Breaking the Mold of Natufian Basalt Mortars: Experimental Production and Archeological Implications

Hadar Ahituv^{1,2} · Ehud Weiss^{1,2} · Nira Alperson-Afil¹

Published online: 9 January 2019
© The Author(s) 2018

Abstract

This paper presents an experimental study on the production of basalt mortars, common at Levantine Natufian sites (15,000–11,500 cal. BP). An increase in the gathering and processing of plant foods is among the Natufian cultural innovations preceding the Neolithic agricultural revolution, as documented in “agricultural” tools such as sickle blades and ground stone tools (GST). Studies of Natufian GST have focused on their typology and function; production methods are rarely discussed. We present 15 systematic experiments focusing on two methods—drilling and carving—and using a variety of techniques (bow/twist/pump/hand drilling, pecking, and battering) and tools. Our results demonstrate that drilling techniques are efficient only in the initial stages of depression preparation and only for a limited duration. Pecking and battering with a hand-held basalt chisel was found to be the preferable production method, allowing for longer, continuous working time, and producing deeper and larger depressions than other techniques. In addition, pecking and battering makes it possible to produce a complete mortar—from the initial depression to modification of the interior and exterior faces. We suggest that producing a Natufian basalt mortar takes only 5 h and produces specific waste products, and that such repetitive work causes severe pain, particularly to the elbow and palm of the working hand, which may be associated with the variety of physical deformations reported for male Natufian and Neolithic populations.

Keywords Basalt · Experimental archeology · Ground stone tools (GST) · Natufian · Prehistoric technology

✉ Hadar Ahituv
hadarahituv@gmail.com

¹ Institute of Archaeology, Martin (Szusz) Department of Land of Israel Studies and Archaeology, Bar-Ilan University, 52900 Ramat Gan, Israel

² Archaeobotany Laboratory, Bar-Ilan University, 52900 Ramat Gan, Israel

Introduction

The Natufian culture (15,000–11,500 cal. BP), recorded in the Levant during the final stages of the Epipalaeolithic (Belfer-Cohen and Goring-Morris 2011; Weinstein-Evron et al. 2012; Grosman 2013), demonstrates the gradual transition from hunting and gathering to a more sedentary lifestyle (Bar-Yosef and Valla 1991). This change is manifested in the Natufian material culture, which presents, for the first time, stone dwellings alongside a wealth of “agricultural” tools. The latter, testifying to the increase in plant food gathering and processing, include sickle blades and ground stone tools (GST).

A wide range of types of GST, documented worldwide by archeological, ethnographic, and historical data, were produced and used in a variety of functions and social contexts. This variety is expressed in the diversity of raw materials (e.g., basalt, granite, limestone, sandstone), wide range of techniques (e.g., flaking, pounding, pecking, drilling), and variability of sizes and forms. Natufian GST are made of basalt and limestone and were likely used for grinding and processing organic (e.g., grains, roots, bones) and inorganic (e.g., ochre) materials. The use of these tools was often in pairs (a stationary container/slab and a mobile hand-held tool, such as mortar and pestle) (Adams 2002; Dubreuil 2004; Piperno et al. 2004; Belfer-Cohen and Hovers 2005; Hardy et al. 2013). Previous studies of Natufian GST focused on their typology (e.g., Rosenberg and Gopher 2010) and function (e.g., Dubreuil 2004), while their production methods and techniques have only occasionally been discussed (e.g., Dubreuil and Grossman 2009; Dubreuil and Savage 2014). However, production of GST is discussed for later periods and for a variety of raw materials (e.g., Schneider and Osborne 1996; Osborne 1998; Stroulia 2003; Squitieri and Eitam 2016). Ideas regarding possible production processes can be gleaned from ethnographic observations and depictions (e.g., Ayad 2014) and suggest a variety of production methods, tested using a range of materials such as granite, copper, and iron (e.g., Heizer and Hester 1981; Hayden 1987; Stocks 2013). The different methods include flaking, battering, pounding, pecking, and drilling (Wright 1992). Another good source of information regarding GST production methods would be a Natufian workshop site, yet assigning a cultural classification to such sites is a difficult task and none of the published workshop sites (e.g., Abadi-Reiss and Rosen 2008; Schneider and LaPorta 2008; Gluhak and Rosenberg 2013; Vardi 2013) have been classified as Natufian. When recovered from archeological sites, Natufian GST are often found as finished tools with no associated production waste; mortars and pestles are the most common type of Natufian GST. We follow the typology of Wright (1992), who describes a mortar as the “lower, stationary stone in a pair of tools used for pounding and ‘vertical rotary grinding’ on side walls of use surface ... concave in section (dished to U-shaped)” (Wright 1992: 65). Pestles are thus the “upper, mobile stone in a pair of pounding tools... Preform often pecked to even elongated shape” (Wright 1992: 69).

Exploring the production processes of Natufian mortars may have two major implications for our understanding of Natufian culture. First, these apparently domestic tools are frequently associated with burials (e.g., Rosenberg and Nadel 2014) and are often found broken, a phenomenon considered by some to result from intentional ritual practices (e.g., Rosenberg and Nadel 2014; Ovadia 2016). Experimental production of such mortars may cast doubt on the assertion of intentional breakage by demonstrating

that accidental breakage may well occur during production. Second is the issue of craft specialization (e.g., Childe 1950; Costin 1991; Clark 1995; Flad and Hruby 2007). It has been suggested that the production of Natufian mortars is a very time-consuming process that may even require the work of craft specialists—highly trained professionals—who had to be supported by the community during the long duration of mortar production (Bar-Yosef: pers. comm.). If so, Natufian groups should be considered communities of increasing social complexity, practicing social stratification.

