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Benefits of Big Mortars: Considering Performance Characteristics and Economic Trade-Offs of Women's Technology

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In California archaeology, and in many contexts world-wide, few data exist to compare functional differences among traditional ground-stone mortar designs. Here, experimental small-seed and acorn/nut processing rates are reported for three mortar designs (deep bowl, deep conical, and shallow cup) and two grinding slab designs (flat unshaped, and shallow basin). These designs, in various combinations, are common in many plant-based hunting and gathering societies. Results of the grinding experiments are considered in reference to manufacturing costs, mobility, and resource use. Unexpected relationships are demonstrated for bowl and conical mortar shapes and seed processing. In particular, large mortars with deep, broad interiors are highly effective tools for producing flour from both small wild seeds and acorns. Conical mortar shapes are good for acorn processing, but perform poorly for processing small seeds into flour. As expected, shallow mortars are the least productive, but least expensive, tools. Large mortars with broad, bowl-shaped interiors would have been excellent tools for long-term use in settings where multiple types of plant resources were processed into finer particles. Despite their superior performance, steep costs of manufacturing, including the transport of suitable raw materials, may have limited the use and ownership of these mortars.

GROUND-STONE ARTIFACTS such as mortars, pestles, grinding slabs, and handstones represent durable evidence of ancient human processing activities. Modeling manufacturing costs and performance benefits of traditional milling tool designs can provide insights into modes of food processing, landscape use, and scheduling constraints faced by women in plant-based foraging societies (Bright et al. 2002; Buonasera 2013, 2015; Jackson 1984; Mauldin 1993; Murray 2014; Stevens and McElreath 2015). If we assume that women in these societies often had to perform multiple daily tasks—from foraging, food processing, and fuel collection, to the manufacture and repair of processing equipment, or the care of young children and others—it is reasonable to assume that decisions were made daily about where to place one's efforts.

A lack of comparative data on the performance characteristics and manufacturing costs of different types of mortars is a significant roadblock to understanding women's decisions surrounding food processing and associated technologies among some ancient hunting and

gathering societies. Experimental and ethnoarchaeological studies on ground-stone use have largely focused on domesticated grains and large, formalized grinding slabs (e.g., metates, querns) among small-scale farmers (Cook 1973; Gonzalez 2014; Hersh 1981; Hillman 1981; Mauldin 1993; Searcy 2011; Wright 1993). While some ethnographic estimates of time exist for acorn processing in mortars (McCarthy 1993), or for grinding wild seeds on small grinding slabs (Cane 1989), this information does not allow us to compare differences in surface area, shape, or volume. Moreover, very little quantitative information exists with which to make comparisons between small wild seeds processed in different mortar shapes (see Murray 2014 for an exception) or acorns/nuts processed on different grinding slabs. To formally model economic trade-offs of traditional grinding technologies, we need replicable data that are comparable across different resource types and different tool forms.

Experiments using and manufacturing various ground-stone tool designs can provide these sorts of comparative data. Previous grinding experiments with

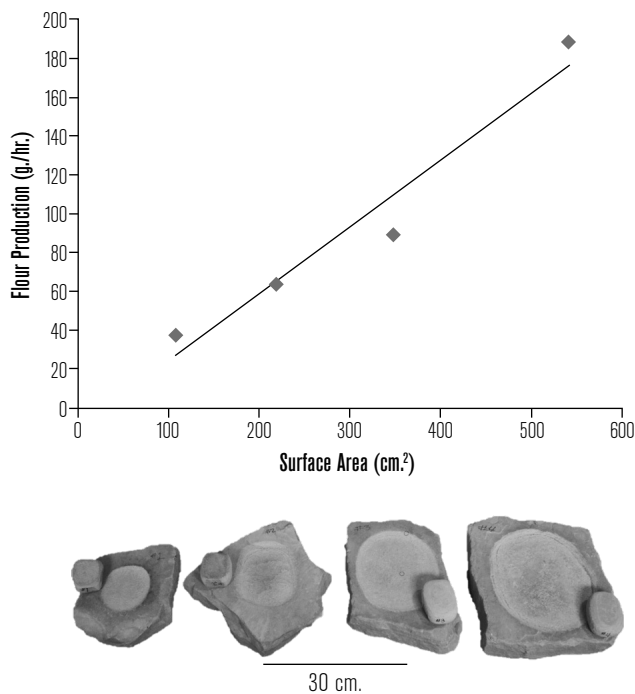


Figure 1. This graph shows increases in grams of flour produced per hour with increasing surface area. The tool-sets used to generate these data are shown above.

expedient ground-stone technologies typical of short-term use (Buonasera 2015) have shown that increasing the surface area of grinding slabs increases the rate of flour production for small wild seeds (Fig. 1). A similar relationship has also been documented for large formal manos and metates used to process maize and quinoa (Hard et al. 1996; Mauldin 1993). In the experiments with expedient milling tools and small wild seeds reported in Buonasera (2015), all variables were held constant except for increases in surface area. Each tool-set was used to grind Indian ricegrass (*Achnatherum hymenoides*) in four 30-minute trials, and flour weights of the finest fraction were combined and averaged.

Next, the increase in productivity was modeled following the point estimate model for technological intensification (Bettinger et al. 2006). Figure 2 shows this model adapted to compare gains in grinding rates for time invested in manufacture. Manufacturing times were compared for sandstone and granite grinding slabs. Manufacturing time is represented by the right side of the X-axis and use times on the left side of the X-axis. The Y-axis is the rate of flour production. The X-intercept to the left of the Y-axis shows the threshold use times

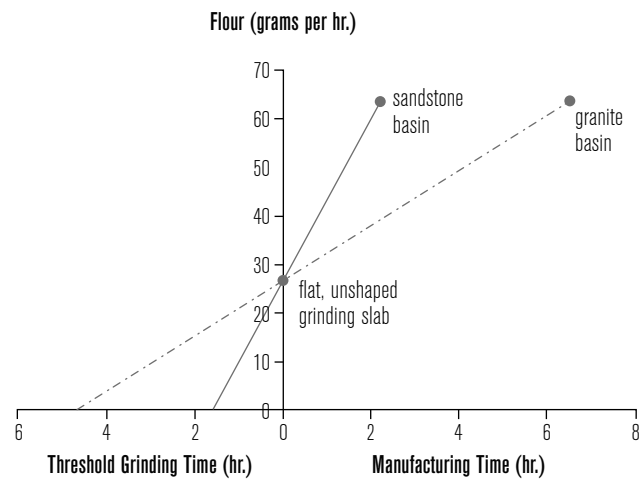


Figure 2. Point-estimate model (following Bettinger et al. 2006) for decision to manufacture a shallow basin or use a flat, unshaped slab (Buonasera 2015).

required to shift between the cheaper form and the more productive but more expensive form. The initial surface of either an unshaped slab, or a small, previously shaped surface, could be used as found, with no improvement, or could be improved by increasing the shaped surface area. The grinding rate of the initial state is plotted as point A. The grinding rates and manufacturing costs of the improved granite surface (point B) or sandstone surface (point C) are then plotted.

Results of this modeling exercise suggest two things. First, only a few hours of anticipated grinding time are required to make some investment in the shaping of stone surfaces worthwhile. This finding means that we should look for evidence of manufacture on and around milling surfaces, even on so-called expedient ground stone tools with no exterior shaping. Second, raw materials that are easier to shape should be preferred for short-term use over those that are more resistant to modification. This would allow grinding rates to be improved sooner (see the threshold grinding times of sandstone versus granite on the left side of the x-axis). Yet, if long-term use can be anticipated, this benefit is likely to be reduced as materials that are easier to shape also tend to be less durable.

However, the previous research only addressed flat grinding tools, not mortars. Mortars were important to hunter-gatherers and small-scale societies in many regions of the world, particularly in California. To address the lack of comparable data on mortar functionality, an extensive series of controlled grinding experiments was conducted

over several years (with the help of many volunteers and several institutions). The experiments were designed to measure and compare the efficiency of different milling tool forms (three types of mortars and two types of grinding slabs), and different tool raw materials (basalt and sandstone), in processing different resources (acorns and wild grass seeds) with different physical characteristics (oily, bulky, and relatively soft acorns versus dry, small, and relatively hard grass seeds). Resultant grinding efficiencies and other performance characteristics are reported here, and relationships to resource use, mobility, and manufacturing costs are discussed.

