMR data collected during field investigations are often anecdotal, impressionistic, and qualitative; rarely can such data be subjected to quantitative analysis or reliably used to detect assemblage patterning across space and over time (Brink and Dawe, 2003).

A third impediment to TMR studies is the absence of a robust body of data deriving from experimental archaeological research. Archaeologists seldom have a sufficient understanding of the constellation of physical and chemical variables entailed in the practice(s) of using rock to cook food. This is all the more problematic given that different roasting, steaming, and convective cooking techniques may produce empirically different assemblages (Ingbar, 1985; Thoms, 2003, 2008). Many questions about the origins of TMR persist: how often and to what extent do rocks fracture in the fire, in solution, or both? Does duration of exposure to intense heat affect rates at which rocks fracture? How effective are cobbles at heating water to cooking temperatures? Do different types of cooking activities involving heated rocks produce distinctive TMR assemblages? The extent to which archaeologists can use TMR assemblages to inferentially reconstruct the details of midden formation processes and (in turn) cooking-related practices ultimately hinges on our ability to use the answers to these questions to explain the sizes, quantities, and types of TMR specimens in the archaeological record (Schutt et al., 1991).

Experimental Research Addressing TMR

Our research builds on a corpus of archaeological studies and archaeological experiments, much of which dates to the last three decades. TMR has received growing attention in Texas, the American Southwest, and the Great Basin, where North American archaeologists have long grappled with the interpretive significance of burned rock middens distributed across vast areas and spanning Archaic to late pre-contact site occupations. Systematic approaches to the study of TMR features in these regions have emphasized the modeling of formation processes with empirical observations of variable but patterned burned rock assemblages (Abbott and Frederick, 1990; Goode, 1991; Hester, 1991; Shiner and Shiner, 1977; Sullivan et al., 2001). Other research has been designed around questions pertaining to changes in the macro- and microscopic properties of rocks when exposed to intense heat (e.g., Backhouse and Johnson, 2007; Bates et al., 2004; Crandell, 2007; Gur-Arieh et al., 2012; Homsey, 2009; Jackson, 1998; Jensen et al., 1999; Lintz, 1989; McDowell-Loudan, 1983; McFarland, 1977; Pagoulatos, 2005; Pierce, 1989; Rapp et al., 1999; Witkind, 1977). Still other studies have been instrumental in generating insights into the ways that differences in hearth construction relate to variability in the thermal performance characteristics of hearths (e.g., Odgaard, 2003; Shockey, 1997). Thoms (1998, 2003, 2008, 2009) has perhaps most rigorously explored the ways that ethnographic and experimental data addressing variability in hot rock cooking methods (e.g., earth ovens, pit-steaming features, cook-stone grills, and stone-boiling features) can be used to generate expectations for archaeological features containing TMR assemblages. Few studies have examined cobble fracture rates, although Buckley (1990) and Jensen et al. (1999) are notable exceptions.

In this article, we present and discuss data deriving from multi-phase experiments designed to examine the processes that account for the generation of TMR assemblages when water-worn cobbles are used as heat reservoirs for convective cooking. Our study can be distinguished from most previous experimental research in that our data address several variables accounting for different types and sizes of TMR, including duration of cobble exposure to heat, hearth temperature, cobble material, and water temperature in rinsing and cooking containers. We allocate comparatively more attention to cobble fracture rates, although we argue that low-level (or middle-range) archaeological inferences concerning cooking activities, fuel consumption, and site formation processes benefit from a consideration of experimental data addressing all phases of cooking by convection.

RESEARCH FRAMEWORK

Cooking by convection—sometimes referred to as "stone boiling"—entailed the transfer of cobbles heated in a hearth to a vessel containing water and food. This method of cooking both plant and animal foods was common throughout much of North America, especially in regions where basketry and wooden vessels (e.g., California, Northwest Coast), rather than pottery, constituted local container technology. In lieu of heating foods directly over combusting fuels in a hearth, cobbles were used as heat reservoirs whereby radiant heat from hearth embers would be absorbed and transferred to the contents of cooking containers.

In many regions of the Pacific Northwest Coast, archaeological data suggest that cooking with convected heat was among a routinized and quotidian set of household practices. Archaeological investigations at *Welqámex* (DiRi-15), a large, island-based Stó:lō-Coast Salish settlement in the Gulf of Georgia region of southwestern British Columbia (Figure 1), have recovered over 1.7 metric tons (75,000+ fragments) of TMR in only 6 m^3 of excavated cultural deposits. Excepting several concentrated piles, most of the TMR is recovered in house-associated middens and constitutes upwards of 90% of enumerated objects classified as refuse generated by the occupants of residential architecture (Graesch, 2007, 2009; Graesch et al., 2010) (see Figure 2). As such, a study of the generative processes accounting for TMR assemblages is also a study of domestic midden formation processes.

For the purpose of elucidating the relationship of TMR assemblages to cooking practices, the objectives of our experimental approach were threefold:

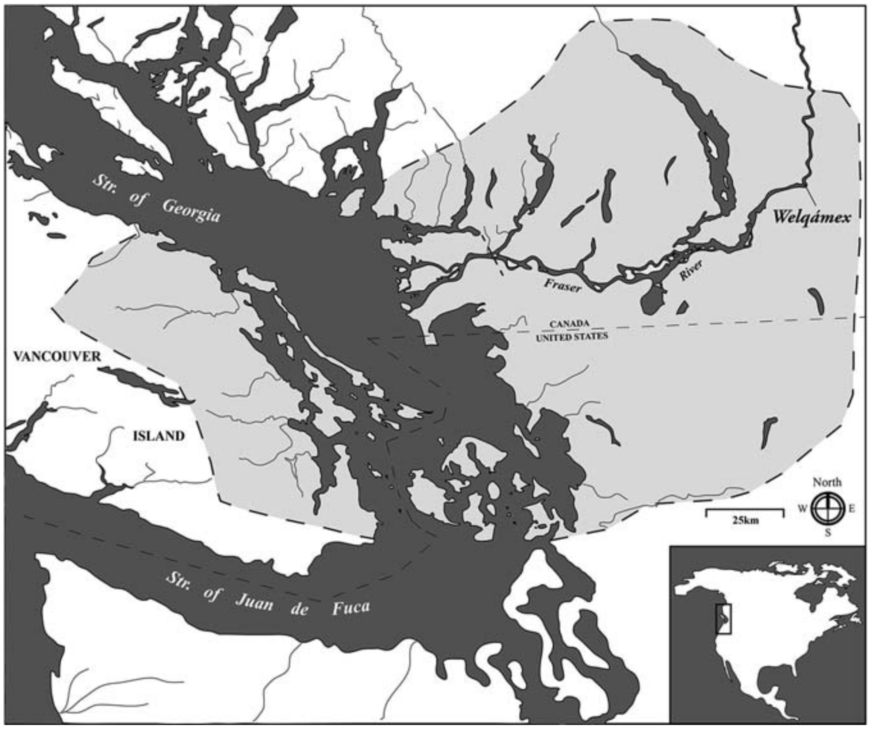

Figure 1. *Welqámex* situated in Stó:lō-Coast Salish territory (shaded) in southwestern British Columbia. Map adapted from Graesch, 2007.

1. develop a more nuanced understanding of the thermal circumstances in which unmodified cobbles break when used for cooking by convection;
2. systematically document the attributes of the assemblages of cracked rock resulting from the experimental process; and
3. evaluate the effectiveness of hot cobbles at heating water.

Importantly, our research was not designed to examine any one hypothesis concerning the ways that TMR is generated when cooking by convection. Indeed, it is difficult to identify overlapping questions, methods, or experimental datasets from the small body of TMR studies and by which such hypotheses can be formulated. Nevertheless, we advocate an empirical and replicable approach to the study of TMR via controlled experimentation and expressly for the purpose of developing archaeological inference (Marsh and Ferguson, 2010; Schiffer et al., 1994).

Figure 2. Thermally modified rock recovered from the excavation of a 1 × 1 m unit in a dwelling-associated midden at *Welqámex* (DiRi-15). This backdirt assemblage includes most specimens larger than 12.8 mm (0.5 inch) mesh. All TMR recovered during excavation was counted and weighed prior to discard.

MATERIALS AND METHODS

Cobble Sample

All cobbles used in our multi-phase experiments were collected from the *Welqámex* shoreline in July 2009, several weeks after the Fraser River reached maximum seasonal flow and water levels had begun to drop. Selected cobbles featured smooth, water-polished exteriors and were grouped into "lots" by material category and approximate size (Table 1). The number of cobbles per lot ranged from 2 to 8 (most comprised four cobbles), and the average maximum cobble diameter per lot ranged from 7.9 to 17.8 cm.