Other possible implications relate to our understanding of Natufian basalt assemblages. Experimental production of basalt mortars can provide information on possible work tools (e.g., chisels or drills) and waste products (e.g., basalt flakes) that can be traced within archeological assemblages. The presence of such tools and/or waste may contribute to our understanding of the production processes of Natufian GST as well as their place of production.

We suggest that experimental studies can serve as a suitable means of gaining insight into the production time, skill needed for production, and breakage of basalt mortars. The experiments described in this paper examine a variety of methods for the production of basalt mortars similar in shape and size to the medium-sized mortars found at Natufian sites (Fig. 1).

In our attempts to produce Natufian-like mortars, we modified the mortars' depressions to a depth similar to that observed on medium-sized Natufian mortars (ca. 7–12 cm.). Previous experimental studies suggest that after working with basalt GST against a variety of materials, the surface topography scarcely change (Savage 2014). Yet, there is evidence of Natufian mortars that their depression reached and pierced the base of the mortar (e.g., Rosenberg and Nadel 2014). Clearly, we cannot determine how much of the depth of Natufian mortars is the result of its primary modification and how much represents use-wear. This issue should be studied more thoroughly in future studies.

Materials and Methods

According to Schiffer and Skibo (1987), “recipes for action” are a component of technological knowledge: “Recipes for action are the rules that underlie the processing of raw materials into finished products ... A recipe for action consists of (1) a list of raw

Fig. 1 Archeological and experimental mortars. **a** Natufian Nahal Oren, limestone; height 16 cm; diameter 17 cm. **b** Experimental mortar no. 2, basalt; height 21 cm; diameter 25 cm. Scale bar = 10 cm

materials, (2) a list of tools and facilities employed, (3) a description of the sequence of specific actions undertaken in the technological process, and (4) the contingent rules used to solve problems that may arise ... A recipe for action, then, attempts to summarize the knowledge which, if possessed by the artisan (or artisans), would account for the technological behavior” (Schiffer and Skibo 1987: 597).

In designing the experiments, we follow that concept and suggest a recipe for action that includes several variables: raw material for mortar production (i.e., different types of basalt), tools for modification of mortars (e.g., drills or chisels), and a list of questions that may be answered following the experiments. Below, we describe these variables, starting with raw material and tools. A description of these is necessary for understanding the third variable: our list of questions, which constitute the experimental design and are presented at the end of this section (Table 1).

Raw Material Selection

A total of 15 systematic experiments were carried out on 6 different basalt boulders. The selection of basalt boulders for the experiments followed careful observations of an archeological assemblage of Natufian GST. The assemblage, originating in Hayonim Cave (Belfer-Cohen 1970), included mortars and pestles that were studied in order to evaluate the characteristics of basalt raw material. In addition, numerous informal experimental attempts were carried out prior to the experiments described below in order to establish a set of criteria for workable basalt raw material that was likely preferred by Natufian people for the production of GST. These criteria include texture (fine- vs. coarse-grained basalt), size, density of vesicles, and durability (i.e., the presence of secondary minerals). Thus, based on observations of archeological Natufian mortars and on previous informal experimental attempts, we suggest that the most suitable raw materials for mortar production would be a fine-grained basalt with small, relatively dense vesicles (up to 0.5 cm in diameter and less than 0.5 cm or so between vesicles), preferably with minimal presence of durable secondary minerals within them (e.g., basalt A in Fig. 2). In addition, as recorded in Natufian GST assemblages, it is possible to work with coarser-grained basalts if they exhibit negligible vesicles and no secondary minerals (e.g., basalt B in Fig. 2). These criteria result from the particular function of mortars, which requires a raw material that is workable on the one hand, i.e., with a certain number of vesicles, but is also durable so as to allow intensive future use, i.e., fine-grained. In addition, it should be less durable than the tool that will be used to modify it, i.e., the hammerstone, and the tools that will eventually be used to work against it, i.e., the pestle. The experimental design took into consideration these two features of the basalt raw material to which the different techniques were applied (Table 1).

We suggest that the selected basalt nodules, whether fine or coarse, would be comparable in size and shape to the desired mortars (or slightly larger). Such nodules require less investment in the exterior design of the mortar, and their inner structure enables the craftsman to follow an “onion-like” configuration that dictates the work and assists in the modification of the exterior part of the mortar.

Tools and Techniques

Previous studies provided the terminology of GST analysis and contributed greatly to our understanding of the variability, techniques for modification, and use of GST (e.g., Wright 1992, 1994; Adams 2002; Eitam 2009; Rosenberg and Gopher 2010). Our experiments focused on two methods—drilling and carving—and used a variety of techniques and tools, some of them specially designed (Fig. 3).

The assumption that drilling may have been used for GST production is based on the emergence of this method during the Levantine Epipalaeolithic (e.g., Nadel et al. 1991; Grosman and Goren-Inbar 2007). Three drilling techniques were examined, based on both archaeological and ethnographic data (e.g., Martin 1934; Stocks 2013; Ayad 2014): the pump drill (composed of a 3-kg basalt weight, 0.3-cm-thick plastic strings, a 145-cm-long straight wooden stick, a wooden plank, and a flint drill), the bow drill (composed of a 71 cm olive branch bow, 0.3 cm plastic string, a 145-cm straight wooden stick, a flint drill, and a small wooden hand piece with a socket), and the twist-reverse-twist drill (TRTD) (e.g., Stocks 2013) composed of a 6-kg stone weight and a 108-cm curved wooden branch that was naturally split). However, unlike the technique suggested by Stocks (2013), here only a single, clockwise direction was employed, i.e., twist but not reverse, and only a single weight was used for gaining leverage for the twisting. We use the term twist-reverse-twist drill as we followed Stock's methods in the construction of the drilling equipment; however, it seems that our final tool operates differently in terms of the drilling directions and the purpose served by the weight.

