Experimental Grinding and Ancient Egyptian Flour Production*

Delwen Samuel
King's College London, Nutritional Sciences Division

Introduction

What was the nature of cereal grinding in ancient Egypt? The question may seem obscure and trivial. Yet for a large proportion of the population, this was a time-consuming, day-by-day task. An exploration of flour production can give us some understanding of daily life for the ordinary Egyptian, most often the women. Cereal processing seems an appropriate topic to offer as a tribute to Barry Kemp, who has spent a lifetime exploring the domestic and economic aspects of ancient Egyptian society, as well as the traditional subjects of temple and palace. The discovery by Barry Kemp in 1986 of both a box oven full of fired bread moulds and a bread oven in the annexe of Chapel 556 of the Amarna Workmen's Village, brought together perfectly this interest in both the domestic and the ritual of ancient Egyptian life (Kemp 1987). It also sparked the beginning of my involvement with ancient Egypt, and so makes an apt start to this contribution. I am deeply grateful to Barry for his advice, very practical support, and interest throughout my career studying ancient Egyptian food.

The inclusion of nearly whole or roughly cracked grains in many ancient Egyptian loaves has led some scholars to conclude that coarse bread texture was due to crude milling technology (Leek 1972: 130, Strouhal 1992: 125). Not all loaves have this texture, however. Some have a finer and more homogeneous consistency, approximately comparable to fine pinhead oatmeal. The variation in ancient bread texture suggests that the saddle querns used for flour production in Pharaonic Egypt could have been used quite flexibly to produce a range of meal types.

The purpose of this study is to investigate under repeatable experimental conditions how the saddle quern can be used to produce emmer flour, and what implications this might have for Pharaonic millers. Emmer (*Triticum dicoccum Schubler*) was chosen because most ancient Egyptian bread for which cereal can be identified is made from it (Samuel 2000: 558). Hand-milling by its nature cannot be precisely controlled and replicated, but

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the use of a consistent, if somewhat artificial, methodology can overcome this to some extent. Furthermore, this study focuses on patterns, not detailed results. The analytical approach uses particle size distribution, in order to examine patterns of grain breakage and how particle size can be controlled. The results from these experiments are supplemented by some reference to the artistic record and to archaeological finds. Ethnographic studies are valuable for comparison, although there are few detailed investigations of saddle quern grinding of emmer or other wheat types.

Grain hardness

One of the most important factors influencing cereal grinding is the hardness of the grain (Campbell 2007, Campbell et al. 2007: 8–9, Osborne and Anderssen 2003). Hardness refers to how hard and 'flinty', or soft and 'mealy', the grains are. Crushing is more difficult for hard grains and initially produces a high proportion of large fragments with fewer small grain particles. Soft grains show the opposite characteristics. In the literature, grain hardness can also be referred to as 'texture' (Williams 1998), but I have not used this term, to avoid confusion with particle size texture.

We do not know how hard ancient Egyptian grain was. Hardness is a genetic characteristic, and little affected by local growing conditions (Pomeranz and Mattern 1988, Pomeranz, Peterson and Mattern 1985, Pomeranz and Williams 1990). It is highly likely that different races, and thus hardnesses, of emmer were grown or developed in local areas throughout Egypt. The ancient Egyptians distinguished between many different types of emmer and barley (see for example Murray 2000: 512). As I show in this paper, given the influence of hardness on ancient grain processing, it is probable that this trait was an important category for the ancient Egyptians.

To investigate the effects of hardness on saddle quern grinding, I tested three different emmer wheats exhibiting a range of hardness, and compared them with a hard-grained durum wheat (*Triticum durum* Desf.), and a soft-grained bread wheat (*T. aestivum* L.). Durum wheat and emmer are both tetraploid wheats. They lack the D genome found in bread wheat, which confers the familiar dough characteristics of elasticity and viscosity so useful in modern spongy bread production. Durum wheats are virtually all hard, as are most emmer wheats, but the degree of hardness varies. The hardness of bread wheat is highly variable (Campbell 2007, Campbell et al. 2007, Osborne and Anderssen 2003), and future comparison with a hard bread wheat would be worthwhile.

Wheat samples

Table 1 lists the five wheat varieties used for the grinding experiments. The emmer varieties cannot be identified as any particular race and are named here after the individual who supplied them (Zimmerhackl, Hucl) or the region where they were grown (Garfagnana). The durum Duilio and the bread wheat Centauro are recognised Italian varieties.