Our material categories include quartzite and a combination of volcanic and plutonic igneous rocks, all of which are abundantly available at the river's edge and within a 30-60 second walk of the settlement. Quartzite found at *Welqámex* is typically white or pink, notably hard (7 on the Mohs scale), and features a moderately glassy texture that often results from recrystallization of quartz grains that are embedded in a fine, silica-dominant cement. Most quartzite cobbles found on the island perimeter yield conchoidal fractures through (and not *around*) the

Table 1. Water-Worn Cobbles Used in the Experiments

Material	Number of cobbles	Number of lots	Average diameter (cm) min	max
Course-Grain Igneous (CGI)	50	12	9.5	15.5
Medium-Grain Igneous (MGI)	44	11	10.4	13.5
Fine-Grain Igneous (FGI)	128	31	9.6	16.4
Quartzite	137	33	7.9	17.8

quartz grains when subjected to standard hard-hammer percussion techniques. Despite their suitability to a variety of everyday tasks, quartzite flakes are rarely found in *Welqámex* archaeological assemblages.

The igneous cobbles at *Welqámex* are subdivided into three intentionally broad categories: fine-, medium-, and course-grain igneous. We refrain from classifying igneous rocks to specific geological types for three reasons:

1. none of the authors or investigators have the extensive expertise needed to distinguish geologically distinct rocks with similar composition (e.g., granodiorite, monzonite, and granite);
2. we observe considerable variability among specimens that are distinctly classifiable (e.g., basalt and andesite); and
3. it is not always possible to identify specific rock types from visible attributes on the patinated surface of a water-smoothed river cobble.

Nevertheless, our categories match those applied during archaeological investigations at *Welqámex* (e.g., Graesch, 2009), and because we rarely observe slate, schists, and other metamorphic and sedimentary materials in the *Welqámex* archaeological assemblages, we did not incorporate these materials into our experiments.

All three categories of igneous rock are abundantly represented in archaeological assemblages of TMR at *Welqámex*. Specimens classified as fine-grain igneous (FGI) are volcanic rocks, typically dark grey or black, and exhibit aphanitic texture with occasional dark phenocrysts. FGI is moderately hard (4.5-6 on the Mohs scale) and affords a predictable conchoidal fracture when used for knapping. Indeed, FGI dominates the aggregate assemblage of chipped stone tools and byproducts recovered during archaeological investigations in *Welqámex* houses and middens. Medium-grain igneous (MGI) specimens are also volcanic but tend to be lighter in color, contain larger microscopic and sometimes macroscopic mineral grains, and are rarely represented in lithic assemblages when compared with FGI. The visible abundance of phenocrysts in MGI is also often greater than that observed for rocks classified as FGI, although MGI specimens tend to be as variable in hardness (4.5-6 on the Mohs scale). Cobbles labeled as course-grain igneous (CGI) are plutonic igneous rocks that exhibit uneven-granular surfaces with an array of macroscopic quartz, feldspar, and/or hornblende mineral grains. Depending on the mineral constituents, CGI cobbles are sometimes harder (5.5-6.5 on the Mohs scale) than their MGI and FGI counterparts. CGI cobbles tend to strongly resemble granite in color and texture, and all fracture unpredictably around grains that are somewhat poorly cemented.

Experimental Procedures

Experiments were organized into two phases in which we applied standardized procedures for observing and measuring changes in the state of river cobbles when subjected to intense heat and then rapidly cooled. Phase 1 entailed the heating of water-rounded river cobbles in a fire pit. Our circular fire pit measured 96 cm in diameter and was excavated to a maximum of 20 cm below ground surface on a culturally sterile and now forested point bar on the southeastern edge of *Welqámex*. This fire pit was intentionally constructed to be larger and deeper than most hearths documented with archaeological methods in residential dwellings at *Welqámex* (Figure 3). Given that our experiment would be conducted outside the protective walls of a house, we sought ways to minimize a bellows-like effect created by predictable afternoon winds in the upper Fraser Valley. To this end, a lower fire basin was vital, but we also stacked more than a cord of maul-split wood into two linear, wall-like barriers that helped to buffer winds blowing out of the west.

All of our firewood was cut from nearby fallen trees and consisted primarily of bigleaf maple (*Acer macrophyllum*) and some black cottonwood (*Populus trichocarpa*). We filled approximately 75% of the fire pit with wood and ignited using cedar kindling. After a substantial bed of hot coals had been created (typically 30-40 minutes), the ambient fire temperature was recorded and cobbles were nestled into the embers. One or more temperature readings were typically recorded at various intervals during the remainder of Phase 1 procedures, and a final temperature reading was recorded immediately before the cobbles were removed from the fire and transferred to the water container (Phase 2, see below).[2] Cobble lots were submerged in hearth embers for 5, 10, 15, 20, and 25 minutes, depending on the specific experiment. Any cobbles that cracked in the fire were documented, and a concerted effort was made to recover cobble fragments from hearth ash and embers before beginning a new experiment.

Phase 2 entailed transferring heated cobbles to a pre-fabricated wooden cooking container. We used tongs to pick hot cobbles out of the fire, briefly dunk them in a

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[2] Unfortunately, our industrial-grade hearth thermometer broke after only 13 experiments, and thus our dataset addressing variation in fire temperatures is modest in comparison to other datasets generated with our experimental procedures.

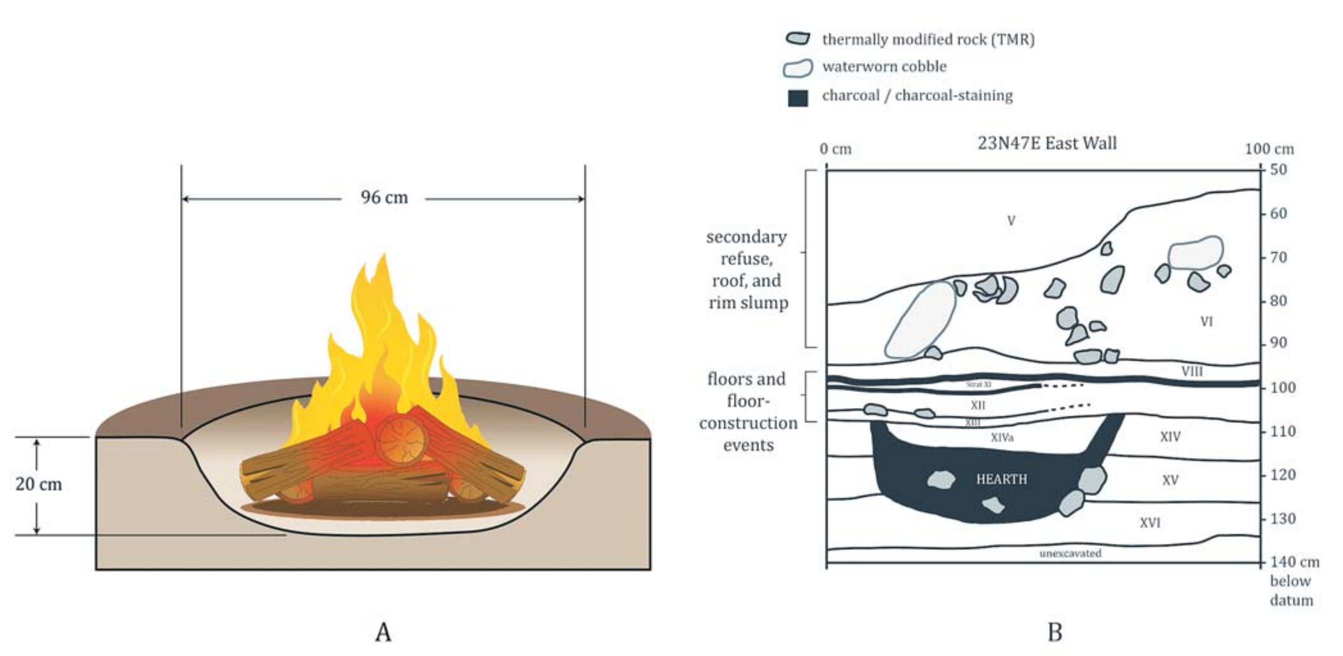

Figure 3. Profile illustrations and dimensions of (A) the experimental hearth and (B) a Late period hearth revealed during the excavation of a 1 × 1 m unit (23N47E) in Structure 7 at *Welqámex* (DiRi-15).

rinsing vessel—a 5-gallon plastic bucket containing 2 gallons of water—so as to remove wood ash and debris, and then submerge the cobbles in the cooking container. Fabricated from commercially milled pine boards, wood screws, and silicone caulk, our cooking container could hold 128 liters (33.8 gallons) of water, although we filled with only 11.4 liters (3 gallons) of river water for each experiment (Figure 4). We did not manufacture or use a lid in our experiments. Instead, we designed a deeper container (70 cm) so as to slow heat dissipation into the atmosphere while still allowing experimenters to stir and thus simultaneously normalize vessel water temperatures and prevent hot cobbles from burning the container's wood bottom. Ambient water temperatures in the rinsing and cooking containers were recorded with a second thermometer prior to cobble submersion, and water temperatures in the cooking container were tracked every 30 seconds after all cobbles had been transferred from the fire. When measurements indicated that water temperatures had plateaued, the intactness of each cobble in the tested lot was recorded, and all cobble specimens (intact and fragmented) were collected for attribute analysis, size sorting with nested-mesh sieves (25.6, 12.8, 6.4, and 3.2 mm), and enumeration.