In addition, a simple hand drill technique was tested, in which the drill is held and twisted by hand. Different flint drills were manufactured and used: For the pump and bow techniques, the drills were triangular flint flakes approximately 0.5–1 cm thick and 4 cm long, inserted into a slot carved at the edge of the wooden stick and then wrapped with leather straps. For the twist-reverse-twist drill, a larger drill was used (a triangular flake approximately 3–4 cm thick, 4–5 cm long, and bifacially retouched) and was forcefully inserted into the spot where the stick naturally branches out. All drilling experiments focused on the modification of the interior part (i.e., depression) of the mortars.

The second method, carving, refers to percussion of a mobile tool against both the interior and exterior of the mortar preform. Carving includes battering and pecking techniques that differ in the kind of tools used and the intensity and strength of percussion. Battering is more powerful and may produce micro flakes, while pecking is gentler and more regular in spacing and produces mainly small particles. The exterior modification of the mortars involved both battering and pecking, using three tools: a hafted flint axe (bifacial flint axe, 12–13 cm long and 6–7 cm thick, with a shaft 30 cm long and 7.5 cm thick), a basalt chisel (16–20 cm long and 5–7 cm thick), and a hafted basalt chisel (Fig. 3). The interior modification involved four tools: a hafted flint axe, a basalt chisel, and two basalt chisels, hafted in different directions (Fig. 3). While pecking was carried out using all four tool types, for the powerful battering, only the basalt chisels were used (Fig. 3). The decision to use both basalt and flint tools for carving was guided by a desire to explore the advantages and disadvantages of each raw material. Like the drilling method, bifacial axes make their appearance during the Levantine Epipalaeolithic, and their occurrence in Natufian assemblages may indicate their use in the modification of GST.

Fig. 2 Schematic illustration of preferable basalt characteristics for Natufian GST production. Vesicularity and secondary minerals are shown from minimal (low) to prominent (high) presence; grain size is shown from fine (low) to coarse (high); and boulder size is shown from small (low) to large (high)

Experimental Design

After having established the criteria for raw material selection and described the techniques and tools constructed for the experiments, we can present our experimental design. Our main research question has to do with evaluating which method and/or technique is preferable for the manufacture of Natufian-like basalt mortars. Various factors may influence the suitability of different techniques, however, such as the type of basalt used (finer- vs. coarser-grained) and the tools used to modify it (flint vs. basalt). Thus, the experiments were structured to examine different techniques, using different tools, and on two different types of basalt (Table 1).

Method	Drilling				Carving

Technique	Pump drilling	Bow drilling	T/R drilling	Hand drilling	Pecking & battering	Pecking & battering	Pecking	Pecking	Pecking & battering
Working tool ^a	Pump drill, flint drill	Bow drill, flint drill	Twist-reverse drill, flint drill	Hafted flint drill	Basalt chisel	Hafted basalt chisel ('axe like')	Hafted flint axe	Hafted flint flake	Hafted basalt chisel ^b ('Pestle like')
WT-M ^c distance	0 cm				0–45 cm				
Working face/area	Interior				Interior and Exterior			Interior	

Fig. 3 Methods, techniques, and tools used in the experimental production of Natufian GST. ^aDetailed descriptions of the apparatus for the various tools are given in the text. ^bScale bar = 30 cm. ^cWT-M: work tool to mortar

Table 1 Experimental design

Research question(s)	Exp. no.	Technique	Raw material ^a	Tool ^b
Is drilling an efficient method for the interior modification (depression) of mortars? Which drilling technique is preferable?	1	Pump drilling	B	Flint drill
	2	Bow drilling	B	Flint drill
	3	Twist drilling	B	Flint drill
	4	Hand drilling	B	Flint drill
Is pecking with a hafted flint tool an efficient means of interior and exterior modification? Which pecking tool (flake or axe) is preferable?	5	Pecking	A	Hafted flint flake
	6	Pecking	A	Hafted flint axe
Are pecking and battering with a hand-held basalt chisel efficient for interior and exterior modification?	7	Pecking and battering	B	Hand-held basalt chisel
	8	Pecking and battering	A	Hand-held basalt chisel
Are pecking and battering equally efficient when working with different types of basalt raw materials (Type a or Type b)?	9	Pecking and battering	A	Hand-held basalt chisel
	10	Pecking and battering	B	Hand-held basalt chisel
	11	Pecking and battering	A	Hand-held basalt chisel
	12	Pecking and battering	A	Hand-held basalt chisel
Are pecking and battering with a hafted basalt chisel efficient for interior modification? Are pecking and battering with a hafted basalt chisel equally efficient when working with different types of basalt raw materials (type a or type b)? Which hafting mode (pestle or axe) is preferable?	13	Pecking and battering	B	Pestle-like hafted basalt chisel
	14	Pecking and battering	A	Pestle-like hafted basalt chisel
	15	Pecking and battering	A	Axe-like hafted basalt chisel

^a Type A is fine-grained basalt with small, relatively dense vesicles containing a minimal amount of durable secondary minerals; type B is coarser-grained basalt with negligible vesicles and no secondary minerals (see Fig. 2)

^b Comprehensive descriptions of the apparatus for the various tools are given in the text; for illustrations, see Fig. 3

Results

In order to determine the suitability of techniques for mortar production, a total of 15 systematic experiments were carried out on 6 different basalt boulders (Table 2). The results are presented for each method: drilling and carving.