BACKGROUND

In various contexts—e.g., mid to late Holocene California, Archaic to Formative periods in the southwestern United States, and the Epipaleolithic to early Neolithic sequences in Southwest Asia—diachronic shifts in grinding tool morphologies are believed to have accompanied major transitions in subsistence, including the beginnings of farming or the intensified use and processing of wild plant staples (Basgall 1987; Baumhoff 1963; Hard et al. 1996; Haury 1950; Mauldin 1993; Wright 1994). In central California, the shift from the use primarily of milling slabs and manos to mortars and pestles is associated with increased sedentism and the use of acorns among hunter-gatherers (Basgall 1987; Baumhoff 1963). In the southwestern United States, flat and shallow-basined grinding slabs used with small “one-hand” handstones are associated with the processing of wild seeds and other resources, while large, formalized trough metates and larger “two-hand” manos are associated with the adoption and intensification of maize agriculture (Hard et al. 1996; Haury 1950; Mauldin 1993). In Southwest Asia, the proliferation of mortars during the Natufian, and the subsequent increase in flat grinding stones in the Neolithic, may reflect a change from earlier patterns of plant use that included more nuts and acorns to later patterns focused on the intensive use of cereals and grasses (Barlow and Heck 2002; Mason 1996; McCorriston 1994; Rosenberg 2008).

However, others have suggested that changes in milling tool morphologies do not reliably track early uses of new foods (Adams 1999; Dubreuil 2004; Morris 1990; Wright 1992, 1994). From this perspective it is

argued that new foods are most likely to be adopted if they do not require new tools or major adjustments in lifestyle, but instead fit into pre-existing patterns of food preparation (Adams 1999; Wills 1995). Following this line of reasoning, widespread shifts in milling tool forms are likely to reflect later phases and more intensive uses of certain resources. Adams (1999) has pointed out that new types of ground-stone tools were not necessary to exploit maize in the southwestern U.S. Similarly, mortars were not required to reduce acorns to meal in California (Mikkelsen 1985; Schroth 1996). Ethnographic and experimental data show that maize can be processed into meal using either smaller, less formalized one-hand manos and grinding slabs or larger and more formalized trough metates and two-hand manos (Adams 1999), while acorns can be processed into meal using either mortars and pestles or grinding slabs and handstones (Mikkelsen 1985; Schroth 1996). Furthermore, it is entirely possible for both maize and acorns to be processed and eaten whole without any grinding at all (Cushing 1920; Gifford 1971). Maize obviously requires cooking, but not grinding. In the case of acorns, tannins were sometimes removed from whole acorns by a process of ‘passive leaching’ in which they were buried in boggy places or submerged in running water for extended periods of time (Gifford 1971).¹

Scholars have argued that during Epipaleolithic through early Neolithic sequences in Southwest Asia, shifts in grinding tools represent an increasingly intensified processing of grains rather than a change in the resources that were routinely processed (Dubreuil 2004; Eitam et al. 2015; Wright 1992, 1994). For example, Wright (1992, 1994) proposed that the increase in grinding slabs versus mortars and pestles served to facilitate the production of fine flour, and that this was one way to increase the amount of food available from the same unit of land. Humans gain more calories from finely ground flour than from the same starting weight of whole grains—in part because more surface area is exposed for efficient digestion and nutrient absorption, and also because there is less fiber to slow movement through the digestive tract (Heaton et al. 1988; O'Donnell et al. 1989; Stahl 1989).

Another benefit to be gained by processing hard seeds and other fibrous plant foods into fine particles is a reduction in cooking time. Whole grains do not cook

as quickly as fine flour, and in many cases, cooking is necessary to turn complex starches and phytotoxins into more digestible foodstuffs (Carmody and Wrangham 2009; Stahl 1989; Wandsnider 1997). If less cooking is needed, significant fuel savings might be achieved. Therefore, it seems plausible that flour production could be adaptive in some fuel-poor settings.

Although it seems reasonable to expect that grains would be reduced to fine particles more quickly using flat grinding surfaces rather than mortars and pestles (based on differences in surface area alone), this assumption is currently supported by only a few largely qualitative observations (Wright 1992:73, 1994:293). Quantitative measurements and standardized comparisons are needed to better evaluate this assertion. Results from quantitative and standardized comparisons will lend greater specificity to economic arguments involving relationships between particular tool morphologies and flour production.

California

Although the grinding experiments discussed here were intended to be informative for a wide range of contexts, the research design was weighted toward addressing specific issues and gaps in the archaeology of central California. On a broad regional and temporal scale, subsistence pursuits in prehistoric California have in the past been characterized by equating mortars and pestles with acorns, and grinding slabs and handstones (manos and metates) with small seeds (Basgall 1987; Bouey 1987). The birth of this morphological dichotomy can probably be traced to a few lines written by Kroeber (1925:411): “All through the interior region the metate is used for dry seeds. The acorn is probably too oily for rubbing.” While the intensive use of acorn really does seem to be tied to mortars and pestles in California (especially ethnographically), attributing this association to the more distant past makes it difficult to recognize less intensive uses of acorns in earlier and more residentially mobile economies associated with a nearly exclusive use of grinding slabs and handstones. The ability to recognize acorn use in earlier settings is of particular interest because such contexts may represent early experiments with small-scale, low-intensity storage (i.e., caching) (Morgan 2012; Tushingham and Bettinger 2013).

This simple dichotomous tool and resource association also tends to downplay trends in increasing

small-seed use that have been documented at Late Period sites in central California (Wohlgemuth 1996, 2004, 2010). Moreover, a consideration of other plant resources—including various geophytes with underground storage organs (bulbs, tubers, corms, rhizomes), which also made large caloric contributions to the diet in California at different times and places—is typically left out of the discussion altogether (Gayton 1948; Gill and Hoppa 2016; Glassow 1996; Scholze 2010). Although many geophytes require only baking to make them edible, both ethnographies and experimental studies indicate that wetland geophytes such as cattail root (*Typha* spp.) and bulrush (*Schoenoplectus* spp.) were pounded in mortars and soaked in water to remove starch from the fibrous rhizomes (Glassow 1996; Wollenstonecroft et al. 2008). The dichotomous association described above has been challenged in recent years as more archaeobotanical work has been performed in California (Gill 2014; Gill and Hoppa 2016; Reddy and Erlandson 2012; Scholze 2010; Wisely 2019; Wohlgemuth 2004), and heavy accumulations of acorn hulls have been recovered from several early sites dominated by grinding slabs and handstones (Rosenthal et al. 2007:161; White 2003).

It is important to recognize that a good deal of variability exists within the broader categories of mortars and pestles or milling slabs and handstones. Remarkably, much of that variability has been ignored in California (Buonasera 2013). In particular, the issue of how and why mortar and pestle types vary in form, frequency, and use through time and space has received little analysis. Although an innovative body of work has focused on the labor costs and spatiotemporal patterning of bedrock mortars (Jackson 1984, 1991; Leftwich 2010; McCarthy et al. 1985; Stevens et al. 2017), and functional associations have been documented for a few mortar shapes in California (McCarthy et al. 1985; Mikkelsen 1985; Schroth 1996), no systematic comparisons of grinding efficiency between distinct mortar shapes exist. While mortars are generally associated with acorn processing in California, several ethnographic accounts do suggest that deep conical depressions were used to process seeds or berries, and were not suitable for pounding acorns because the partially crushed acorns would be compacted into a solid mass at the bottom of the well (Dixon 1905; McCarthy et al. 1985).

In order to clarify these issues, experiments were conducted to address the following questions: (1) Does flour production of acorns or small seeds vary significantly based on differences in mortar shape, size, or raw material? (2) How well do different mortars function for processing acorns and small seeds compared with grinding slabs? (3) Are mortars poor producers of fine flour and grinding slabs good producers of fine flour? (4) If so, how much better are grinding slabs than mortars at producing flour?

METHODS

Selection of Forms, Raw Materials, and Resources

Tool designs are provided in Table 1 and they are based on artifacts from late Holocene sites in the south San Francisco Bay area. Figures 3–5 show archaeological examples of three basic shapes of portable mortars, which were compared with shallow basin grinding slabs and flat unshaped slabs. The ground-stone artifacts in the figures are from late Holocene sites in the south San Francisco Bay area. Similar forms are common in prehistoric hunter-gatherer or mixed gathering and small-scale

Table 1
TOOL-SET DIMENSIONS AND RAW MATERIALS

Lower Stone	Use Surface Shape	Material	Diam.	Length	Width
Shallow mortar	Round, dished, 12.5 cm. diam. × 2.25 cm. deep	sandstone	12.5		
Shallow mortar	Round, dished, 12.5 cm. diam. × 2.25 cm. deep	basalt/andesite	12.5		
Conical mortar	Round, conical, 10 cm. deep	basalt/andesite	14.5		
Bowl mortar	Round, steep walls, 10 cm. deep	basalt/andesite	20.5		
Shallow basin grinding slab	Oval, slight depression, 1 cm.	sandstone	24	18.5	
Shallow basin grinding slab	Oval, slight depression, 1 cm.	basalt/ andesite	24	18.5	
Flat, unshaped grinding slab	Rectangular, flat with natural surface texture	sandstone	30.5	21.3	
Flat, unshaped grinding slab	Rectangular, flat with natural surface texture	basalt/ andesite	30.5	21.3	

Upper stones: With the exception of the conical mortar pestle, all pestles were manufactured to be cylindrical in cross section with slightly rounded working ends. Pestle lengths ranged from 19 to 25 cm. and working ends ranged between 5–6 cm. in diameter (except for the conical pestle which was tapered). Handstones for the shallow basin grinding slabs were 12 × 7.5 × 3.5 cm.