Our research findings derive from 87 experiments conducted with 359 cobbles. Of the 87 experiments conducted, 13 experiments entailed the use of two or more lots for the purpose of assessing the number of fire-heated cobbles required to bring water to cooking temperatures. Another 17 experiments entailed the reheating of intact and/or fractured cobbles two more times in the fire. These experiments were used to evaluate the effects of multiple heatings and cool-downs on cobbles as well as to evaluate the effectiveness of reheated cobbles in heat transfer to water. For the purpose of determining how and how often cobbles fracture, most experiments—57 of 87—were each conducted with only one lot that was heated in the hearth only one time. We focus this article on data from these 57 experiments as well as the smaller number of experiments (*n* = 17) that entailed multiple exposures to Phase 1 and Phase 2 procedures.

RESULTS

The Hearth

Cooking with hot rocks requires an active hearth in which a substantial bed of embers has accumulated. The embers are crucial for the radiation of a more consistent heat than that achieved with open flames. Hearth temperatures (as measured in the embers) at the outset of the experimental process ranged from 655°C to 907°C (mean = 804°C). Figure 5 compares hearth temperatures recorded immediately prior to placing cobbles onto the embers (Phase 1) with temperatures recorded just prior to transferring the cobbles to the rinsing and cooking containers (Phase 2). These data show a significant decline in hearth temperatures

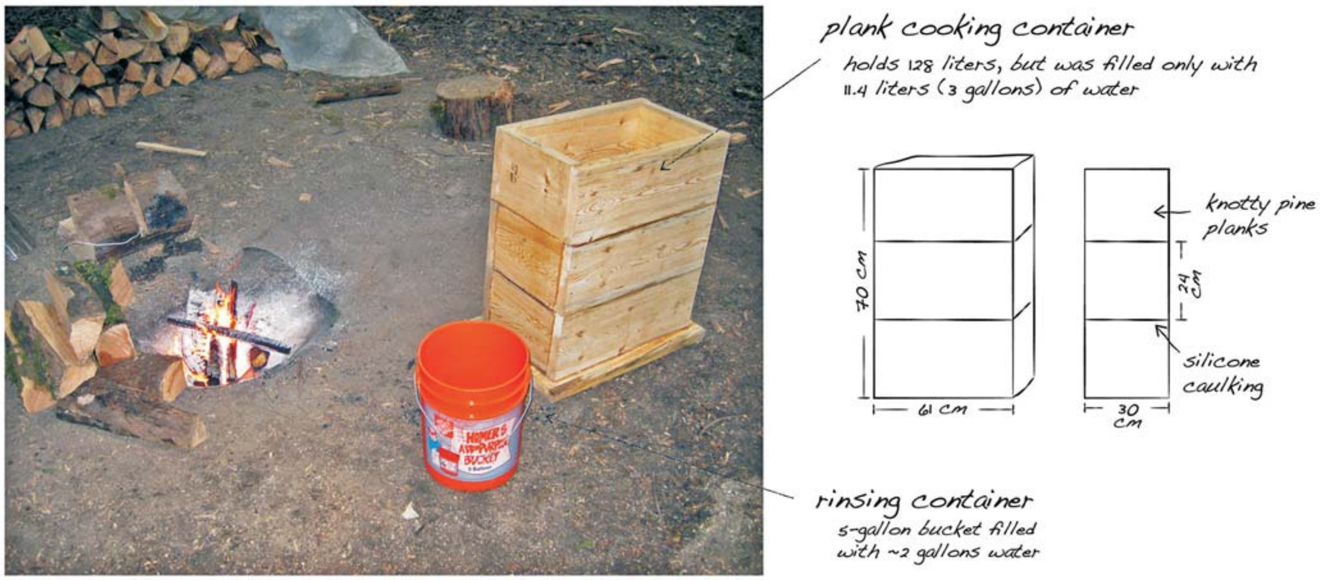

Figure 4. The fabricated plank cooking container used in all TMR experiments. The stacks of wood to either side of the experimental hearth were used as wind shields.

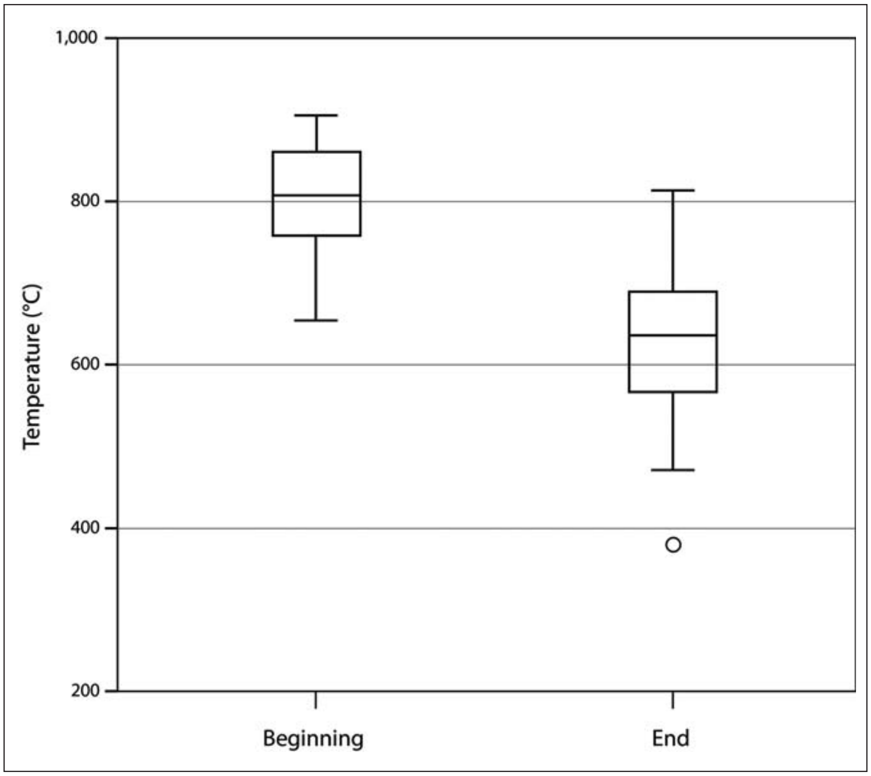

Figure 5. Variation in hearth temperatures as measured at the outset and conclusion of the first 13 experiments.

after cobbles were placed in the fire pit ($t = 4.507$, $p = 0.000$). Thermometer readings recorded in the span between the start and conclusion of nearly all of our experiments indicate a continuous decline in fire pit temperatures throughout much of the cobble heating process, indicating that a simple cobble shielding effect does not explain the differences between temperatures recorded at the outset and conclusion of each experiment (Figure 6). Rather, these data suggest that cobbles initially act as heat sinks or reservoirs, where each cobble absorbs a substantial amount of heat from the fire. Ambient hearth temperatures recorded during some experiments suggest that this effect may last for only 15 or 20 minutes, after which the cobbles likely reach higher core temperatures and the fire-cobble temperature gradient declines (see Figure 6).