Drilling Experiments

Prior to the current study, informal experiments with drilling techniques on a variety of basalts suggested that drilling is feasible on dense basalts with negligible vesicles (type B basalt; Fig. 2). In contrast, when drilling in large vesicles, the drill bit becomes lodged and easily breaks (type A basalt; Fig. 2). Thus, all four drilling experiments (Table 2: experiments 1–4) focused on a single basalt type that has the former properties (basalt B in Fig. 2), and the different drilling techniques were attempted sequentially.

Our work demonstrated that the pump drill is the most advantageous for producing a primary depression, as it provides the stability and speed required in the initial stages of drilling. A drilling session of 1.5 h resulted in a depression 1 cm deep with a diameter of 1 cm (Table 2: experiment 1). However, as drilling continues and the depression expands, the energy inflicted on the drill by the depression walls increases. Eventually, this resistance leads to the termination of spinning and to the breakage of the drill tip. Thus, in the course of the 1.5-h drilling session, three drill heads were used (Table 2: experiment 1). While the pump drill is advantageous for its stability and speed, which are predetermined by the mechanics of the pump weight and structure, it does not allow for control of the drill direction or manipulation of the speed in between pumping. Once an initial depression is formed, the bow drill controls these variables better and was found to be preferable for continued drilling and for deepening the depression.

The bow drill is an excellent tool for drilling, but like the pump drill, it requires constant replacement of the drill tip. After 1 min of drilling, abrasion of the flint drill starts to show and the effectiveness of the drill decreases. Thus, regardless of the efficiency of the bow drill technique (Table 2: experiment 2), maintenance of the drill tips makes systematic, continual work difficult. Our experiments demonstrate that an hour of drilling requires an hour of maintenance, so that in a 20-h drilling session, 10 h was dedicated to the preparation and hafting of drills. Like the bow drill, the hand drill (Table 2: experiment 4) provides relative control over the drill speed and direction, but due to the abrasion inflicted on the hands while spinning it is nearly impossible to use for long bare-handed.

The fourth drill type examined was the twist-reverse-twist drill (Table 2: experiment 3), which was used alternately with the bow drill. This technique is effective only once an initial depression has been formed. It was found to be efficient as it is the only drilling technique that makes it possible to use larger drills and to enlarge the diameter of the depression. Thus, when combined with other drilling techniques, the twist-reverse-twist drill is an efficient means of creating wide and deep depressions. Clearly, larger drills were found to be more durable and to require less maintenance. The twist drill is easy to manipulate and was found to be efficient for producing larger depressions.

To sum up, it is difficult to determine a favorable drilling technique, as each of the experimental methods was found to be efficient in different stages of shaping the depression: the pump drill for forming the initial depression, the bow drill and hand drill for deepening the depression, and the twist drill for enlarging it. Thus, if only drilling is used, it seems that a combination of several drilling techniques is essential in order to successfully produce a basalt mortar.

Carving Experiments

As mentioned above, carving involves pecking and battering, and we experimented with different tools (hafted vs. hand-held) made of different raw materials (flint vs. basalt). In addition, unlike the drilling techniques, carving was used for modification of the interior depression of the mortar as well as its exterior design, and we tested it on the two different types of basalt raw material.

Two experiments were carried out to evaluate carving with flint tools, both on a single basalt boulder (mortar 2, Figs. 1 and 2). In both experiments (Table 2: experiments 5–6), the flint tools were hafted to allow for a comfortable grip and only pecking was used (Fig. 3). Flint was found to be efficient for working on the exterior of the mortar, either with a hafted flake or a hafted axe. Pecking on the exterior requires controlled blows that are not very forceful in order to carefully maintain the desired shape. However, when carving the interior of the mortar, stronger blows are essential in order to deepen the depression and the flint tends to break frequently, making the tools inefficient. Thus, it was possible to work on the exterior of the mortar for 2 h using the same hafted flint flake, but working on the interior resulted in almost immediate breakage of the flint flake. Although the hafted flint axe was also found to be more efficient for modifying the exterior part of the mortar, it seems to be more durable than the flint flake, as it made it possible to deepen the inner depression an additional 2 cm in a similar amount of time (Table 2: experiments 5–6), and the axe was broken only after 1 h.

Due to the frequent breakage of the flint tools, we experimented extensively on basalt tools for modifying basalt mortars through carving. These experiments (Table 2: experiments 7–15) examined the benefits of hafted vs. hand-held basalt chisels and were carried out on six different basalt boulders. Boulders 1 and 2, partially modified in previous experiments (Table 2: experiments 1–6), were used to examine the carving method with a hafted basalt chisel and a hand-held chisel (Table 2: experiments 7–8, 13–15). Two hafting modes were tested: a longitudinal (pestle-like) one and a transverse (axe-like) one (Fig. 3). In addition, six experiments were carried out to evaluate the use of a hand-held basalt chisel for carving, using six different basalt boulders (Table 2: experiments 7–12). The basalt in these boulders resembles basalt types A (boulders 2, 3, 5, 6) and B (boulders 1, 4). Several observations are noted regarding the use of hafted basalt chisels: First, the results clearly suggest that a pestle-like hafting method is preferable and requires less energy. Furthermore, when using an axe-like chisel, the depth of the depression is limited to the length of the working edge of the chisel, so a complete modification of the mortar is not feasible (Table 2: experiments 14–15). Another observation concerns the properties of the basalt raw material: working with a pestle-like hafted basalt chisel made of a finer-grained, vesicular basalt (type A) requires less time (Table 2: experiment 14).