Emmer is a hulled wheat, which means that when threshed the outer chaff layers still tightly enclose the grain. For these grinding experiments, the emmer grain was precleaned by a mechanical paddy rice dehusker (model THU35A, Satake Corp., Hiroshima, Japan). The bran layer of emmer wheat is little affected by mechanical dehusking (personal observation). In this respect the dehusking method is more or less equivalent to hand-dehusking in a mortar and pestle, as would have been done in ancient Egypt (Samuel 1993). Any contribution to the breakage pattern by bran should therefore be unchanged. Duilio and Centauro are both free-threshing wheats and so were available as clean, unhulled grains.

Grain hardness can be measured by a variety of techniques. Emmer hardness data was obtained with a Perten SKCS device (Perten Instruments AB, Huddinge, Sweden), which crushes grains individually and measures the force needed to break them. The average force is expressed in a relative number known as a Hardness Index (Osborne and Anderssen 2003, Campbell 2007). Table 1 includes the hardness index generated from an average of 300 grains, and a descriptive classification for each wheat variety.

Grinding tools

Prior to the invention of the rotary quern, perhaps in north-eastern Spain about the fifth century BC, all grinding was undertaken by rubbing a hand held handstone against a larger base stone (Curtis 2001: 337). The base stone could take a range of forms, and there is a correspondingly wide terminology for them (e.g. Curwen 1937, Adams 2002). In Pharaonic Egypt, the cereal grinding quern was a more or less flat or somewhat curved stone, longer than wide, and with a roughened surface, on which a handstone was rubbed back and forth over the long axis to pulverise the grains, and is also known as a saddle quern (Sumner 1967: 28).

I used a modern flat granite quern and cylindrical handstone for grinding (fig. 1). The equipment was made in south-east Asia (exact source unknown), where it is used for traditional processing of various foods. The working surface of the quern measures 280 mm long by 195 mm wide; the working length of the handstone is 204 mm, thus slightly longer than the quern is wide, and measures 52 mm in diameter (and see also table 6). The surface was not retouched (deliberately modified) throughout the experiments.

Compared with typical domestic saddle querns recovered from Amarna (fig. 2), the modern quern is about the same width but shorter. One ancient example measures about 400 mm by 180 mm (Samuel 1989: 260, 262: fig. 12.4). No definitely identified ancient Egyptian handstones are known, but artistic representations suggest they may have been elongated domes which were longer than the width of the base stone, and with a flattened grinding surface (for a good example, see <http://www.touregypt.net/featurestories/bread11.jpg> and below, Quern surface wear and handstone shape). The action of the modern cylindrical handstone is probably not precisely analogous to the ancient Egyptian type.

Grinding method

Modern flour has a very fine and consistent particle size. White flour is composed only of the starchy endosperm, with no bran particles. It can pass through a sieve with an aperture of 0.140 mm (Kent and Evers 1994: 141, 144). Wholemeal flour, that is, flour made with 100% of the wheat grain, is less well defined in terms of particle size (Kent and Evers 1994: 144). One American specification states that export flour should have 98% of particles smaller than 0.300 mm, and 90% of particles smaller than 0.250 mm in diameter (USDA Commodity Requirements, 2005: 4 n.4). The desired range in the United States for the coarse particles of ground durum wheats (known as semolina in the US) is 0.150 to 0.350 mm, but more probably the usual range is 0.100 to 0.500 mm (Kent and Evers 1994: 156). Comparison of wholemeal saddle-milled flour to modern white flour is unrealistic. In the figures presented here, I have used the USDA Commodity Requirements specifications as the benchmark. The majority of particles produced on the experimental quern are coarser, and hereafter I mostly use the term 'meal' for them.

All experiments were carried out with the quern on a linoleum floor, and the miller kneeling behind it. Grinding on the ground was the standard method for millers of the Old Kingdom, but by the Middle Kingdom, the quern was raised onto a platform (see below, Inferences for ancient Egyptian grinding). The flat base of the modern quern, its weight and the friction provided by the floor, prevented the quern from slipping or vibrating. I produced coarse and fine meal from all five wheat varieties. I chose emmer Zimmerhackl for two further treatments because it is the hardest wheat of the available types. To investigate whether meal texture is substantially affected by the person doing the grinding, Zimmerhackl was ground into coarse and fine meals by a second person. This experiment is referred to as Zimm 2nd. To gain some indication of the fineness of meal which can be obtained from a saddle quern, Zimmerhackl was also subjected to extra fine grinding.