A caveat is that our hearth temperature data points are few: prior to the failure of our industrial-grade thermometer, we systematically recorded ambient hearth temperatures for only 13 of the 87 experiments. Also, we did not always

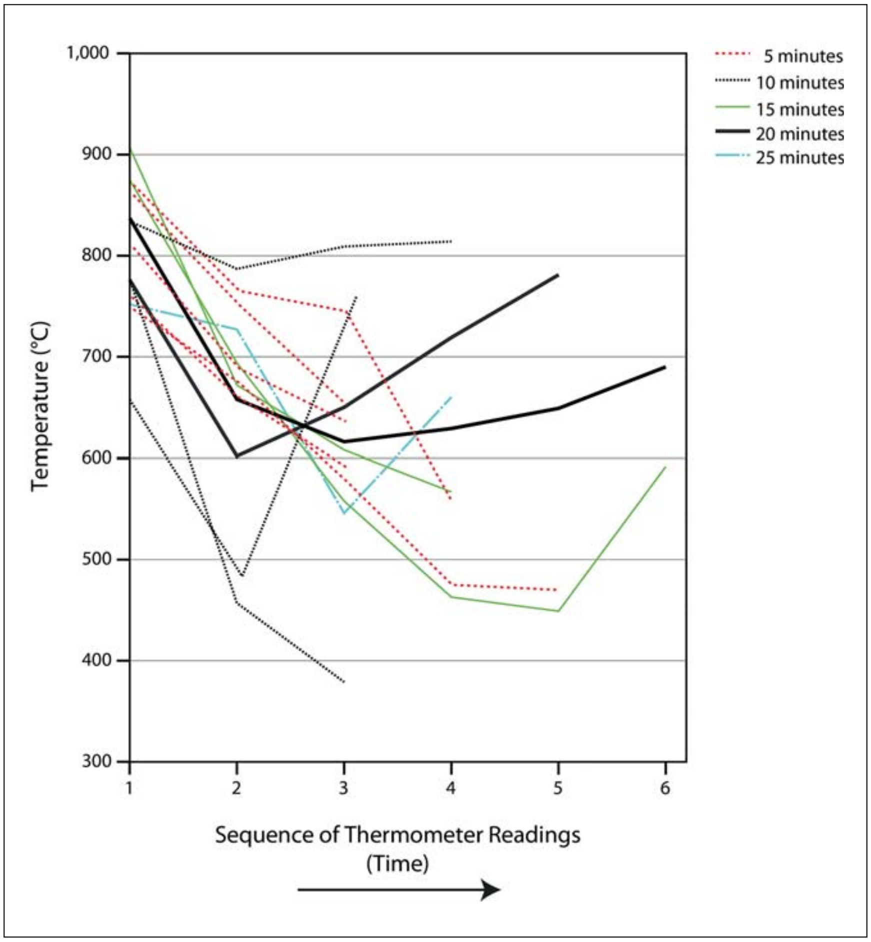

Figure 6. Changes in hearth temperatures by duration of cobble exposure for the first 13 single-exposure experiments, before the hearth thermometer broke. The number of readings taken for each timed experiment ranged from 3 to 6 and was not systematic.

consistently document the same number of temperature readings in each experiment: the number of readings ranged between two and six, with most experiments having three or four readings. A more complete data set is needed, and all patterns and interpretations concerning the thermal properties of the hearth must be regarded as preliminary until further rigorous measuring of hearth temperatures during multi-phase experiments can be performed for a much larger

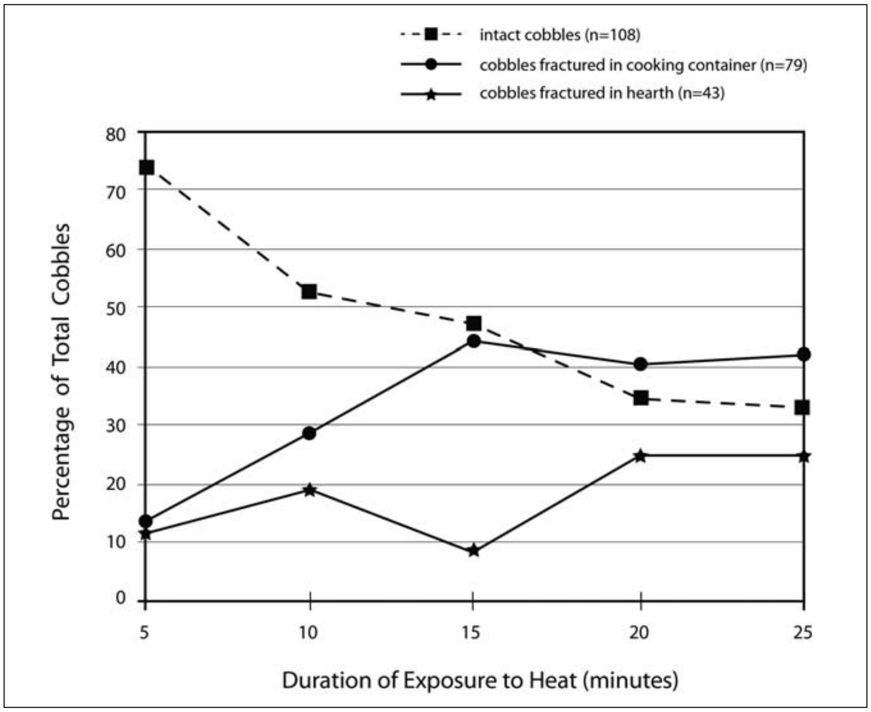

Figure 7. Rate of cobble fracture by duration of exposure to heat in single-exposure experiments.

sample. Nevertheless, these data—hearth temperatures prior and subsequent to the addition of cobbles—are new to the small corpus of literature addressing thermally affected rock in experimental and archaeological contexts and may shed light on other aspects of household organization that are otherwise difficult to assess with archaeological data, such as the labor allocated to wood gathering (see below).

The Rate at Which Cobbles Fractured

A surprisingly large number of cobbles did not break after being subjected to intensive heat and then rapidly cooled. Across 57 single-exposure experiments, 108 of 230 (47%) river cobbles remained intact at the completion of Phase 2 procedures. In most of these experiments, at least one and sometimes several cobbles in the lot fractured, although in nine experiments none of the cobbles (*n* = 34) cracked. This is not to say that intact cobbles were unaltered; most cobbles were permanently discolored, and many specimens—especially quartzite—exhibited varying degrees of crazing and pocking.[3]

Cobbles that cracked did so mostly after being removed from the fire and submersed in cooler water. Among the 122 cobbles that broke in the 57 single-exposure experiments, only 43 cobbles (35%) cracked in the fire (Phase 1), whereas 79 cobbles (65%) cracked in the cooking container (Phase 2) after being subjected to rapid temperature change. Our data also indicate that the duration of cobble exposure to the fire affected the rate of cobble fracture. Figure 7, for example, shows how cobble intactness is inversely correlated with time in hearth: nearly 80% of cobbles remained intact after only 5 minutes in the hearth, whereas only 33% of cobbles were still intact after 25 minutes exposure. In general, the longer that cobbles were exposed to intense heat, the greater the likelihood that they were permanently discolored and exhibited extensive crazing, regardless of whether the cobble fractured. This was particularly true for quartzite specimens, of which 100% exhibited evidence of substantial color change (usually various shades of pink, red, and black) and crazed surfaces when left in the hearth for longer than 5 minutes.

The extent to which cobbles fractured in the fire rather than the water was also partly affected by the duration of cobble exposure to intense heat. Cobbles exposed to only 5 minutes of heat were prone to breaking in the cooking container at only a marginally higher rate than that for the hearth (see Figure 7). However, the difference in rates of fracture in the two mediums increased substantially among experiments entailing 10 and 15 minutes of exposure, but plateaued after 15 minutes. We infer from these data that cobbles exposed to hearth embers for greater lengths of time were hotter and more apt to break when subjected to rapid temperature change. However, to the extent that duration of heat exposure (and presumably maximum cobble temperature) affects fracture rate, a temperature threshold is seemingly reached at or shortly after 15 minutes in the fire.

Analysis of fracture rates among our four material types (see Table 2) reveals that quartzite and MGI cobbles fractured at higher rates (65% and 62.5%, respectively) than their CGI and FGI counterparts (34% and 56.7%, respectively). FGI cobbles, however, rarely fractured in the fire and typically only after 25 minutes exposure. CGI cobbles were the least likely to crack in the hearth and the cooking container. In general, the longer specific types of cobbles were exposed to intense heat, the more likely they cracked in the fire and/or the water.

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[3] We use the term "crazing" to mean a macroscopically visible network of fine lines indicative of the cracking process but that have not resulted in complete breakage. A "pocked" surface exhibits visible, topographically irregular craters from which bits of rock outwardly exploded. We use the terms "fracture" and "crack" synonymously, and we intend both to mean that a rock broke into two or more pieces.