Shallow Mortar

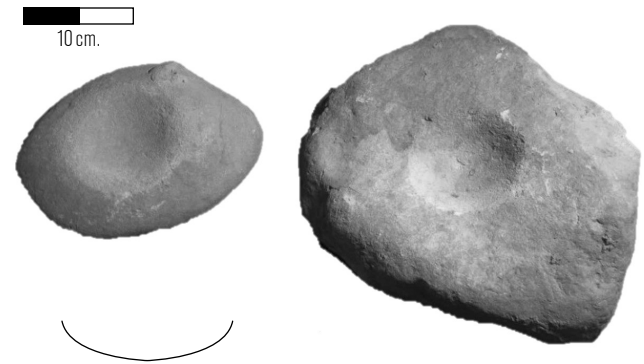


Figure 3. Shallow mortars from late Holocene contexts in the south San Francisco Bay area.

Conical Mortar

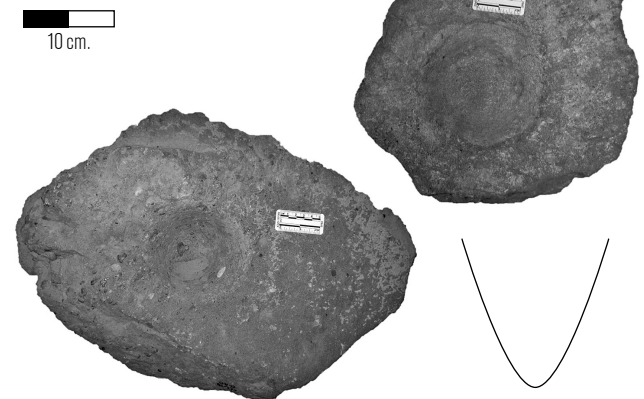


Figure 4. Conical mortars from late Holocene contexts in the south San Francisco Bay area.

Bowl Mortar

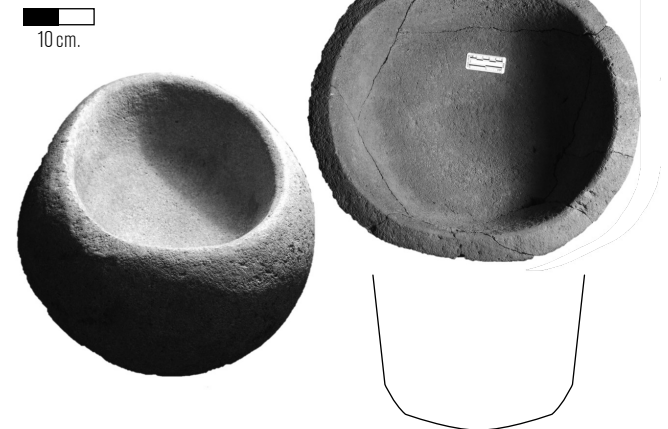


Figure 5. Bowl and flower-pot mortars from late Holocene contexts in the south San Francisco Bay area.



Figure 6. Mortars with deep conical and some shallow depressions from Aşıklı Höyük, Turkey.

farming contexts throughout the world (Kraybill 1977; Wright 1994). For example, Figure 6 shows several portable mortars with deep conical depressions and a few shallower ones from Aşıklı Höyük, an early Aceramic Neolithic site in Turkey with a basal layer dating to approximately 10,500 B.P. (Stiner et al. 2014). Archaeobotanical remains at the site included wild and domesticated wheat and barley, as well as legumes, wild nuts, and hackberry (Özbaşaran 2011).

Shallow mortars are the least expensive type of mortar to manufacture, and they are common throughout the world (Bednarik 2008; Mikkelsen 1985; Rosenberg and Nadel 2017; Wright 1991). Although Figure 3 shows portable forms, similar shallow mortars are also common in bedrock milling features.

Conical mortars are also widely found in both bedrock features and portable forms (Kraybill 1977; Nadel et al. 2009; Wright 1991). Conical mortars may have begun their use-lives as shallow mortars, with depths increasing through long use, or through a combination of

long use and shaping. Some may have been intentionally shaped to their final depth. It can be difficult to distinguish intentional shaping in conical mortars, since a tapered shape can form naturally through long use. On the other hand, broad, symmetrical bowl shapes with steep or nearly perpendicular walls and very large volumes are not likely to develop through use. Such mortars would have required a focused manufacturing effort to remove large quantities of material and create steep-sided walls.

Figure 5 shows a bowl mortar on the left and a flower-pot mortar on the right. There are obvious differences in the exterior shaping, and there are some interior differences as well. The interiors of flower-pot mortars tend to have even broader basins and larger diameters than bowl mortars. However, both have deep (>10 cm.), broad basins. These features were considered in creating an idealized interior bowl-shape for the sake of the experiments.

Upper and lower stones (e.g., mortars and pestles, or grinding slabs and handstones) that are used together tend to have complementary use surfaces. Even if they are not

originally designed (i.e., intentionally shaped) to fit, they will conform to one another after many hours of use. Figure 7 shows a simple line-drawing of three mortar and pestle shapes: a shallow mortar and pestle, a conical mortar and pestle, and a bowl mortar and pestle.

Collection of Resources and Manufacturing of Tool-Sets

Valley oak (*Quercus lobata*) and black oak (*Q. kelloggii*) acorns were gathered from public and private lands with the help of volunteers. Necessary permits were obtained in advance for collecting the resources on public lands. All acorns were air dried for a minimum of four months prior to processing; some were dried for more than a year. Indian ricegrass (*Achnatherum hymenoides*) seeds, free of chaff, were purchased in bulk from a native seed supplier.

Figure 8 shows the five tool-set morphologies in basalt/andesite, while Figure 9 shows the three complementary sets made from sandstone. Most tools were manufactured to a preliminary shape using power tools. All manufactured tool surfaces (as opposed to the two unshaped, flat-surfaced tool sets) were pecked by hand

with hammerstones until all visible manufacturing marks were removed from the contacting (use) surfaces. To obtain data on manufacturing costs, several tools were made entirely with hammerstones through a combination of flaking and pecking. The most effective hammerstones were made from very hard and durable metamorphic materials. Where possible, these were broken and flaked to create pointed or sharp edges.

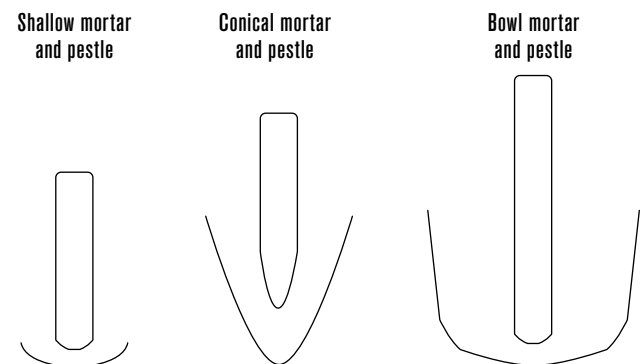


Figure 7. Complementary shapes of mortar and pestle use-surfaces.



Figure 8. Five sets of experimental basalt/andesite milling tools.



Figure 9. Three sets of experimental sandstone milling tools.

Ethnographic and experimental studies on ground-stone manufacturing note the importance of pointed or chisel-shaped tools, particularly in later stages of pecking and shaping (Hayden 1987; Huckell 1986; Schneider 1993; Schneider and LaPorta 2009). Interior mortar dimensions were based on averages from my dissertation research on south San Francisco Bay area assemblages (Buonasera 2013). Measurements are provided in Table 1.

Grinding Experiments

The experiments employed a factorial design (Czitrom 1999) to compare the main effects and interactions of three factors (tool form, raw material, and resource) on flour production; five forms, two rock types, and three resource types were compared. Multiple grinding sessions took place between October 2014 and June 2017. The participants included students, professional

archaeologists, and interested members of the public. After an initial 20-minute practice, the results of which were discarded, volunteers ground a single type of resource with one tool-set for two, non-consecutive, 30-minute sessions (Fig. 10).

Working in teams of two, one person recorded observations and monitored start and stop times, while their partner processed for 30 minutes. Partners then switched roles for an additional 30 minutes. After a break, the teams repeated the same process one more time. The final result was two hours of processing for a particular tool, raw material, and resource combination, averaged over two trials by two users.

At the end of each 30 minutes, all of the ground and partially ground material was carefully collected from the tool surface and surrounding grinding area and placed in a labelled bag. This product was later sifted through



Figure 10. Volunteers ground a single type of resource with one tool-set for two, non-consecutive, 30-minute sessions.

a set of standard testing sieves that ranged from 1 mm. to 0.5 mm. in mesh size. The finest fraction (<0.5 mm.) was considered “flour” and was used for all comparisons (Fig. 11).