The final modification technique tested was the use of a hand-held basalt chisel, which was examined on six different basalt boulders, two of which had been partially modified in earlier experiments. The results of these experiments demonstrate the superiority of this technique over all other methods examined. Table 2 clearly illustrates that this technique allows for longer, successive working time and produces deeper mortar depressions that can even exceed 10 cm. Furthermore, the diameters of these

Table 2 Experimental results

Technique	Experiment no.	Work time in hours	No. of RPM/blows ^a	Depression depth	Depression diameter	No. of tools used up	Basalt boulder ^b	Depression volume ^c
Pump drilling	1	1.5	420 RPM	1 cm	1 cm	3	1	0.25 ml
Bow drilling ^d	2	10	360 RPM	5 cm	–	17	1	76.75 ml
Twist drilling ^d	3	10	90 RPM	–	6 cm	–	–	–
Hand drilling	4	1	360 RPM	0.5 cm	Unchanged	1	1	0.4 ml
Pecking: hafted flint flake	5	2 (+ 0.5 for external shaping)	~ 5000 blows	1 cm	5 cm	1 flake	2	19 ml
Pecking hafted flint axe	6	1 (+ 1.5 for external shaping)	~ 5000 blows	2 cm	Unchanged	2 bifacial axes	2	40 ml
Pecking and battering: hand-held basalt chisel, exp. 7–12	7	2 (+ 0.3 for external shaping)	~ 20,000 blows	5 cm	5 cm	3	1	477 ml ^e
	8	3.5 (+ 1 for external shaping)	~ 15,000 blows	5.5 cm	7.5 cm	3	2	366 ml
	9	3	~ 12,000 blows	9 cm	12 cm	–	3	/
	10	1	~ 4000 blows	4 cm	10 cm	–	4	210 ml
	11	4 (+ 1.5 for external shaping)	~ 17,000 blows	12 cm	13 cm	2	5	830 ml
	12	3	~ 12,000 blows	11 cm	12 cm	–	6	375 ml
Pecking and battering: pestle-like hafted basalt	13	1.667	~ 10,000 blows	1.5 cm	Unchanged	1	1	477 ml ^e
	14	1	~ 6000 blows	2 cm	–	–	2	40 ml
Pecking and battering: axe-like hafted basalt chisel	15	0.25	~ 1500 blows	0.5 cm	Unchanged	1 wooden shaft	2	4 ml

^a The number of blows was calculated as the average number of blows per second multiplied by the total time in seconds, with time of break as recorded in the experiment video. The number of rounds (360° spin of the drill) per minute was calculated differently for each drilling technique: Pump drill: Lowering and raising the pump takes 1 s and includes 7 rounds. Bow drill: Moving the bow twice (forward and backward) takes 1 s and includes 6 rounds. Hand drill: 6 rounds per second. Twist-reverse-twist drill: 1.5 rounds per second

^b Boulders 1 and 4 are of basalt type B (Fig. 2); boulders 2, 3, 5, and 6 are of basalt type A (Fig. 2)

^c Volume was calculated using two different methods: volume formulas for a cone (experiments 1–4) and a cylinder (experiments 5–6), and sand filling (experiments 7–15)

^d The bow drill and the twist-reverse-twist drill were used alternately in experiments 2 and 3, for a total duration of 20 h

^e The volume of 477 ml relates to experiments 7 and 13 combined

depressions are larger than those produced using other techniques—ranging from 9 to 13 cm. Experiment 11, for example, lasting 5.5 h, produced a mortar with a depression 12 cm deep and having a diameter of 13 cm, a process that reduced its weight by 15 kg (Fig. 4).

Discussion and Conclusions

Natufian mortars were used in the Levant during a significant cultural transitional stage, starting at the end of the Epipalaeolithic (Natufian: 15,000–11,500 cal. BP). The mortars, like other ground stone tools, are among a variety of cultural innovations that preceded the Neolithic agricultural transformation, making possible the processing of plant foods. Only some segments of the history of ground stone tools are preserved in the archeological record (Dubreuil and Savage 2014); their production process remains unclear. The goal of the present study was to use experimental archeology to examine possible techniques for producing Natufian mortars. The results suggested a variety of insights relating to the properties of

Fig. 4 Experimental mortar with its associated waste flake, produced during the shaping of the exterior. Scale bar = 15 cm. Brown areas are remnants of the original nodule surface (experiment 11 in Table 2; mortar 5)

basalt raw material, the efficiency of different production methods, the subsequent waste products, and the implications of these for understanding Natufian culture.

Clearly, it is impossible to estimate the full range of basalts available during Natufian times or their geological source (but see the attempt by Weinstein-Evron et al. 1995); however, our experimental study enables us to evaluate the preferable properties of basalt intended for GST production. These refer to morphology (preferably round boulders requiring minimal exterior design) and durability (fine- vs. coarse-grained). As illustrated in Fig. 2, we recognize two types of basalt suitable for the modification of mortars. These can be described generally as vesiculated, fine-grained basalt (type A) and non-vesiculated, coarse-grained basalt (type B). The latter is also preferable for the modification of work tools, i.e., pestles.

Regarding the efficiency of production methods, drilling techniques were found to be efficient only for the initial stages of depression preparation and only for a limited duration, as they all required frequent renewal of the drill heads. We found these results to be somewhat surprising as the use of drills during the Epipalaeolithic is well known, and prior to our experimental work, they were promising candidates for the production of Natufian mortars. Instead, pecking and battering with a hand-held basalt chisel was found to be the preferable production method. This is the only method that allows for the production of complete mortars—from the initial preparation of the depression through modification of the interior face as well as the exterior face. Furthermore, this technique, and carving in general, are more efficient than drilling, requiring less time and investment (Table 3).