Table 2. Rate and Source of Cobble Fracture by Material for Single-Exposure Experiments ($n = 57$)

			Fractured cobbles					
			In fire		In water		Intact cobbles	
Material	Minutes in fire	Number of cobbles	*n*	%	*n*	%	*n*	%
Course-Grain Igneous (CGI)	5	8	0	0.0	0	0.0	8	100.0
	10	8	1	12.5	2	25.0	5	62.5
	15	8	0	0.0	3	37.5	5	62.5
	20	8	2	25.0	1	12.5	5	62.5
	25	18	4	22.2	4	22.2	10	55.6
Subtotal	—	50	7	14.0	10	20.0	33	66.0
Medium-Grain Igneous (MGI)	5	8	3	37.5	1	12.5	4	50.0
	10	8	5	62.5	1	12.5	2	25.0
	15	8	1	12.5	1	12.5	6	75.0
	20	8	1	12.5	5	62.5	2	25.0
	25	8	4	50.0	3	37.5	1	12.5
Subtotal	—	40	14	35.0	11	27.5	15	37.5
Fine-Grain Igneous (FGI)	5	8	0	0.0	1	12.5	7	87.5
	10	8	0	0.0	2	25.0	6	75.0
	15	8	0	0.0	4	50.0	4	50.0
	20	8	0	0.0	4	50.0	4	50.0
	25	28	4	14.3	13	46.4	11	39.3
Subtotal	—	60	4	6.7	24	40.0	32	53.3
Quartzite	5	20	2	10.0	4	20.0	14	70.0
	10	18	2	11.1	7	38.9	9	50.0
	15	12	2	16.7	8	66.7	2	16.7
	20	8	5	62.5	3	37.5	0	0.0
	25	22	7	31.8	12	54.5	3	13.6
Subtotal	—	80	18	22.5	34	42.5	28	35.0

The Assemblages of Cracked Rock

The 122 cobbles that broke during the 57 single-exposure experiments fractured into 2,208 recovered specimens. Over 55% (*n* = 1,231) of this assemblage is constituted by fragments so small that they can be captured only with 3.2-mm mesh sieves (Figure 8). Only 20% (*n* = 428) of the specimens were recovered in the largest (25.6 mm) of our mesh screens.

When cracked rock assemblages are analyzed in the aggregate (i.e., irrespective of material type), we found little difference in the size profiles of assemblages recovered from the hearth and the cooking container (Table 3). In general, cobbles that cracked in the fire produced only slightly more small fragments than those that cracked in the cooking container. This is most apparent in the proportions of cobble fragments recovered with 3.2-mm mesh sieves (69.1% vs. 57.2%, respectively). However, the differences are marginal when fragments from the 6.4-mm mesh are also considered (76.9% vs. 72%, respectively).

Important differences emerge when size-sorted assemblages are analyzed by material category. Figure 9 shows the proportional abundance of fragmented rock by mesh size for each of the four material categories while simultaneously distinguishing among assemblages recovered from the hearth and the cooking container. Among the more apparent patterns is the fact that greater than 90% of the CGI assemblages are constituted by small fragments recovered only with 3.2-mm mesh. The 17 CGI cobbles that cracked during Phase 1 or Phase 2 of our experiments resulted in 86 fragments found in the three largest-mesh sieves, whereas 708 fragments were captured with 3.2-mm mesh. In part, this is the result of poorly cemented CGI specimens crumbling into many small pieces when subjected to major temperature changes. Although not as pronounced as CGI, the FGI size profile is also "bottom heavy," with nearly 50% of the assemblage recovered in our smallest mesh sieves (see Figure 9). In contrast, MGI specimens that cracked in the fire, were typically recovered with 12.8- and 25.6-mm mesh screens. Quartzite assemblages of cracked rock are somewhat more evenly divided between large and small fragments.

Our data suggest that the rate at which cobbles cracked as well as the size profiles of resulting TMR assemblages were affected by the duration of cobble exposure to heat. Excluding CGI specimens, cobbles exposed for only 5 or 10 minutes generated less than 10% of the total assemblage of TMR fragments. In contrast, TMR fragments from cobbles exposed for 25 minutes account for over 50% of the assemblage. On average, the longer a cobble was left in the hearth, the more likely it was to crack into numerous small pieces during the course of the experiment. Between 35 and 50% of TMR fragments were recovered in 3.2-mm mesh for experiments in which cobbles were heated for 15 minutes or longer (Figure 10). By comparison, the smallest of measured fragments constitute only 5 to 12% of TMR assemblages associated with cobbles heated for only 5 and 10 minutes.

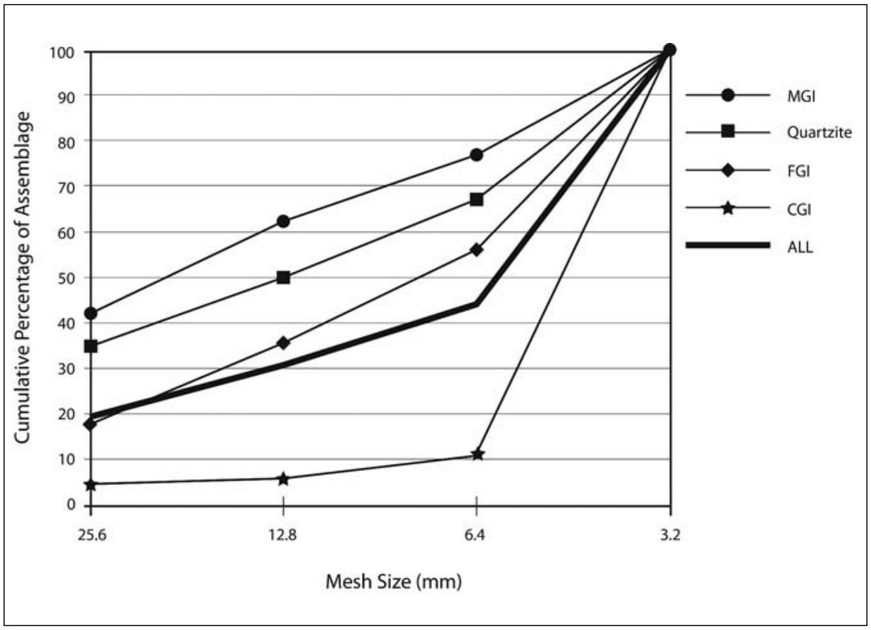

Figure 8. Cumulative percentage of TMR fragments ($n = 2{,}208$) resulting from single-exposure experiments and recovered with four mesh sizes.

Table 3. Size Profiles of Aggregate Assemblage of Cracked Rock by Source for Single-Exposure Experiments ($n = 57$)

	Mesh size (in mm)							
	25.6		12.8		6.4		3.2	
Source	*n*	%	*n*	%	*n*	%	*n*	%
Hearth	96	15.4	48.0	7.7	49	7.8	431	69.1
Cooking container	223	19.8	92.0	8.2	167	14.8	645	57.2

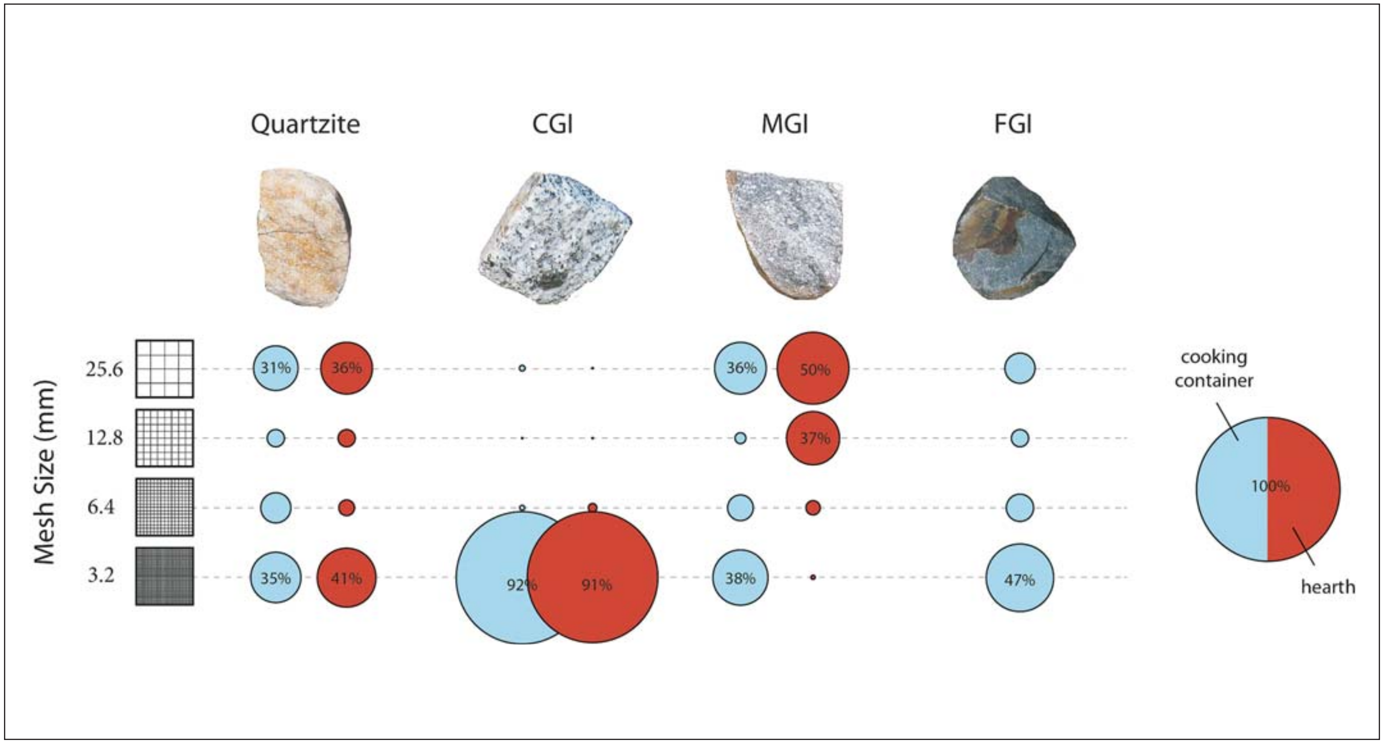

Figure 9. Relative frequency of size-sorted fragmented rock recovered from the cooking container (water) and the hearth during single-exposure experiments. Experiments ($n = 7$) for which we were unable to reconstruct the source/origin of the cobble fracture (i.e., water or fire) were excluded from this analysis.