The possibility that emmer was wet-milled in ancient Egypt can probably be discounted. In some cultures this technique is used for sorghum (Dirar 1993: 74–76) and maize (Bauer 1990: 4–5), and produces a fine or very fine paste. Even the finest-textured ancient loaves contain small grain fragments that were unlikely to have survived wet-milling unless it was a partial process.

The coarse meal production method was as follows. For each wheat variety a sample of grain weighing 200 g was divided into approximately 10 g batches. One batch at a time was placed on the surface of the quern and the handstone was passed firmly ten times over the grain. One 'pass' consisted of the handstone pushed from the end of the base stone closest to the miller, across the length of the stone to the other end, and back again. The first strokes passed over about half the length of the quern because the pile of grain was compact at this stage. As grinding progressed and the grain and meal mixture spread out over the surface of the stone, a greater proportion of the quern length was covered by the handstone. The resulting meal was carefully swept off the surfaces of the quern and handstone with a brush onto a tray, and the process repeated with another batch until the whole sample had been ground.

Fine meal was produced by repeating the coarse milling process (200 g of grain divided into 10 g batches, each batch ground with 10 passes of the handstone). The amalgamated coarse meal was then mixed and re-measured into 10 g batches. Each of these coarse meal batches was ground with 20 passes of the handstone over the saddle stone (30 passes in total). The reason for this two-stage procedure is that if one whole grain batch is processed with 30 consecutive passes of the handstone, a certain number of whole or partially fragmented grains is inevitably incorporated into the meal. The extra fine grinding for Zimmerhackl consisted of 30 passes of the handstone for each coarse meal batch (40 passes in total).

A small number of grains and grain fragments fell off the sides of the quern during coarse and fine grinding. When all batches of measured grain had been processed, these scattered items were gathered up, placed on the quern and re-ground as one batch (generally of about 8 g). I used five passes for coarse meal and 10 passes for the fine meal. After this process, the resulting particles resembled the same texture as the remainder of the meal, as estimated by eye.

Meal samples were stored in sealed glass jars at room temperature until ready for particle size measurements.

Ease of milling and fracture patterns

For all samples apart from very soft bread wheat Centauro, breaking the whole grains into coarse particles was the most difficult stage of the milling process. When the grains are whole, they present a relatively smooth, rounded surface which slides over the slightly roughened surface of the saddle stone and which is difficult to grip with the rounded surface of the handstone. The initial few strokes required very firm pressure and had to be done slowly, but once completed the grains began to fracture and break. As soon as some irregular grain fragments were produced, along with the exposure of the more easily abraded inner grain (the starchy endosperm), it became quicker to grind but firm pressure was still needed.

The grinding method used in these experiments is artificial because, to ensure reproducibility, it uses complete passes over the pile of grain from the start. A more effective method is to work at the edge of a pile of grains, cracking the outer grains to large fragments and exposing the starchy endosperm. The irregular pieces 'stick' onto the rough stone much better than the smooth rounded whole grains and also allow the handstone to grip the adjoining whole grains so that they can be quickly cracked. Once some of the whole grain is reduced to coarse fragments in this fashion, it is easy to mill across increasingly larger areas of the quern surface. The initial 'cracking' stage is quite rapid. Using this more effective method, it is possible on this size of quern to mill much more than 10 g of grain at a time to a coarse or a fine meal.

Unexpectedly, the harder wheats were much easier to mill on the saddle quern compared to the soft wheat Centauro. The soft wheat fractured into large flat bran particles and very fine inner grain particles. This made milling exceptionally difficult because the fine particles clogged the irregularities in the stone surface, substantially reducing its capacity to grip and shear. At the same time, the large bran particles made the meal very slippery and seemed to protect particles from being broken up. It took longer, and much more effort, to make the same number of passes over the saddle stone surface compared with the harder wheats. The largest particles for Centauro coarse and fine meals were not fragments of endosperm, as for the hard wheats, but flakes of bran (fig. 3). Menasanch and colleagues found similar problems when they experimented with wheat and barley grinding on saddle querns; the soft barley grain was slower and more difficult to grind (Menasanch et al. 2002: 98).