One would expect greater productivity from people in the past who routinely processed resources on similar tool types, due to their increased opportunities to learn from skilled grinders, as well as to inevitable muscle

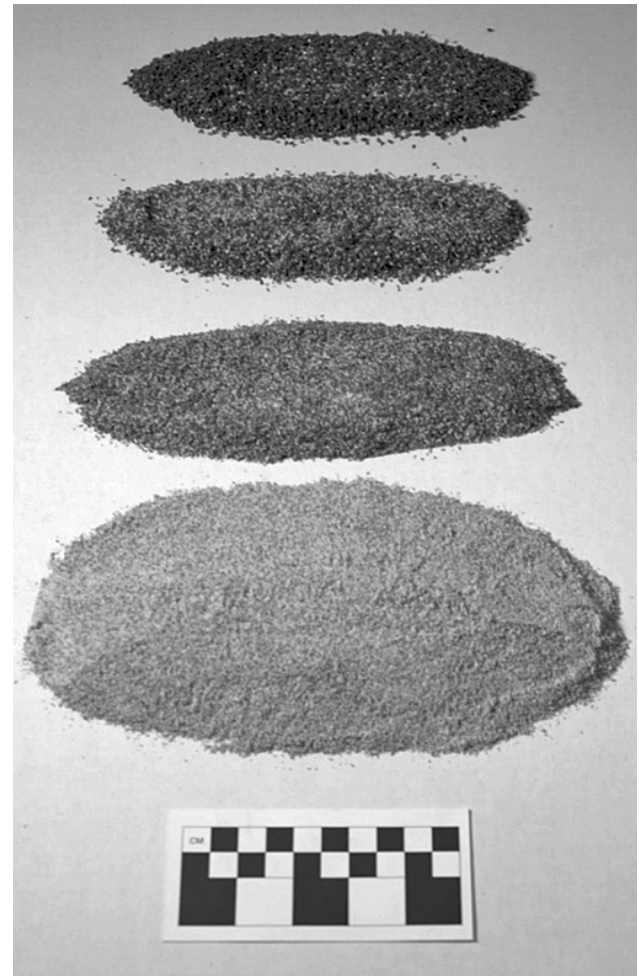


Figure 11. Sifted fractions of processed Indian ricegrass. The finest fraction (< 500 μm .) was used for all comparisons.

development and kinetic memory. Based on this, it is assumed that the average results presented here are probably less than the routine outputs achieved by people in the past. However, these results allow us to compare productivity between tools, because the experiments were conducted under the same conditions and outputs were measured in the same way. Moreover, the outputs of multiple volunteers over several hours were combined and compared, thus evening out the effects of one or two exceptional or lackadaisical grinders.

RESULTS

Grinding productivity was measured over 141, 30-minute grinding sessions (70.5 hrs.; Table 2). Of this total, 47.5 hours were spent processing Indian ricegrass seeds

Table 2
FLOUR TOTALS FOR THREE RESOURCES PER 30 MIN.
GRINDING SESSION (g. OF <500 μ m. FRACTION)

sst ^a shallow mortar	sst ^a shallow basin	sst ^a flat unshaped slab	ba ^b shallow mortar	ba ^b conical mortar	ba ^b bowl mortar	ba ^b shallow basin	ba ^b flat unshaped slab
Indian ricegrass seeds							
9.7	44.7 ^c	13.4 ^c	36.6	39.9	100.4	71.9 ^c	29.4 ^c
24.2	44.7 ^c	13.4 ^c	48.8	21.7	110.1	71.9 ^c	29.4 ^c
16.2	44.7 ^c	13.4 ^c	39.1	39.6	98.1	71.9 ^c	29.4 ^c
27.8	44.7 ^c	13.4 ^c	62.7	29.6	105.1	71.9 ^c	29.4 ^c
15.9	28.6	21.6	17.0	16.1	100.0	33.7	27.9
22.6	41.2	38.7	23.0	19.3	60.1	39.7	35.4
22.9	62.2	22.4	22.7	22.0	108.3	42.2	44.4
24.6	35.5	27.7	20.2	47.6	91.3	55.7	44.1
25.2	69.2		15.0	30.6	107.6	42.8	
11.3	29.0		16.3	32.3	75.5	38.7	
28.7	19.1		14.9	34.7	119.4	44.5	
8.3	46.2		20.3	48.3	96.3	48.5	
					129.0	38.9	
					109.3	45.0	
					68.0		
					87.8		
					97.9		
Black oak acorns							
			60.3	98.9	140.0	44.2	38.3
			56.3	181.3	140.8	57.2	32.1
			64.7	105.8	142.3	60.7	39.1
			53.5	135.0	149.8	111.1	
				125.4	138.2	96.4	
					138.5		
					169.8		
Valley oak acorns							
			13.9	17.0	63.4	16.2	22.5
			32.3	24.8	68.4	16.0	17.0
			19.6	33.5		23.7	22.0
			26.9	26.9		16.6	18.0
				80.5		36.3	
						22.0	
						54.5	

^aSandstone.^bBasalt/andesite.^cAverage value for the first four trials, which were combined and sifted together.

(*Achnatherum hymenoides*) and 23 hours were spent processing acorns. Acorn processing time was further divided nearly equally between processing valley oak (*Q. lobata*) and black oak (*Q. kelloggii*).

The productivity averages for all tool form and resource combinations are shown in Figure 12. Values for

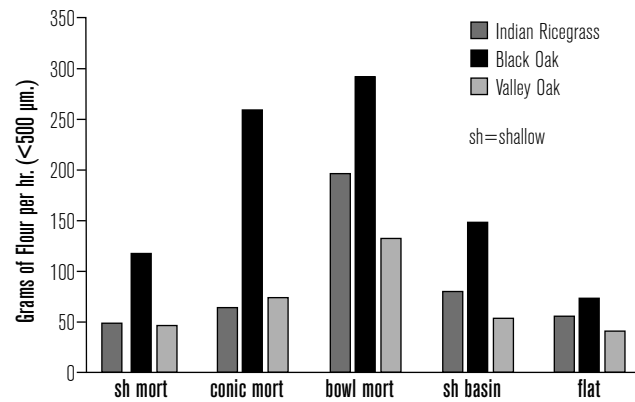


Figure 12. Average productivity of all grinding tools for three resources.

Table 3
INDEPENDENT T-TESTS

Sample	n	mean	SD	df	t	Sig. (2-tailed)
Sandstone shallow mortar vs. basalt shallow mortar						
Sandstone	12	39.57	14.36	15.57	1.69	0.112
Basalt	12	56.10	30.78			
equal variances not assumed						
Sandstone shallow basin grinding slab vs. basalt shallow basin grinding slab						
Sandstone	9	76.04	38.00	11.22	0.385	0.707
Basalt	11	81.40	18.96			
equal variances not assumed						
Sandstone unshaped flat grinding slab vs. basalt unshaped flat grinding slab						
Sandstone	5		25.63	8	1.02	0.339
Basalt	5	63.66	30.59			

duplicate tool forms (i.e., sandstone versions and basalt versions) are combined because no significant difference was detected between the amount of flour produced on sandstone or basalt versions of the same tools (see following section and Table 3). Figures 13–15 show box and whisker plots of grams of flour produced per hour for each form, along with median and average values for all cases across each resource.

Productivity Based on Tool Material

Paired tool forms of equivalent shape and surface area were made from two different raw materials (sandstone and basalt) and both were used to process Indian ricegrass. These dual sets included the shallow mortar, shallow

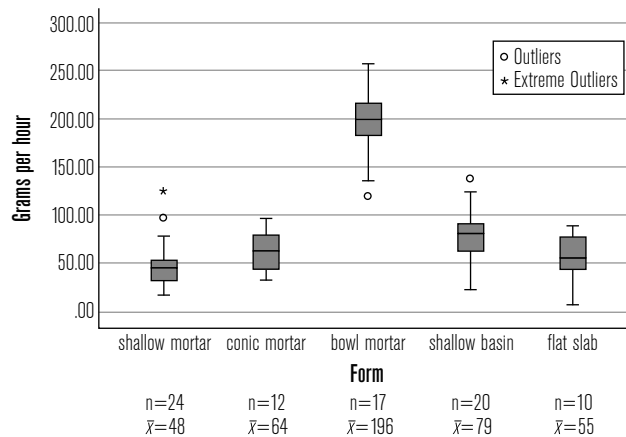


Figure 13. Productivity of forms for Indian ricegrass seeds (*Achnatherum hymenoides*).

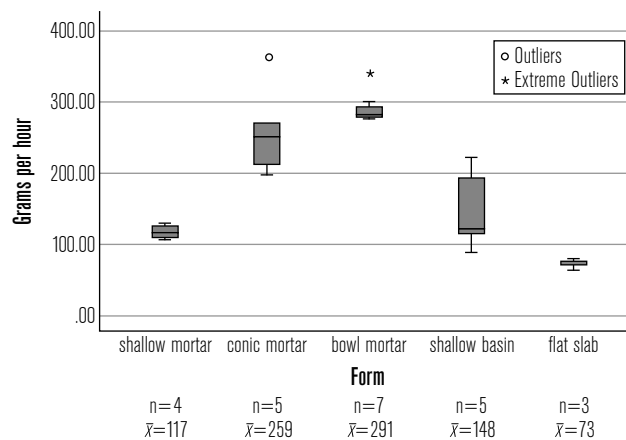


Figure 14. Productivity of forms for black oak acorns (*Quercus kelloggii*).