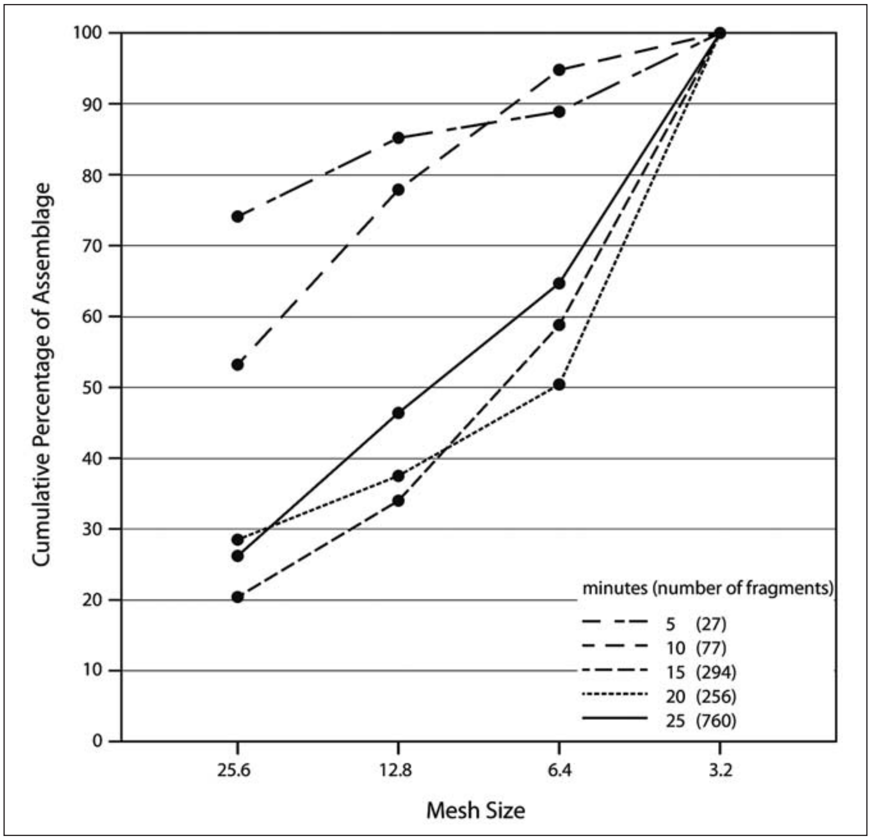

Figure 10. Cumulative percentage of TMR fragments (*n* = 1,414) resulting from single-exposure experiments, by material, and as recovered in four nested mesh screens. CGI specimens were removed from this analysis due to high friability.

The Cooking Container

Systematically collected every 30 seconds after cobbles had been submerged, temperature data from the cooking container indicate that the extent to which cobbles conduct heat is affected, in part, by the length of time the cobbles were heated in the hearth. Figure 11 shows that cobbles pulled from the hearth after 5 minutes were, on average, effective at heating water to 25°C, whereas cobbles exposed to heat for 25 minutes could heat water to an average of 45°C within the first 180 seconds of submersion. In general, the longer that cobbles were in the fire, the more effective they were at heating water within the first 3 minutes of submersion, although our data indicate little difference

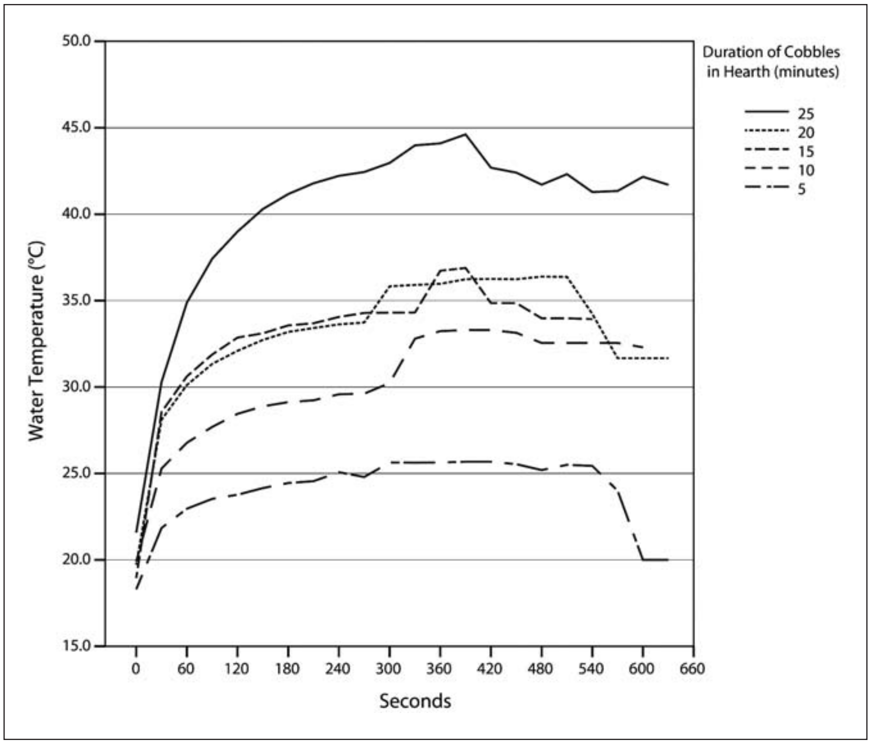

Figure 11. Water temperature (°C) recorded in cooking container during Phase 2 of the experimental process and for cobbles heated only once in the hearth. Temperatures were recorded every 30 seconds and are averaged for each hearth-exposure duration (e.g., 5 min, 10 min, etc.).

in the effectiveness of cobbles exposed for 15 and 20 minutes (Graesch and DiMare, 2013).

Our temperature data also demonstrate variability in the heating effectiveness of different rock types. Figure 12 shows that FGI and quartzite were most effective at achieving the highest temperatures in the cooking container when cobbles were exposed to 25 minutes of heat in the fire. FGI cobbles generated the highest mean maximum temperatures (46.4°C) for single-lot, single-exposure experiments. Furthermore, FGI cobbles tended to transfer heat quicker and for longer than all other rock types. Temperature data indicate that quartzite cobbles had comparable transfer rates within the first minute of submersion and could achieve almost as high a mean maximum temperature (45.8°C) as FGI, but were far less effective at sustaining this temperature for longer than 6 or 7 minutes. CGI cobbles transferred heat more slowly, and MGI cobbles were demonstrated to be rather poor conductors.

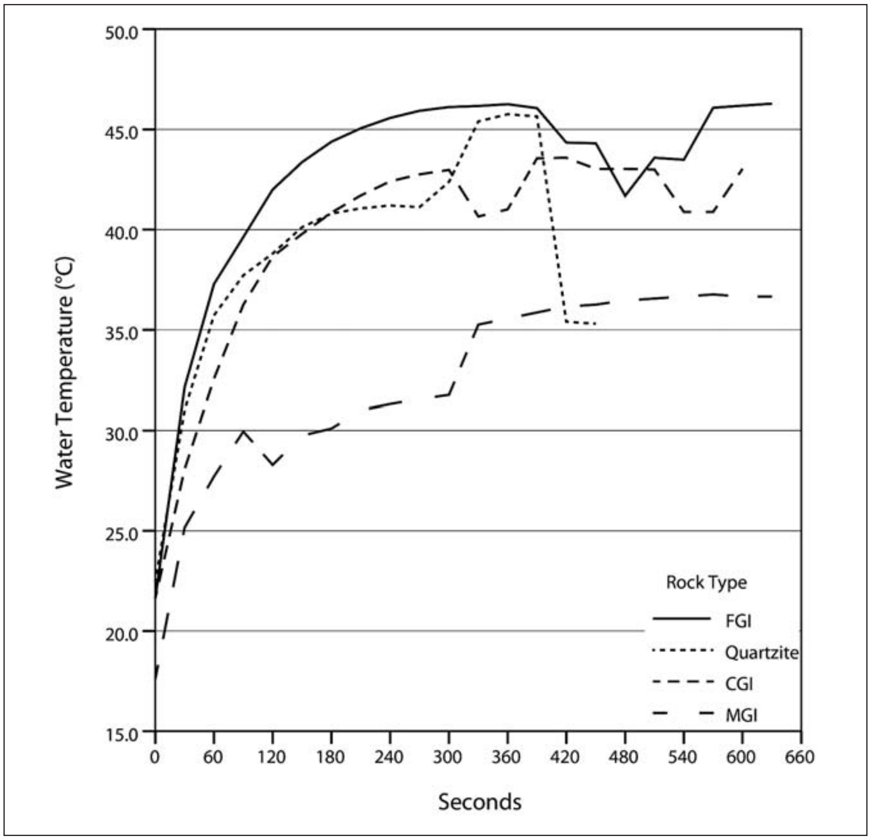

Figure 12. Water temperature (°C) recorded in cooking container after cobbles were heated for 25 minutes in 17 single-exposure experiments. Temperatures were recorded every 30 seconds and are averaged for each rock type.