Table 3 Summary of experimental results regarding different production techniques. To allow for comparison, the data are presented for a uniform working time of 1 h (calculated based on the data in Table 2); the data refer to interior modification (time invested in shaping the exterior is excluded from the calculations)

Tool	RPH ^a	BPH ^b	Depth (cm)	Diameter (cm)	Volume (ml)
Pump drill (flint)	25,200		0.66	0.66	0.17
Bow drill (flint)	21,600		0.5	— ^c	3.27
Hand-held drill (flint)	21,600		0.5	— ^c	
Twist drill (flint)	5400		—	0.5	
Hafted flake (flint)		2000	1.25	2.5	10
Hafted axe (flint)		2000	1.25	2.5	20
Hafted axe-like axe (basalt)		6000	2	— ^c	16
Hafted pestle-like axe (basalt)		3000	2	— ^c	40
Hand-held chisel (basalt)		4100	2.9	3.6	165.40

^a Rounds per hour

^b Blows per hour

^c These experiments used mortars 1 and 2 and changed only the depth of the depression, not its diameter. The diameter can be enlarged, depending on the thickness of the tool used for modification (in the case of drill heads) or a decision by the craftsman (using carving tools). In these experiments, the modification tools preserved the initial diameter

Fig. 5 Waste products from experimental mortar production. **a** Fragments of basalt chisels. **b** Flakes produced during exterior design. **c** Powder produced during interior design. Scale bar = 15 cm

To sum up, we conclude that the most efficient technique for the production of Natufian basalt mortars is pecking and battering with a hand-held basalt chisel. Clearly, a comparison with the Natufian archeological record is beyond the scope of this study. Similar chisels can be found at quarry/workshop sites (e.g., Rosenberg et al. 2008: Fig. 10; Schneider and LaPorta 2008: fig. 2.7), but are rarely reported at Natufian sites. The Natufian assemblage from Hayonim Cave, however, contains several potential chisels made of limestone and flint (Belfer-Cohen 1970: Figs. V-16, V-18[1–2], V-19[1], V-20[2], V-21, V-22[1], V-24[2]).

A small number of waste products were formed as byproducts of the mortar modification process (Fig. 5). We should differentiate between the waste resulting from the modification of the interior face and that of the exterior face. The modification of the interior face, regardless of the technique used, contributes mostly powder/small particles that cannot be detected with the naked eye. Analyses of sediment samples may discover the presence of such powder, but it is difficult to determine whether this originates from the production or use of the basalt mortars. The modification of the exterior face produces small and medium-sized flakes (Figs. 4 and 5), and their presence at archeological sites can suggest that some exterior design work was carried out at the site and not at remote quarry/workshop sites. However, in the process of making a basalt mortar, the energy inflicted on the basalt chisel (during both interior and exterior modification) causes fragmentation and results in basalt flakes and fragments that may resemble those produced during the modification of the exterior face of the mortar itself (Fig. 5).

The presence of such waste products at Natufian sites is rarely described, and when waste from ground stone tools is reported, it consists mostly of broken pestles and GST fragments. The fragmentation of these tools is considered by many to result from intensive usage or from intentional ritual practices (e.g., Rosenberg and Nadel 2014; Ovadia 2016). Our experimental study provides another possibility—that a mortar can accidentally break during production (Fig. 6).

Such data regarding possible waste products have implications for our understanding of Natufian basalt assemblages, as some can be traced archeologically. Other possible implications relate to the physical load involved in the production of GST, although this subject was not included in our research questions. Our personal experience suggests that such repetitive work causes severe pain, particularly to the elbow and wrist of the working hand, to such an extent that changing hands was required. Although these are subjective effects, they may be related to

Fig. 6 Experimental mortar broken during production. Scale bar = 15 cm

the variety of physical deformations reported for Natufian (Peterson 1998; Eshed et al. 2004) and Neolithic (Eshed et al. 2004) male populations. The bilateral asymmetry in MSM scores for males, indicative of right-side dominance, is often interpreted as a result of continued hunting with spears or bows and arrows but may in fact result from GST production. The repetitive use of GST can also cause physical deformations (e.g., Molleson 2007).

The approximate production time for a medium-sized mortar (exterior diameter of approximately 30 cm) is only 5 h. Similar time estimates have been reported by Squitieri and Eitam (2016). However, we should be cautious when estimating production time for larger mortars, as it depends on a variety of factors, including raw material type, weight, size (length and diameter), depth, and the design of the rim and other decorative elements on the exterior face of the mortar (e.g., Perrot 1966; Edwards 1991). Such large, decorative mortars may suggest the next phase of experimental research on Natufian GST. It is likely that such mortars required a longer production time and may have involved skilled craftsmen. Another suggestion that stems from our results concerns analysis of Natufian archeological assemblages. Tracing basalt chisels and basalt waste products, such as those reported in the current study, may support our conclusion regarding the modification of basalt mortars by battering with a basalt chisel.

Ground stone tools are common components of ancient and modern households and exhibit a wide range of forms and production techniques. Although this study focused on Natufian mortars, our results may contribute to our understanding of the production of ground stone tools in general.