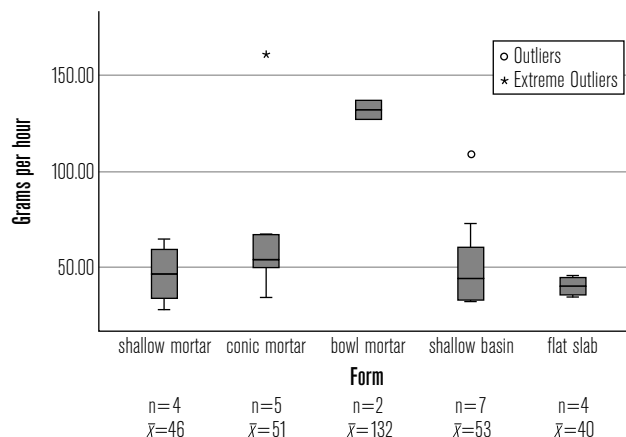


Figure 15. Productivity of forms for valley oak acorns (*Quercus lobata*).

basin grinding slab, and the unshaped flat grinding slab. No significant difference in flour production with Indian ricegrass seeds was detected for equivalent tool forms



Figure 16. Indian ricegrass flour produced in the bowl mortar during the first 30-minute grinding session.

made from basalt or sandstone (independent t-tests, with cut-off of 0.05 for significance, Table 3). The sandstone tools were not used to process acorns, although this is planned for future experiments.

Productivity of Tool Forms by Resource Type

Indian ricegrass. The bowl mortar was more productive than all the other tool-sets for processing Indian ricegrass (a small, wild grass seed) into flour (Figs. 12, 13 and 16). This result was not anticipated at the outset of the experiments since mortars are generally believed to be poor for seed processing, but it was found to be consistent across all experiments and each group of volunteers. As expected, the shallow basin grinding slab performed better than the shallow mortar for seeds. Both of these differences were statistically significant. Comparisons of means across the tool-sets were made with a one-way ANOVA (Table 4) and Bonferroni post-hoc tests. Differences were deemed significant if p-values were less than 0.05.

Black oak acorns. Although the bowl mortar also produced the highest returns for processing black oak acorns (Fig. 14), the conical mortar was not statistically different in mean productivity—even with the outliers removed (data not shown). The conical mortar had a higher degree of variation than the bowl mortar, however. Possible implications of this are discussed below. For processing black oak acorns, both the bowl mortar and conical mortar were significantly more productive than the remaining three tool sets (shallow basin grinding slab, shallow mortar, or flat grinding slab), which did not differ statistically from one another.

Table 4
COMPARISONS OF MEANS ACROSS TOOL-SETS
WITH ONE-WAY ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Grams of flour, Indian ricegrass seeds (<i>Achnatherum hymenoides</i>)					
Between groups	256,115.487	4	64,028.872	80.998	0
Within groups	61,659.104	78	790.501		
Total	317,774.592	82			
Grams of flour, black oak acorn (<i>Q. kelloggii</i>)					
Between groups	143,280.414	4	35,820.103	39.782	0
Within groups	15,306.984	17	900.411		
Total	158,587.398	21			
Extreme outliers removed					
Grams of flour, valley oak acorn (<i>Q. lobata</i>)					
Between groups	13,079.150	4	3,269.787	8.211	0.001
Within groups	6,371.197	16	398.200		
Total	158,587.398	21			

Extreme outlier removed

Valley oak acorns. All tool sets had their lowest productivity when processing valley oak acorns (Figs. 12 and 15). The bowl mortar was significantly more productive than all the other tool sets after removal of the extreme outlier (Fig. 15), but the overall rate of flour production for valley oak acorns was still lower than it was for the other two resources. Differences in mean productivity between the remaining tool sets were not significant; the grinding slabs, conical mortar, and shallow mortar all produced similarly low amounts of flour.

Overall Flour Production by Resource

For all tool-sets, the greatest rate of flour production was obtained with black oak acorns (Fig. 13). The rate of flour production for Indian ricegrass seeds was lower (for all tool-sets) than for black oak acorns. This result was not unexpected, as acorns are very large seeds and are softer than small, wild grass seeds. On the other hand, the lowest rate of flour production (across all tool-sets) was obtained for valley oak acorns. This result was not anticipated. Valley oak acorns were a difficult resource to process into flour. During the experiments, volunteers uniformly reported that the physical properties of this resource made it difficult to reduce it to finer particles. The first experiments with valley oak used acorns that

had been dried for six months. Later experiments used acorns that had been dried even longer, up to several years. It did not matter whether they were dried for less than one year or for several years—valley oak acorns simply did not crumble and break apart as easily as black oak acorns. Instead, valley oak acorns flattened into a tacky and cohesive mass during processing. With continued effort, valley oak acorns were eventually reduced to flour, but they required more time and physical effort of grinding and pounding than equivalent amounts of black oak acorns.

DISCUSSION

The bowl mortar was the best tool for processing all of the resource types tested—wild grass seeds and two types of acorns. The conical mortar was good for processing black oak acorns, but performed poorly for processing seeds (although still better than a shallow mortar). If mainly acorns are being processed, a large conical mortar can work about as well as the bowl form. However, if seed processing is also important, the bowl form would be the most productive tool, of those tested, for the job. The bowl form was also the most expensive tool to manufacture in the experimental set.

The second-best tool for processing wild grass seeds was the shallow basin grinding slab. Knowing that grinding productivity increases with grinding surface area (Fig. 1), it is interesting to predict how large an area would be required for a grinding slab to equal or exceed the flour production of a bowl mortar. Based on prior experimental data (Buonasera 2015), we can predict the approximate surface area that a grinding slab would need to match the productivity of the bowl mortar. Extrapolating from Figure 1, and assuming a continued linear increase, experiments predict that this threshold is met at a surface area of about 600 cm.².

$$196 \text{ g./hr.} = 0.346x - 10.407, x = 597 \text{ cm.}^2$$

The shallow basin grinding slab used in the experiments had an ovoid use surface 24 cm. × 18.5 cm. in size. Using the formula² for the area of an ellipse, this gives a grinding surface area of approximately 350 cm.². If an ovoid surface with similar proportions was used, this would require grinding surface dimensions greater than 31 × 24 cm. (584 cm.²). A rectangular area with slightly

smaller maximum dimensions (e.g., 30 cm. × 20 cm.) could also meet this surface area requirement. However, in order to maintain a rectangular grinding surface with these dimensions, the grinding activity would need to employ a reciprocal grinding motion³ and use a handstone at least as long as the width of the lower grinding surface—otherwise a trough or a basin would be created (Adams 2002:103). In this case, the mechanics of use would be similar to those employed with large, formalized two-hand manos and metates, which places the user at one end of the long axis of the lower stone, with both hands pressing equally on the mano.

It is likely that two-hand manos operated with a reciprocal motion against a large rectangular grinding surface would have a different gain function than small handstones (one-hand manos) operated with a circular motion on a slightly basined ovoid surface because the former allows for greater use of the grinder's body weight during processing (see Bettinger et al. 2006 for a discussion of gain functions for different categories of technology). The limits where these forms intersect is an area that deserves further experimentation and modeling. Large bowl mortars and small basined milling slabs are associated with hunter-gatherers who have a high reliance on plant foods, but differing degrees of sedentism. For example, large bowl mortars are found among more sedentary contexts of Late Period California and the Epipaleolithic Natufian, while small grinding slabs are associated with mobile foragers and task specific sites. On the other hand, large rectangular grinding slabs and handstones (e.g., two-hand manos and metates) are typically associated with settled farmers.