The Rinsing Container

Initial water temperatures in the rinsing container ranged from 16.8°C to 26.4°C (mean = 20.8°C). This ~10°C range reflects not only differences in ambient daytime temperatures across 30 days of experimentation (July-August 2009), but also the reuse of rinsing water for several experiments. Unlike the cooking water, which was always replaced with fresh river water after the conclusion of Phase 2 procedures, water in the rinsing vessel was sometimes used for two or three consecutive experiments. Not surprisingly, our data suggest that the temperature of water in the rinsing container affects the maximum temperature reached in the cooking vessel. That is, in experiments (*n* = 18) in which cobbles were subjected to

25 minutes of heat exposure, we observed a positive correlation between rinsing container temperatures and cooking vessel temperatures as recorded after 180 seconds of cobble submersion ($r^s = .754$, $p = .000$). Rinsing hot cobbles in warmer solutions helps to maximize cobble heating effectiveness in the cooking container.

Multi-Exposure Experiments

Multi-exposure or reheating experiments (*n* = 17) were conducted for the purpose of examining how cobbles performed and cracked when used for more than a single cooking session. After an initial round of heating and rapid cooling, six lots, each comprising four cobbles, were subjected to two additional rounds of Phase 1 and Phase 2 experimental procedures. These six lots included two lots of quartzite cobbles, two lots of FGI cobbles, and one lot each of MGI and CGI cobbles. Multi-exposure experiments entailed gathering the unbroken cobbles and/or large cobble fragments (> 25.6 mm) recovered at the conclusion of Phase 2 procedures and returning these to the hearth for another round of Phase 1 heating. All TMR subjected to multi-exposure experiments was allowed to dry for several days before a subsequent round of heating, and all experiments entailed only 15 minutes of exposure to the hearth.[4]

Although the dataset is considerably smaller than that generated for the 57 single-exposure experiments, results indicate that three successive rounds of heating and rapid cooling more than quadrupled the total number of cracked TMR specimens. Rates of fracture varied by material, with the CGI assemblage predictably featuring the largest proportion (61%) of small (3.2 mm) fragments (Figure 13). However, and contrary to our expectations, we did not see an overall increase in the proportional representation of TMR recovered in smaller mesh sieves. Instead, nearly 50% of TMR resulting from multi-exposure experiments was recovered in 25.6-mm and 12.5-mm sieves, whereas equivalently sized rock resulting from single-exposure experiments constituted only 30% of that assemblage (see Figure 8). This pattern may be explained, in part, by a selection bias. That is, the cobbles and large cobble fragments selected for reheating may simply have been more durable or suitable for heating than those deemed too small.

DISCUSSION

Our series of experiments provide new baseline data on the rate at which cobbles fracture, the processes accounting for this breakage, the heating effectiveness of four categories of rock material, and the size profiles of resulting TMR

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[4] Here, we report only on rates of cobble fracture. We do not present data addressing mean maximum water temperatures as recorded in the cooking container owing to the fact that we did not control for declining mass in the increasingly fragmented assemblage re-subjected to Phase 1 and Phase 2 experimental procedures.

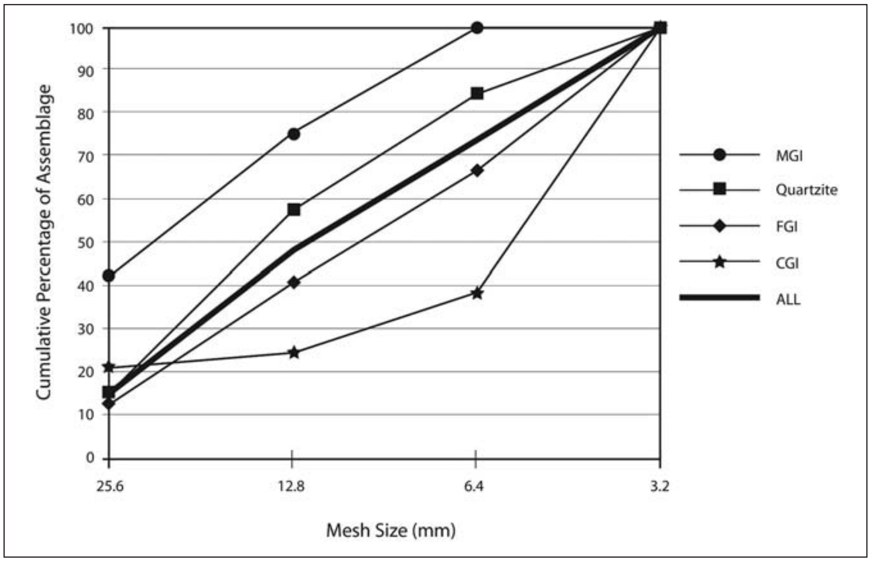

Figure 13. Cumulative percentage of TMR fragments (*n* = 997) resulting from multi-exposure experiments and recovered with four mesh sizes.

assemblages. The corpus of experimental research is still small, but aggregation of these data permit a more nuanced interpretation of archaeological TMR data collected at *Welqámex*. If archaeological data are sufficient in quality and kind, these data may also provide specific insights into:

1. the behaviors and processes underlying the formation of household midden deposits; and
2. inter-household variability in cooking practices in other Northwest Coast and North American settings where cooking by convection was a routine practice.

Major findings from our series of experiments include the following:

- The duration of cobble exposure to heat affects the extent to which cobbles fracture as well as the size profiles of resulting TMR assemblages. On average, each round of heating four cobbles and then submerging the cobbles in a cooking solution generated 38 cobble fragments. Given that many of these experiments entailed only 5 minutes of heating in the hearth, we argue that this rate of fragmentation is significantly lower than that to be expected for typical cooking by convection, a process that required cobbles to be exposed to heat for longer durations (see below).

- Reheating (multi-exposure) experiments indicate that the rate of cobble fragmentation increases when cobbles are subjected to two or more rounds of successive heating and cooling.
- The duration of cobble exposure to heat affects: (a) the rate at which heat is transferred; and (b) the maximum temperatures achieved in the cooking container. Based on our data, 25 minutes or more is most effective for cooking.
- The effectiveness of cobbles at absorbing and transferring heat varies by rock material. Quartzite proved to be a good heat reservoir (cf. Backhouse and Johnson, 2007), a finding that is predicted by experimentally derived thermal inertia and diffusivity values reported by Pierce (1989). Quartzite, however, was not as effective as FGI (contra Pierce, 1989). Plutonic igneous rock (CGI) was very friable, a poor reservoir, and did not withstand thermal weathering better than quartzite (contra Jackson, 1998; Odgaard, 2003).
- Cobble fracture rates were consistently greater in the water-filled cooking container than in the hearth. This finding supports conclusions drawn from some archaeological experiments (e.g., Bates et al., 2004), but contradicts others (e.g., McDowell-Loudan, 1983; Pierce, 1983, as reported by Wedel, 1986) and suggests that a dramatic change in temperature is responsible for the majority of cobble breakage, rather than simple exposure to fire. As such, “fire-cracked” is a less accurate descriptor than “thermally modified,” and uncritical application of “fire-cracked” may constrain a fuller consideration of the varied cooking behaviors responsible for archaeological assemblages.

Insights into Cooking Practices

The combined datasets resulting from intentionally multivariate and multiphase experimental procedures, including temperature data collected at the hearth, provide some insights into the intersection of cooking practices and other household activities. For example, although the subset of data is small, the recurrent drop in hearth temperatures recorded when cobbles were added to the embers may implicate higher rates of wood consumption when households engaged in cooking activities. Excavation data from *Welqámex* suggest that most residential hearths were smaller than the hearth created for our experiment (see Figure 3), and thus the effects of four cobbles on ambient fire temperatures likely would have been even greater. Like FGI, quartzite was a better conductor of heat when compared to other rock types available in cobble form on the *Welqámex* shoreline. Although rocks are generally poor conductors of heat (especially when compared with metals), conductivity tends to correspond with heat sink potential. As such, heating quartzite cobbles may have differentially lowered hearth temperatures and placed greater demand on local fuel sources.