During saddle quern milling, the bran of the emmer and the durum grains adhered to, rather than broke off from, the starchy endosperm. The bran, along with the rest of the grain particles, became smaller as milling progressed. Only Centauro fractured in the pattern familiar to current-day millers, in which the bran splits open and remains in large flakes. This toughness of the bran is enhanced in modern milling by conditioning the grain, that is, by slightly raising the moisture content of the grain. It remains to be investigated whether conditioning affects emmer bran in the same way. It may be that emmer bran has a different underlying structural or biochemical composition compared with bread wheats, which leads it to shatter more easily (Galletti, Bocchini and D'Antuono 1996, D'Antuono, Galletti and Bocchini 1998, Mabille, Gril and Abecassis 2001).

Particle size measurement

Each glass jar containing a meal sample was mechanically mixed in a Turbula mixer (Glen Creston Ltd., Stanmore, Middsx, UK) for 5 minutes. The Centauro meal samples needed 10 minutes of mixing to distribute the particles evenly. Then a 50 g or 100 g sample was measured from each mixed sample and placed in the top of a stack of brass Endecott test sieves (CSC Scientific Co. Inc., Fairfax, VA, USA).

The height of the mechanical sieve shaker limited the number of sieves to seven sieves and the base pan. Coarse meal was sieved through mesh sizes of 1.400, 1.000, 0.710, 0.500, 0.355, 0.250 and 0.180 mm. Fine meal was sieved without the 1.400 mm mesh but with the addition of a 0.125 mm mesh above the base pan.

The sample-loaded sieve stack was covered and placed on the mechanical shaker for 10 minutes. After shaking, each sieve was carefully turned over onto greaseproof paper and the underside of the mesh thoroughly brushed by hand. The meal from each sieve was then weighed. The fine meal from sample Centauro did not move properly through the sieve stack by this method, as it tended to stick to the larger particles. For this sample, after 10 minutes on the mechanical shaker, the meal in each sieve was thoroughly hand-brushed through the mesh prior to removal from the stack and weighing.

General breakage patterns

Table 2 (coarse meal) and table 3 (fine meal) present the raw data of these experiments: the weights of the meal fractions recovered from the sieves. In order to compare samples, I have converted the weights into percentages, and plotted these as histograms. fig. 3 (coarse meal) and fig. 5 (fine meal) present pooled size fractions, to give an overview of particle size distribution.

Fig. 4 (coarse meal) and fig. 6 (fine meal) re-group the finer particle sizes so that the distribution patterns of this finer size range are clearer. For these Figures, the particle sizes are pooled in such a way that the size ranges are more or less equal, and the smallest fraction (0.250 mm and smaller) is comparable to modern American export flour — 90% of particles 0.200 mm and smaller (USDA Commodity Requirements, 2005).

All the coarsely ground emmers, and the durum wheat, broke up in a similar way (figs. 3 and 4), with progressively fewer particles in the smaller sieve sizes, apart from a small increase in the finest grade (less than 0.250 mm) in some cases. The majority of the coarse meal particles are greater than 1.000 mm in diameter (fig. 3). In fact, the 1.400 mm mesh contained most of the meal, which consisted of large quantities of whole or nearly whole grain. Nevertheless, all the coarse meals contained a greater or lesser proportion of fine particles. As might be expected, the softer wheats produced more fine particles.

When coarsely ground, the soft bread wheat Centauro fractured very differently. Compared with the other wheats, Centauro coarse meal has fewer of the coarsest particles. The smaller particles are more or less evenly distributed across the size fractions below 1.000 mm, but there is a somewhat higher proportion of the finest particles of less than 0.180 mm diameter (fig. 3). Meal from coarsely ground Centauro has a considerably more particles smaller than 0.250 mm compared with the other wheats tested (fig. 4).

The particle distribution is somewhat more variable with fine milling (fig. 5). For all the hard wheats (Zimmerhackl, Hucl, Duilio), the size distribution is quite similar. Between 13–25% of the particles are larger than 1.000 mm, while approximately 50% of the particles are between 1.000 and 0.500 mm. For the soft emmer Garfagnana, the great majority of particles are smaller than 0.500 mm. The soft bread wheat Centauro again broke quite differently. Over 50% of the particles are less than 0.180 mm.

It was possible to produce meal from the hardest grain (Zimmerhackl) relatively quickly in which over 85% of the particles are smaller than 1.000 mm in diameter (fig. 5). Milling for extra fine texture reduced the particle sizes to a meal in which virtually all particles are smaller than 0.710 mm in diameter, and 87% of the particles are smaller than 0.500 mm.