Performance Characteristics of Conical Mortars and Bowl Mortars

There was greater variation in the grinding efficiency of the conical mortar than there was with the bowl mortar. This variability is probably due to a difference in the amount of physical effort required to use these two tools. Based on the observations of volunteers, the conical mortar and pestle seemed to require greater muscular effort than the bowl mortar to achieve similar outputs. Though the depth is helpful for containing the resource being processed, the shape of the conical mortar (with a small basal surface area and steeply parabolic walls) restricts the processing motions to pounding or to

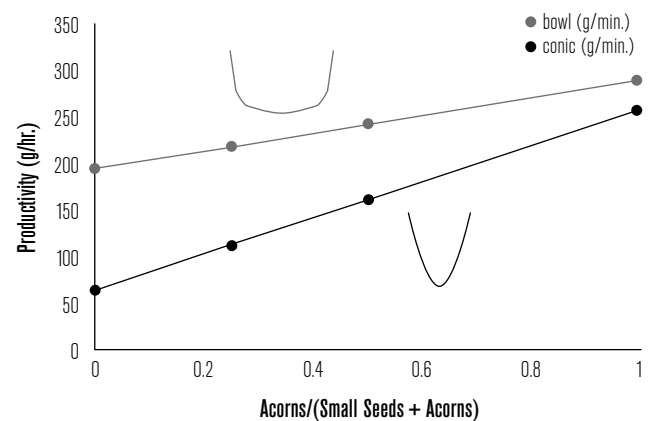


Figure 17. Rate of flour production for bowl and conical mortars as the proportion of acorns to small seeds increases.

vertical grinding along the walls—both motions require a repeated lifting of the pestle. Skill and practice may play a role in reducing the sheer muscular effort required to process acorns in this way. In contrast, the bowl mortar allows a wide range of motions to be employed and seems to require less physical exertion. It is deep enough to contain particles during pounding, and the bowl is broad enough that circular grinding, as well as back-and-forth grinding, can be employed without lifting the pestle from the surface. In addition to requiring less lifting, the grinding motions are able to leverage the length of the pestle. In the bowl mortar, these grinding motions were very effective for reducing both seeds and acorns to flour.

Figure 17 models the rate of flour production for two large mortars of different shapes—the deep conical mortar and the deep bowl mortar. The x-axis shows the proportion of acorns (a large seed/nut) to total seeds (acorns+small seeds)—with only small seeds at 0 and only acorns at 1. Both conical and bowl mortars produce similar amounts of flour from black oak acorns (right side of figure), but diverge quite a bit for processing small, wild seeds (left side of the figure). There are mechanical reasons for these differences in performance. As noted previously, the broad base of the bowl mortar allows for a range of both grinding and pounding motions, and the bowl is very good at containing resources. These properties contribute to its effectiveness for grinding both acorns and small seeds (Fig. 15).

In what contexts, then, might it be advantageous to use a conical mortar instead of a bowl/flower-pot mortar? The most obvious answer might be if small seed grinding

is much less important than acorn processing, which could be the case at seasonal locations focused on acorns or large nut processing. Assuming that more than a trivial amount of small seed processing will be required over the lifetime of the tool, another way to think about this would be to compare differences in manufacturing costs and the expected duration of use. Based on differences in volume, if both tools were manufactured to a usable depth, conical mortars would be much less costly to manufacture than bowl-shaped mortars with interiors of a similar depth.⁴

The point estimate model (Fig. 2) can be used to estimate how many hours of seed grinding would be required before making and using a bowl mortar would be as profitable as making and using a conical mortar or a shallow mortar. Any additional use beyond that would make shaping and using the bowl mortar more productive. The equation for shifting from a cheaper, less productive technology to a more expensive but more productive technology (Bettinger et al. 2006:541) is shown below, along with experimentally determined grinding rates for small seeds (Fig. 13) and the estimated manufacturing costs.⁴

Conical mortar grinding rate (r_1)=64 g./hr.,
manufacturing time (m_1)=40 hrs.

Bowl mortar grinding rate (r_2)=196 g./hr.,
manufacturing time (m_2)=260 hrs.

Threshold grinding time= $(r_1m_2-r_2m_1)/r_2-r_1$
 $(64 \times 260 - 40 \times 196)/(196-64)=67$ hrs.

Using these figures, an estimated use-time of 67 hours is calculated. If a woman expected to process seeds for several hours a day three times a week, this threshold could be met in less than two months. With very long use-lives, increased productivity would greatly surpass the additional cost of manufacture. In fact, this is likely to be the case with large, expensive bowl and flower-pot-shaped mortars made from durable raw materials. Use-lives of several decades and slow rates of wear have been recorded for formal grinding tools made from durable materials (Horsfall 1987; Searcy 2011; Wright 1993). Given this high degree of utility, we might expect large mortars to be even more common in relatively sedentary settings such as large village sites in Late Period Central California, where there is evidence for both intensive seed use and acorn use.

Although these would have been highly effective and desirable tools under conditions of reduced mobility where long use could be assured, it is also likely that there would be significant opportunity costs for manufacturing these very time-intensive technologies. Manufacturing stone grinding tools is very loud and dusty work. The noise alone may have required this activity to be performed away from living areas, making it difficult to fit between other daily tasks. Even if a tool can be expected to be in use long enough to recoup the cost of manufacturing many times over, perhaps few individuals could afford the upfront opportunity costs of that manufacture. Other significant impediments to manufacturing very large mortars could be the acquisition and transport of suitable raw materials. A lack of specialized knowledge or experience in removing large volumes of rock might also prevent many individuals from making a deep bowl mortar.

In addition to large bowl mortars, formally shaped flower-pot mortars have a very similar interior shape and are present in Late Period Central California. On average, flower-pot mortars tend to be larger than deep bowl mortars and have finely shaped exteriors with thinner walls (Buonasera 2013). Flower-pot mortars are usually associated with burial contexts. However, based upon the abundant wear present on many of these mortars, they were not manufactured specifically as burial offerings. Their rarity in mundane settings instead suggests they were valued possessions linked to specific individuals (see discussion in Buonasera 2013).

Shallow Mortars

The shallow mortar was the least productive of all the tools for seeds, and the second least productive for acorns. The poor results obtained for processing acorns with the shallow mortar were not expected. However, it seems likely that a little depth could improve acorn processing by quite a bit. Comparing returns between the shallow mortar and the deep conical mortar, we can see that seed processing remains poor, while the productivity of acorn processing more than doubles with increased depth (Figs. 13 and 14).

The greatest difficulty encountered with the shallow mortar was retaining partially ground material on the surface during processing. It is worth noting that during the experiments, the use-surface of portable shallow mortars sat above the floor and had fairly small surface

areas surrounding the mortar depressions. This made it difficult to retain materials falling outside the bowl. Increasing the flat surface area around a shallow mortar would help to collect and control partially ground material during grinding. With this in mind, sinking a shallow mortar into a house floor would have made it easier to retain and control the resource. Likewise, greater control of partially ground material, and better processing rates, could also be expected for shallow mortar depressions located in broad bedrock surfaces. Improved control would also be possible with the addition of a basketry hopper (Dixon 1905:184–186). Although a hopper would not increase the surface area used in processing, it would confine the material being processed and allow greater force to be used during pounding. Moreover, basketry hoppers are much lighter and easier to transport than large mortars, making them especially useful in mobile settings.

Resource Comparisons

During the same time interval, nearly twice as much California black oak acorn flour could be produced as either valley oak or Indian ricegrass flour (Fig. 12). This difference is further magnified by the greater caloric content per gram of black oak acorns than is found in the other two resources (due to its significantly higher fat content). For equivalent weights, fats contain about twice the calories of carbohydrates or protein (Speth and Spielman 1983). Black oak acorns contain around 18 percent fat, compared to about 5.5 percent for valley oak acorns (Baumhoff 1963:Table 1). Indian ricegrass contains only around 2.3 percent fat (Stearns and Booth 1980).

The higher fat and calorie content of black oak acorns, coupled with significantly lower grinding times required for equivalent amounts of flour, explain ethnographic accounts stating that black oak acorns were a preferred acorn resource in many areas of California (Barrett and Gifford 1933; Baumhoff 1963; Dixon 1905; Gayton 1948).

CONCLUDING REMARKS

Deep bowl mortars are excellent tools for processing small, wild grass seeds and for processing acorns. The experiments show that deep bowl mortars consistently perform better than all other tool sets (i.e., shallow mortars, conical mortars, unshaped grinding slabs, or shallow basin grinding slabs) for processing small seeds

into fine flour. Shallow basin grinding slabs work second-best for grinding small seeds, while deep conical mortars perform well for processing black oak acorns, but not for small seeds.

Modeling the increased productivity of larger grinding surfaces against the bowl mortar leads to the prediction that grinding slabs with greater surface areas would eventually meet and surpass large bowl mortars for producing flour from small seeds. However, based on surface area requirements, this could be near the limit of the shift from small handstones and grinding slabs (i.e., one-hand manos and metates) to two-hand manos and metates.

The conical mortar is good for pounding black oak acorns, and allows for some grinding along the angled walls, but its surface area is small and requires a vertical motion for grinding small seeds. Direct observations indicate that greater muscular effort may be required to use the conical mortar effectively as opposed to the bowl mortar, since the former requires more lifting of the pestle. On the other hand, conical and shallow mortars would have been less expensive to manufacture than deep bowl mortars made of the same materials.

Stone mortars with deep and broad interiors are among the most expensive durable objects recovered from archaeological contexts in California. Although they are highly effective for processing a wide range of resource types in more sedentary contexts, the steep manufacturing costs may have limited the ownership of these tools to individuals or families with greater social status or wealth.

The grinding experiments also demonstrated that there were big differences in the grinding rates achieved with different acorn types and with small seeds. Differences in processing costs are further magnified by caloric differences involving variations in fat proportions. It is likely that these differences would have affected resource preferences and methods of preparation.