Acknowledgements We are grateful to Prof. Ofer Bar-Yosef for allowing us to consult with him and encouraging us to proceed with our experimental study. We thank Prof. Anna Belfer-Cohen for reading and commenting on earlier drafts of this paper. The members of the Archaeobotany Laboratory at Bar-Ilan University, particularly Dr. Yael Mahler-Slesky, helped us with the study. Yoav Ahituv participated in the collection and transport of raw material, and the artist Yuval Lufan (UV) served as a consultant on basalt properties, as well as providing working space. We thank Deborah Stern for her skillful editing of the manuscript, and two anonymous reviewers for commenting on and improving the manuscript.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

- Abadi-Reiss, Y., & Rosen, S. (2008). A chip off the old millstone: Grinding stone production and distribution in the Early Bronze Age of the Negev. In Y. M. Rowan & J. R. Ebeling (Eds.), *New approaches to old stones: Recent studies of ground stone artifacts* (pp. 99–115). London: Equinox.
- Adams, J. (2002). *Ground stone analysis: a technological approach*. Salt Lake City: University of Utah Press.
- Ayad, E. (2014). Drilling tools and stone vessels of Heit el-Ghurab. Unpublished PhD thesis. Cairo: American University in Cairo.
- Bar-Yosef, O., & Valla, F. (Eds.). (1991). *The Natufian culture in the Levant*. Ann Arbor: International Monographs in Prehistory.
- Belfer-Cohen, A. (1970). The Natufian settlement at Hayonim cave: a hunter-gatherer band, on the threshold of agriculture. In *Unpublished PhD thesis*. Jerusalem: Hebrew University of Jerusalem.
- Belfer-Cohen, A., & Goring-Morris, N. (2011). Becoming farmers: the inside story. *Current Anthropology*, 52(S4), S209–S220. <https://doi.org/10.1086/658861>.
- Belfer-Cohen, A., & Hovers, E. (2005). The ground stone assemblages of the Natufian and Neolithic societies in the Levant: a brief review. *Journal of the Israel Prehistoric Society*, 35, 299–308.
- Childe, V. G. (1950/2004). The urban revolution. In T. C. Patterson & C. E. Orser, Jr. (Eds.), *Foundations of social archaeology: Selected writings of V. Gordon Childe* (pp. 107–116). Walnut Creek: AltaMira Press.
- Clark, J. E. (1995). Craft specialization as an archaeological category. *Research in Economic Anthropology*, 16, 267–294.
- Costin, C. L. (1991). Craft specialization: issues in defining, documenting, and explaining the organization of production. In M. B. Schiffer (Ed.), *Archaeological method and theory* (Vol. 3, pp. 1–56). Tucson: University of Arizona Press.
- Dubreuil, L. (2004). Long-term trends in Natufian subsistence: a use-wear analysis of ground stone tools. *Journal of Archaeological Science*, 31, 1613–1629. <https://doi.org/10.1016/j.jas.2004.04.003>.
- Dubreuil, L., & Grosman, L. (2009). Ochre and hide-working at a Natufian burial place. *Antiquity*, 83(322), 935–954. <https://doi.org/10.1017/S0003598X00099269>.
- Dubreuil, L., & Savage, D. (2014). Ground stones: a synthesis of the use-wear approach. *Journal of Archaeological Science*, 48, 139–153. <https://doi.org/10.1016/j.jas.2013.06.023>.
- Edwards, P. (1991). Wadi Hammeh 27: an early Natufian site at Pella, Jordan. In O. Bar-Yosef & F. Valla (Eds.), *The Natufian culture in the Levant* (pp. 123–148). Ann Arbor: International Monographs in Prehistory.
- Eitam, D. (2009). Late Epipalaeolithic rock-cut installations and groundstone tools in the southern Levant: Methodology and classification system. *Paléorient*, 35, 77–104. <https://doi.org/10.3406/paleo.2009.5279>.
- Eshed, V., Gopher, A., Galili, E., & Hershkovitz, I. (2004). Musculoskeletal stress markers (MSM) in Natufian hunter-gatherers and Neolithic farmers in the Levant: the upper limb. *American Journal of Physical Anthropology*, 123, 303–315. <https://doi.org/10.1002/ajpa.10312>.