To this end, the heating capacity of most residential hearths may have been altogether inadequate for large-scale cooking projects entailing stone boiling methods, including preparations for competitive and ritual feasts but perhaps also for some of the larger extended-family households at *Welqámex*, at least one of which is estimated to have been greater than 50 people. Indeed, the cooking required for events involving groups larger than the local household may have entailed the use of massive bentwood boxes and wooden troughs too large to situate in house interiors (Duff, 1952). In these cases, we might expect cobbles to have been heated in larger fire pits prepared outside the house and adjacent to the cooking vessels.

An important caveat is that the design of our cooking container departs from the design of nineteenth century bentwood boxes in southwestern British Columbia in several ways, not the least of which is its height. To this end, our data addressing changes in water temperature in the cooking container may under- or over-estimate the effectiveness of hot cobbles at heating food. Another caveat is that we never covered our experimental cooking container after submerging the hot cobbles. This undoubtedly reduced the efficiency of cooking by convection: covering the vessel helps to trap steam and reach cooking temperatures with less heat. Then again, hot cobbles cannot rest for too long on the bottom of a wooden cooking container without compromising the vessel (see Graesch and DiMare, 2013, panel 1), and frequent stirring is required. The ethnographic record is silent on the issue of whether Stó:lō-Coast Salish cooking practices entailed the regular use of lids. It is also unclear whether cooks regularly rinsed cobbles after removing from hearth embers and before submerging in the cooking vessel. To the south, cobble rinsing was not uncommon among the Pomo and other Native Californians who regularly used convectional heating to cook acorn meal (Kroeber and Barrett, 1962).

Regardless, further experimentation is needed to evaluate the effectiveness of cobbles in heating solution to cooking temperatures. Neither our single-exposure nor our multi-exposure experiments resulted in temperatures high enough to boil. However, food does not need to be brought to boiling temperatures to cook for safe consumption. Sustaining temperatures of only 65-75°C for 12-15 minutes will kill harmful bacteria (e.g., salmonella) when cooking meats (Goodfellow and Brown, 1978), and plant materials may be cooked at even lower temps. Although we do not present the data here, temperatures in excess of 70°C were achieved with multi-lot exposures, or when two or more cobble lots are sequentially heated and immersed in a short span of time. Based on these combined experimentally derived datasets, we suggest that traditional convective cooking practices entailed the use of 8-12 cobbles when preparing the food-equivalent of 3 gallons of water. Furthermore, each of these cobbles required at least 25 minutes exposure to the fire, and all were likely transferred to the cooking container in a short period of time (e.g., 5-10 minutes). Cobble size, cobble material, and salinity of the solution, among other chemical factors affecting boiling point, are all variables that undoubtedly shaped decisions about the requisite number of cobbles and the time each was heated in the hearth.

Inferences About Residential Midden Formation Processes

Surprisingly, neither the single-exposure nor the multi-exposure experiments yielded assemblages of cracked rock that closely approximate the size profiles of archaeological assemblages from *Welqámex* (Table 4). TMR recovered in and near residential architecture at *Welqámex* tends to be highly fragmented, and the majority (61.8%) of specimens are captured with 6.4-mm (or smaller) mesh. The extent to which cobbles fractured in multi-exposure experiments is somewhat a better match to rates of breakage indicated by archaeological assemblages, although the differences are still notable. In Table 5, for example, the proportional representation of small (6.4 mm) MGI, FGI, and quartzite fragments resulting from experimentation is substantially lower than that observed in residential middens.

A comparison of TMR datasets deriving from archaeological and experimental research suggest that the size and kinds of TMR in residential middens are the result of several cultural and natural formation processes. Clearly, the practice of using cobbles and cobble fragments for two or more rounds of cooking results in a larger aggregate assemblage of cracked rock. Yet, in spite of an increase in total number of fragments across all four material categories, only CGI specimens tend be disproportionally smaller and thus most similar to size profiles evident in archaeological assemblages. This suggests that the circumstances by which

Table 4. Size Profiles of Aggregate Assemblages of Cracked Rock as Generated with Single- and Multi-Exposure Experiments and Archaeological Investigations at *Welqámex*

Mesh size (mm)	Experimenal TMR: single-exposure		Experimental TMR: multi-exposure		Archaeological TMR[a]	
	n	%	*n*	%	*n*	%
25.6	428	43.8	153	20.8	584	17.8
12.8	251	25.7	329	44.6	672	20.5
6.4	298	30.5	255	34.6	2028	61.8

[a] Archaeological data derive from the totality of subsurface investigations in Structures 3, 4, 8, and 9, all of which are residential architecture inhabited as recently as the Contact/Colonial period. Specimens captured in 3.2-mm mesh were weighed but not counted and thus are not reported here.

Table 5. Size Profiles of Cracked Rock by Material as Generated with Single- and Multi-Exposure Experiments and Archaeological Investigations at *Welqámex*

Material	Mesh size (mm)	Experimenal TMR: single-exposure		Experimental TMR: multi-exposure		Archaeological TMR[a]	
		n	%	*n*	%	*n*	%
Course-Grain	12.8	12	23.5	2	20.0	261	10.5
Igneous (CGI)	6.4	39	76.5	8	80.0	2226	89.5
Medium-Grain	12.8	28	58.3	11	57.9	470	19.2
Igneous (MGI)	6.4	20	41.7	8	42.1	1981	80.8
Fine-Grain	12.8	114	46.2	135	52.1	8	14.3
Igneous (FGI)	6.4	133	53.8	124	47.9	48	85.7
Quartzite	12.8	97	47.8	181	61.1	335	27.4
	6.4	106	52.2	115	38.9	889	72.6

[a] Archaeological TMR data derive from the full retention and sorting of screen residue (see Graesch, 2009) for a random selection of strata in units 06S17E and 28S41E. Specimens larger than 25.6-mm mesh were counted and weighed but not catalogued by material before discard in the field. Specimens captured in 3.2-mm mesh were weighed but not counted and thus are not reported here.

CGI cobbles break into large collections of mostly small fragments are largely accounted for by the experimental process outlined in this article. By contrast, our experiments seemingly account for only *some* of the circumstances by which MGI, FGI, and quartzite specimens break into smaller pieces. Other processes, including trampling and chemical weathering, may result in greater fragmentation, and still other processes (e.g., heating rocks in earth ovens or roasting pits) may explain the proportional abundance of small TMR in the archaeological record. This said, it is important to note that our multi-exposure experimental dataset is substantially less robust than our corpus of data deriving from single-exposure experiments. As such, patterns of aggregate and material-specific fragmentation may be hampered by selection biases and other factors attributable to a small sample size, and in turn, we may be underestimating the extent to which cobbles break when reheated.

CONCLUSION

The methods used in this experimental process generated baseline data addressing rates of fracture, origins of fracture, and size profiles of TMR assemblages.

Combined, our findings suggest that cooking by convection required access to an abundant supply of cobbles and an abundant supply of wood. Indeed, the collection of both cobbles and wood likely constituted a significant daily expenditure of household labor. At *Welqámex*, an island-based settlement, the recovery of nearly 2 metric tons of TMR from such a small sample of residential middens suggests that the cooking required of daily life as well as special events may have eventually exhausted local wood supplies and forced residents to gather off island and via boats. These experimental data also provide a starting point for analyses of inter-household variability in cooking activities and the ways that byproducts of routine cooking relate to evidence for household participation in salmon fishing as well as regional exchange.

Although experimentally derived cracked-rock assemblages do not closely match those recovered archaeologically, baseline data addressing the rate of cobble fracture, variable heat-transfer effectiveness, and hearth temperatures move us closer to a fuller understanding of the generative processes accounting for house-associated middens and, in turn, more nuanced interpretations of aggregate residues of household activities. We argue that archaeologists' collective perception of the utility of TMR to archaeological interpretation is shaped by a comparatively smaller corpus of experimental research than that dedicated to chipped stone technology and taphonomy. To this end, we advocate:

1. for more systematic and rigorous treatments of TMR in the field and lab; and
2. for more data-robust and methodologically rigorous experimental studies.

Further experimentation should apply similar methods to the study of TMR generated with several cooking methods (e.g., earth ovens and pit-steaming features) for the purpose of parsing the signatures of various cooking technologies and evaluating refuse disposal patterns and other site formation processes. Baseline data generated with replicable experimental methods are critical to the task of developing and testing hypotheses concerning the circumstances and behaviors by which TMR assemblages are created and transformed in various archaeological contexts. This is important to the development of an experimental archaeology, in general (Schiffer et al., 1994), and experimental archaeological research addressing TMR, in particular.

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