These experiments have produced a wealth of data to begin evaluating and reevaluating a number of questions concerning food processing technologies. Additional experiments will continue to improve and expand efforts at modeling economic trade-offs surrounding the use and manufacture of ground-stone processing tools. These efforts will help us to better understand shifts in technology and focus greater attention on the conditions surrounding women's technological choices.

NOTES

¹The tannins in acorns can also be inactivated chemically, avoiding the time-intensive leaching process. In an interesting case of cultural convergence, Johns and Duquette (1991) compare the making of so-called black acorn bread among the Pomo and among some traditional Sardinians. This process involved mixing iron-rich sediments with ground acorn meal and baking the mixture (in an underground oven in the case of the Pomo). The iron chelates and deactivates the tannins, and in the process turns the bread black.

²Area of an ellipse = πab , where $a = 1/2$ length, $b = 1/2$ width

³The shape of a lower grinding surface is maintained and altered by the type of grinding motion and the shape of the upper stone (see Adams 2002:103 for a discussion). Likewise, the shape of the lower stone can constrain the range of motions used with an upper stone.

⁴Based on average mortar volumes from several south San Francisco Bay area sites, and experimental manufacturing rates for granite, estimated manufacturing times for mortar depressions are as follows: 10 hrs. for shallow mortars, 40 hrs. for conical mortars, 260 hrs. for bowl mortars, and 493 hrs. for flower-pot mortars (Buonasera 2013:Table 4).

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REFERENCES

- Adams, J. L.
1999 Refocusing the Role of Food-Grinding Tools as Correlates for Subsistence Strategies in the U.S. Southwest. *American Antiquity* 64(3):475–498.
2002 *Ground Stone Analysis: A Technological Approach*. Salt Lake City: The University of Utah Press.
- Barrett, S. A., and E. W. Gifford
1933 Miwok Material Culture. *Bulletins of the Public Museum of Milwaukee* 2(4):117–376.
- Barlow, K. R., and M. Heck
2002 More on acorn eating during the Natufian: expected patterning in diet and the archaeological record of subsistence. In *Hunter-Gatherer Archaeobotany: Perspectives from the Northern Temperate Zone*, Sarah Mason and Jon G. Hather, eds., pp. 128–145. London: Routledge.
- Basgall, M. E.
1987 Resource Intensification among Hunter-Gatherers: Acorn Economies in Prehistoric California. *Research in Economic Anthropology* 9:21–52.
- Baumhoff, M. A.
1963 Ecological Determinants of Aboriginal California Populations. *University of California Publications in American Archaeology and Ethnology* 49(2):155–236.
- Bednarik, R. G.
2008 Cupules. *Rock Art Research: The Journal of the Australian Rock Art Research Association (AURA)* 25(1):61.
- Bettinger, R. L., B. Winterhalder, and R. McElreath
2006 A Simple Model of Technological Intensification. *Journal of Archaeological Science* 33:538–545.
- Bright, J., A. Ugan, and L. Hunsaker
2002 The Effect of Handling Time on Subsistence Technology. *World Archaeology* 34(1):164–181.
- Buonasera, T.
2013 More than Acorns and Small Seeds: A Diachronic Analysis of Mortuary Associated Ground Stone from the South San Francisco Bay Area. *Journal of Anthropological Archaeology* 32(2):190–211.
2015 Modeling the Costs and Benefits of Manufacturing Expedient Milling Tools. *Journal of Archaeological Science* 57:335–344.
- Bouey, P.
1987 The Intensification of Hunter-Gatherer Economies in the Southern North Coast Ranges of California. *Research in Economic Anthropology* 9:53–101.
- Carmody, Rachel N., and Richard W. Wrangham
2009 The Energetic Significance of Cooking. *Journal of Human Evolution* 57(4):379–391.
- Cane, S.
1989 Australian Aboriginal Seed Grinding and its Archaeological Record: A Case Study from the Western Desert. In *Foraging and Farming: The Evolution of Plant Exploitation*, D. R. Harris and G. C. Hillman, eds., pp. 99–135. London: Unwin Hyman Ltd.
- Cook, S.
1973 Stone Tools for Steel-Age Mexicans? Aspects of Production in a Zapotec Stoneworking Industry. *American Anthropologist* 75(5):1485–1503.
- Cushing, F. H.
1920 Zuni Breadstuff. *Indian Notes and Monographs* 8. New York: Museum of the American Indian, Heye Foundation.

- Czitrom, V.
1999 One-Factor-at-a-Time Versus Designed Experiments. *American Statistician* 53(2):126–131.
- Dixon, R. B.
1905 The Northern Maidu. *American Museum of Natural History Bulletins* 17(3):119–346.
- Dubreuil, L.
2004 Long-term Trends in Natufian Subsistence: A Use-Wear Analysis of Ground Stone Tools. *Journal of Archaeological Science* 31:1613–1629.
- Eitam D., M. Kislev, A. Karty, and O. Bar-Yosef
2015 Experimental Barley Flour Production in 12,500-Year-Old Rock-Cut Mortars in Southwestern Asia. *PLoS One* 10: e0133306.
- Gayton, A. H.
1948 Yokuts and Western Mono Ethnography. *University of California Anthropological Records* 10. Berkeley.
- Gifford, E. W.
1971[1936] Californian Balanophagy. In *The California Indians: A Source Book*, 2nd edition, R. F. Heizer and M. A. Whipple, eds., pp. 301–305. Berkeley: University of California Press.
- Gill, K. M.
2014 Seasons of Change: Using Seasonal Morphological Changes in Brodiaea Corms to Determine Season of Harvest from Archaeobotanical Remains. *American Antiquity* 79:638–654.
- Gill, K. M., and K. M. Hoppa
2016 Evidence for an Island Chumash Geophyte-Based Subsistence Economy on the Northern Channel Islands. *Journal of California and Great Basin Anthropology* 36:51–71.
- Glassow, M. A.
1996 The Significance to California Prehistory of the Earliest Mortars and Pestles. *Pacific Coast Archaeological Society Quarterly* 32(4):14–26.
- Gonzalez, G. P.
2014 *Understanding the Maize Grinding Technology at Cerro Juanaqueña, Chihuahua, Mexico*. Master's thesis, University of Texas, San Antonio.
- Hard, R. J., R. P. Mauldin, and G. R. Raymond
1996 Mano Size, Stable Carbon Isotope Ratios, and Macro-botanical Remains as Multiple Lines of Evidence of Maize Dependence in the American Southwest. *Journal of Archaeological Method and Theory* 3(4):253–318.
- Hayden, B.
1987 Traditional Metate Manufacturing in Guatemala using Chipped Stone Tools. In *Lithic Studies among the Contemporary Highland Maya*, Brian Hayden, ed., pp. 8–119. Tucson: University of Arizona Press.
- Haury, E.
1950 *The Stratigraphy and Archaeology of Ventana Cave*. Tucson: University of Arizona Press.
- Heaton, K. W., S. N. Marcus, P. M. Emmett, and C. H. Bolton
1988 Particle Size of Wheat, Maize, and Oat Meals: Effects on Plasma Glucose and Insulin Responses and on the Rate of Starch Digestion in Vitro. *American Journal of Clinical Nutrition* 47:675–682.
- Hersh, T. L.
1981 *Stones and Food Processing Techniques of the Neolithic Societies of Turkey and Greece: Statistical, Experimental and Ethnographic Approaches to Archaeological Problem-Solving*. Ph.D. dissertation, Columbia University, New York. University Microfilms, Ann Arbor.
- Hillman, G.
1981 Reconstructing Crop Husbandry Practices from the Charred Remains of Crops. In *Farming Practice in British Prehistory*, R. J. Mercer, ed., pp. 123–162. Edinburgh: Edinburgh University Press.
- Horsfall, G.
1987 Design Theory Perspectives on Variability in Grinding Stones. In *Lithic Studies among the Contemporary Highland Maya*, B. Hayden, ed. pp. 332–377. Tucson: University of Arizona Press.
- Huckell, Bruce B.
1986 *A Ground Stone Implement Quarry on the Lower Colorado River, Northwestern Arizona*. (Cultural Resource Series 3.) Phoenix: Arizona State Office of the Bureau of Land Management.
- Jackson, T. L.
1984 Predictive Model of Prehistoric Settlement Patterning in the Southern Sierra Nevada. In *Cultural Resources Overview of the Southern Sierra Nevada*, pp. 179–203. Fresno: Theodoratus Cultural Resource, Inc. and Archaeological Consulting and Research Services, Inc.
1991 Pounding Acorn: Women's Production as Social and Economic Focus. In *Engendering Archaeology*, J. M. Gero and M. W. Conkey, eds. Oxford: Basil Blackwell.
- Johns, T., and M. Duquette
1991 Traditional Detoxification of Acorn Bread with Clay. *Ecology of Food and Nutrition* 25(3):221–228.
- Kraybill, N.
1977 Pre-Agricultural Tools for the Preparation of Foods in the Old World. In *Origins of Agriculture*, C. Reed, ed., pp. 485–521. The Hague: Mouton Publishers.
- Kroeber, A. L.
1925 Handbook of the Indians of North America. *Bureau of American Ethnology Bulletins* 78. Washington DC: Smithsonian Institution.
- Leftwich, B. M.
2010 *Set in Stone: Bedrock Mortars and Behavior in the North-Central Sierra Nevada*. Ph.D. dissertation, University of California, Santa Barbara.
- Mason, S. L. R.
1996 Acorn-Eating and Ethnographic Analogies: A Reply to McCorriston. *Antiquity* 69:1025–1030.