- Flad, R. K., & Hruby, Z. X. (2007). “Specialized” production in archaeological contexts: rethinking specialization, the social value of products, and the practice of production. *Archaeological Papers of the American Anthropological Association*, 17, 1–19.
- Gluhak, T., & Rosenberg, D. (2013). Geochemical discrimination of basaltic sources as a tool for provenance analyses of bifacial tools in the southern Levant: first results from the Jezreel Valley. *Israel. Journal of Archaeological Science*, 40(3), 1611–1622. <https://doi.org/10.1016/j.jas.2012.11.003>.
- Grosman, L. (2013). The Natufian chronology scheme: new insights and their implications. In O. Bar-Yosef & F. Valla (Eds.), *Natufian foragers in the Levant* (pp. 622–637). Ann Arbor: International Monographs in Prehistory.
- Grosman, L., & Goren-Inbar, N. (2007). “Taming” rocks and changing landscapes: a new interpretation of Neolithic cupmarks. *Current Anthropology*, 48, 732–740. <https://doi.org/10.1086/520966>.
- Hardy, K., van de Locht, R., Wilson, J., & Tugay, O. (2013). Starch granules and complex carbohydrates at Çatalhöyük. In I. Hodder (Ed.), *Humans and landscapes of Çatalhöyük: Reports from the 2000–2008 seasons*. Ankara: British Institute of Archaeology.
- Hayden, B. (1987). Traditional metate manufacturing in Guatemala using chipped stone tools. In B. Hayden (Ed.), *Lithic studies among the contemporary highland Maya* (pp. 8–119). Tucson: University of Arizona Press.
- Heizer, R., & Hester, T. (1981). Making stone vases: ethnoarchaeological studies at an alabaster workshop in upper Egypt. *Monographic Journals of the Near East*, 1(2), 21–66.
- Martin, P. (1934). The bow-drill in North America. *American Anthropology*, 36(1), 94–97. <https://doi.org/10.1525/aa.1934.36.1.02a00080>.
- Molleson, T. (2007). A method for the study of activity related skeletal morphologies. *Bioarchaeology of the Near East*, 1, 5–33.
- Nadel, D., Bar-Yosef, O., & Gopher, A. (1991). Early Neolithic arrowhead types in the southern Levant: a typological suggestion. *Paléorient*, 17, 109–119. <https://doi.org/10.3406/paleo.1991.4544>.
- Osborne, R. (1998). The experimental replication of a stone mortar. *Lithic Technology*, 23(2), 116–123. <https://doi.org/10.1080/01977261.1998.11754399>.
- Ovadia, A. (2016). *Ritualistic breakage of ground stone tools at the verge of agriculture*. Unpublished MA thesis. Jerusalem: Hebrew University of Jerusalem.
- Perrot, J. (1966). Le gisement Natoufien de Mallaha (Eynan), Israel. *L'anthropologie*, 70(5–6), 437–484.
- Peterson, J. (1998). The Natufian hunting conundrum: Spears, atlatls, or bows? Musculoskeletal and armature evidence. *International Journal of Osteoarchaeology*, 8, 378–389. [https://doi.org/10.1002/\(SICI\)1099-1212\(199809\)8:5<378::AID-OA436>3.0.CO;2-I](https://doi.org/10.1002/(SICI)1099-1212(199809)8:5<378::AID-OA436>3.0.CO;2-I).
- Piperno, D., Weiss, E., Holst, I., & Nadel, D. (2004). Processing of wild cereal grains in the upper Palaeolithic revealed by starch grain analysis. *Nature*, 430(7000), 670–673. <https://doi.org/10.1038/nature02734>.
- Rosenberg, D., & Gopher, A. (2010). Food processing tools and other groundstone implements from Gilgal I and Gilgal III. In O. Bar-Yosef, N. Goring-Morris, & A. Gopher (Eds.), *Gilgal: Early Neolithic occupations in the lower Jordan Valley: the excavations of Tamar Noy* (pp. 139–176). Oxford: Oxbow Books.
- Rosenberg, D., & Nadel, D. (2014). The sounds of pounding: boulder mortars and their significance to Natufian burial customs. *Current Anthropology*, 55(6), 1–29. <https://doi.org/10.1086/679287>.
- Rosenberg, D., Shimelmitz, R., & Nativ, A. (2008). Basalt bifacial tool production in the southern Levant: a glance at the quarry and workshop site of Giv'at Kipod, Israel. *Antiquity*, 82(316), 367–376. <https://doi.org/10.1017/S0003598X00096861>.
- Savage, D. (2014). Arrows before agriculture? A functional study of Natufian and Neolithic grooved stones. In *Unpublished MA thesis*. Ontario: Trent University.
- Schiffer, M. B., & Skibo, J. M. (1987). Theory and experiment in the study of technological change. *Current Anthropology*, 28(5), 595–622.
- Schneider, J., & LaPorta, P. (2008). Geological constraints on ground stone production and consumption in the southern Levant. In Y. Rowan & J. Ebeling (Eds.), *New approaches to old stones: recent studies of ground stone artifacts* (pp. 19–40). London: Equinox.
- Schneider, J., & Osborne, R. (1996). A model for the production of portable stone mortars and bowls. *PCAS Quarterly*, 32(4), 27–40.
- Squitieri, A., & Eitam, D. (2016). An experimental approach to ground stone tool manufacture. *Journal of Lithic Studies*, 3(3), 553–564. <https://doi.org/10.2218/jls.v3i3.1681>.
- Stocks, D. (2013). *Experiments in Egyptian archaeology: stoneworking technology in ancient Egypt*. London: Routledge.
- Stroulia, A. (2003). Ground stone celts from Franchthi cave: a close look. *Hesperia*, 72, 1–30.

- Vardi, J. (2013). Large-scale larnite quarries and production sites for bifacial tools in the southern Judean desert. In F. Borrell, J. Ibáñez, & M. Molist (Eds.), *Stone tools in transition: from hunter-gatherers to farming societies in the near east* (pp. 87–100). Barcelona: Universitat Autònoma de Barcelona.
- Weinstein-Evron, M., Lang, B., Ilani, S., Steinitz, G., & Kaufman, D. (1995). K/Ar dating as a means of sourcing Levantine Epipalaeolithic basalt implements. *Archaeometry*, 37(1), 37–40. <https://doi.org/10.1111/j.1475-4754.1995.tb00725.x>.
- Weinstein-Evron, M., Yeshurun, R., Kaufman, D., Boaretto, E., & Eckmeier, E. (2012). New ^{14}C dates for the early Natufian of el-Wad terrace, Mount Carmel, Israel. *Radiocarbon*, 54, 813–822. <https://doi.org/10.1017/S0033822200047469>.
- Wright, K. (1992). A classification system for ground stone tools from the prehistoric Levant. *Paléorient*, 18(2), 53–81. <https://doi.org/10.3406/paleo.1992.4573>.
- Wright, K. (1994). Ground-stone tools and hunter-gatherer subsistence in Southwest Asia: implications for the transition to farming. *American Antiquity*, 59(2), 238–263. <https://doi.org/10.2307/281929>.