- Mauldin, R.
1993 The Relationship between Ground Stone and Agricultural Intensification in Western New Mexico. *Kiva* 58(3):317–330.
- McCarthy, H.
1993 *A Political Economy of Western Mono Acorn Processing*. Ph.D. dissertation, University of California, Davis.
- McCarthy, H., C. M. Blount, and R. A. Hicks
1985 A Functional Analysis of Bedrock Mortars: Western Mono Food Processing in the Southern Sierra Nevada, Appendix F, pp. 303–356. In *Cultural Resources of the Crane Valley Hydroelectric Project, Madera County, California*. MS on file at Pacific Gas and Electric Company, San Francisco, California.
- McCorriston, J.
1994 Acorn Eating and Agricultural Origins: California Ethnographies as Analogies for the Ancient Near East. *Antiquity* 68:97–107.
- Mikkelsen, P.
1985 *A Study of Millingtool Form and Function Applied to the North Coast Ranges, California*. Master's thesis, Department of Anthropology, California State University, Sonoma.
- Morgan, C.
2012 Modeling Modes of Hunter-Gatherer Food Storage. *American Antiquity* 77 (4):714–736.
- Morris, D. H.
1990 Changes in Groundstone Following the Introduction of Maize into the American Southwest. *Journal of Anthropological Research* 46(2):177–194.
- Murray, C. M.
2014 Wood vs. Stone Mortar Technologies: An Experimental Approach to Food Grinding Efficiency. *Explorations: The UC Davis Undergraduate Research Journal* 16:1–14.
- Nadel, D., D. Rosenberg, and R. Yeshurun
2009 The Deep and the Shallow: The Role of Natufian Bedrock Features at Rosh Zin, Central Negev, Israel. *Bulletins of the American Schools of Oriental Research* 355:1–29.
- O'Donnell, L. J. D., P. M. Emmett and K. W. Heaton
1989 Size of Flour Particles and Its Relation to Glycaemia, Insulinaemia, and Colonic Disease. *British Medical Journal* 289:1616–1617.
- Özbaşaran, M.
2011 The Neolithic on the Plateau. In *The Oxford Handbook of Ancient Anatolia: (10,000–323 BCE)*, Sharon R. Steadman and Gregory McMahon, eds. Oxford: Oxford University Press.
- Reddy, S. N., and J. M. Erlandson
2012 Macrobotanical Food Remains from a Trans-Holocene Sequence at Daisy Cave (CA-SMI-261), San Miguel Island, California. *Journal of Archaeological Science* 39(1):33–40.
- Rosenberg, D.
2008 The Possible Uses of Acorns in Past Economies of the Southern Levant: A Staple Food or a Negligible Food Source? *Levant* 40(2):167–175.
- Rosenberg, D., and D. Nadel
2017 Down to Bedrock: General Perspectives on Bedrock Features. *Quaternary International* 439:1–4.
- Rosenthal, J. S., G. G. White, and M. Q. Sutton
2007 The Central Valley: A View from the Catbird's Seat. In *California Prehistory: Colonization, Culture Change, and Complexity*, Terry L. Jones and Kathryn A. Klar, eds., pp. 147–163. Lanham, MD: Alta Mira Press.
- Schneider, J. S.
1993 *Aboriginal Milling-Implement Quarries in Eastern California and Western Arizona: A Behavioral Perspective*. Ph.D. dissertation, University of California, Riverside.
- Schneider, J. S. and P. C. LaPorta
2009 Geological Constraints on Ground Stone Production and Consumption in the Southern Levant. In *New Approaches to Old Stones*, Yorke Rowan and Jennie R. Ebeling, eds., pp. 19–39. London: Equinox Publishing.
- Scholze, G.
2010 Potential Role of Starch Grain Analysis in Determining Geophyte Use in Northeastern California. *Proceedings of the Society for California Archaeology* 24:1–12.
- Schroth, A. B.
1996 An Ethnographic Review of Grinding, Pounding, Pulverizing, and Smoothing with Stones. *Pacific Coast Archaeological Society Quarterly* 32(4):55–75.
- Searcy, M.
2011 *The Life-Giving Stone: Ethnoarchaeology of Maya Metates*. Tucson: University of Arizona Press.
- Speth, J. D., and K. A. Spielmann
1983 Energy Source, Protein Metabolism, and Hunter-Gatherer Subsistence Strategies. *Journal of Anthropological Archaeology* 2(1):1–31.
- Stahl, A. B.
1989 Plant Food Processing: Implications for Dietary Quality. In *Foraging and Farming: The Evolution of Plant Exploitation*, D. R. Harris and G. C. Hillman, eds., pp. 171–194. London: Unwin Hyman Ltd.
- Stearns, M. M., and D. T. Booth
1980 Note on the Quality Characteristics of Indian Ricegrass (Wye). *Cereal Chemistry* 57(6):438–439.
- Stevens, N. E., and R. McElreath
2015 When are Two Tools Better than One? Mortars, Millingslabs, and the California Acorn Economy. *Journal of Anthropological Archaeology* 37:100–111.
- Stevens, N. E., A. R. Whitaker, and J. S. Rosenthal
2017 Bedrock Mortars as Indicators of Territorial Behavior in the Sierra Nevada. *Quaternary International* 518:57–68.

- Stiner, M. C., H. Buitenhuis, G. Duru, S. L. Kuhn, S. M. Mentzer, N. D. Munro, N. Pöllath, J. Quade, G. Tsartsidou, and M. Özbaşaran
2014 A Forager–Herder Trade-off, from Broad-Spectrum Hunting to Sheep Management at Aşıklı Höyük, Turkey. *Proceedings of the National Academy of Sciences of the United States of America* 111(23):8404–8409.
- Tushingham, S., and R. L. Bettinger
2013 Why Foragers Choose Acorns Before Salmon: Storage, Mobility, and Risk in Aboriginal California. *Journal of Anthropological Archaeology* 32(4):527–537.
- Wandsnider, LuAnn
1997 The Roasted and the Boiled: Food Composition and Heat Treatment with Special Emphasis on Pit-Hearth Cooking. *Journal of Anthropological Archaeology* 16(1):1–48.
- White, G. G.
2003 *Testing and Mitigation at Four Sites on the Level (3) Long Haul Fiber Optic Alignment, Colusa County, California. (Archaeological Research Program Reports 42.)* Chico: California State University, Chico.
- Wills, W. H.
1995 Archaic Foraging and the Beginning of Food Production in the American Southwest. In *Last Hunters-First Farmers*, T. Price and S. Gebauer, eds., pp. 215–242. Santa Fe: School of American Research Press.
- Wisley, Justin
2019 Best Practices for Integrating Starch Grain Analysis into California Archaeological Research: Strengths, Limitations, and Implications to Eligibility. Paper presented at the Annual Meeting of the Society for California Archaeology, Sacramento California.
- Wollstonecroft M., P. R. Ellis, G. C. Hillman, and D. Q. Fuller
2008 Advancements in Plant Food Processing in the Near Eastern Epipalaeolithic and Implications for Improved Edibility and Nutrient Bioaccessibility: An Experimental Assessment of Sea Club-Rush (*Bolboschoenus maritimus* (L.) Palla). *Vegetation History and Archaeobotany* 17(1):S19–S27.
- Wohlgemuth, E.
1996 Resource Intensification in Prehistoric Central California: Evidence from the Archaeobotanical Data. *Journal of California and Great Basin Anthropology* 18(1):81–103.
- Wohlgemuth, E.
2004 *The Course of Plant Food Intensification in Native Central California*. Ph.D. dissertation, University of California, Davis.
2010 Plant Resource Structure and the Prehistory of Plant Use in Central Alta California. *California Archaeology* 2(1):57–76.
- Wright, K.
1991 The Origins and Development of Ground Stone Assemblages in Late Pleistocene Southwest Asia. *Paléorient* 17(1):19–45.
1992 Ground stone assemblage variation and subsistence strategies in the Levant, 22,000 to 5,500 B.P. (Volumes I and II). Ph.D. dissertation, Yale University, Connecticut.
1994 Ground-Stone Tools and Hunter-Gatherer Subsistence in Southwest Asia: Implications for the Transition to Farming. *American Antiquity* 52:238–262.
- Wright, M.
1993 Simulated Use of Experimental Maize Grinding Tools from Southwestern Colorado. *The Kiva* 58(3):345–355.