Breakage patterns compared

Two operators The profiles of particle size distribution for the two different millers grinding emmer Zimmerhackl are very similar, for both coarse and fine meals. In ancient times, it is likely that each miller had her different style and rhythm of milling, and the resulting meal may have varied somewhat amongst individuals. For the purposes of this experiment, the same results from two different operators appears to confirm that the grinding method used is consistent and the data for all wheat samples are therefore comparable. Ideally, this should be confirmed by further experimentation.

Hard and soft emmer For meal generated from coarse milling, the particle size distributions look very similar for all the emmers (and the durum wheat). The majority of particles consist of very coarsely cracked grain, and the smaller particles mostly evenly distributed across the size ranges (figs. 3, 4). As milling progresses, however, particles from the soft emmer (Garf) show a different pattern of distribution (fig. 5). They are mostly smaller than

0.500 mm in diameter and more closely resemble the soft bread wheat Duilio than the other emmers.

For hard wheats, the endosperm tends to fracture along the lines of the cell boundaries, whereas the endosperm of soft wheats fracture randomly (Kent and Evers 1994: 80). The breakage pattern of soft emmer Garfagnana looks as if it behaves like a hard and a soft wheat, breaking across the cell boundaries initially but once partially broken up, the starchy endosperm disintegrates into fine particles. Bran characteristics might also have an effect on how this wheat first fractures.

Hard emmer and durum Although the durum wheat Duilio is softer than either of the hard emmer wheats, the coarse meal has a bigger proportion of the largest particles. Nearly 80% of the meal consists of particles larger than 1.400 mm, compared with less than 70% for Zimmerhackl and less than 60% for Hucl (table 2, not shown in figures). This leads to a lower proportion of small particles in the durum coarse meal compared with the emmer wheats (figs. 3, 4). With fine meal, the particle size distribution for durum meal is similar to that of the hard emmers (fig. 5).

One explanation for this changing profile may be that grain shape has an important effect on breakage early in the milling process. Free-threshing wheat grains have a rounded cross-section, while emmer grains are somewhat flattened in cross-section. This difference means that emmer should have more grain surface in contact with the quern stone, increasing the friction and 'grip' of the stone tools on the grains, and perhaps consequently the initial grain breakage. Once the configuration of the whole grain is shattered, endosperm hardness determines breakage.

Extra fine grinding The pattern obtained from extra fine grinding of emmer Zimmerhackl shows that even the hardest wheat can be milled to a fine texture. This is contrary to the conclusion reached by R. Sallares for durum wheat. He suggests that due to its hardness, durum cannot be reduced to fine particles (Sallares 1991: 319). The particle size distribution of the meal shows that extra grinding eliminates nearly all the larger fragments (greater than 1.000 mm as shown in fig. 5, but in fact greater than 0.710 mm – see table 3). Extra-finely ground very hard Zimmerhackl has a similar particle size distribution to the fine meal produced from the soft emmer Garfagnana (figs. 5, 6).

The limits of particle size for very hard wheats might be determined by the texture of the quern. For these wheats, the breakage might be solely due to shearing forces, rather than disintegration of the starchy endosperm when fractured. If this is the case, fragments that become small enough to lodge in the quern surface pits would not become further reduced in size, and their presence would reduce the capacity of the quern to shear the remaining loose fragments.

Rotary quern comparision It is worth comparing saddle quern milling with similar experiments using a rotary quern excavated from a British site and dated to the first century AD. The operators found that they needed two passes of the grain and coarse meal to obtain 75% of particles smaller than 0.86 mm (Moritz and Jones 1950: 594; Moritz 1958: 178ff). About a quarter of the resulting meal was smaller than 0.21 mm (i.e. similar to American modern export flour). These rotary quern experiments were carried out with hard and soft bread wheats, and encountered a limit to the fineness of grinding. Like the very soft bread wheat used in this study, the medium-sized soft wheat particles could not be reground because the stone surfaces were quickly clogged by the finest flour particles (Moritz and Jones 1950: 595). This comparison suggests that the rotary quern, at least in the initial stages of development, allowed more rapid meal production with less effort, but did not necessarily produce a more finely milled product.

Is pre-pounding necessary?

These milling experiments show that it is easier to grind hard grain which has first been coarsely broken, and that the resulting meal is much more consistent in particle size. It is therefore worth considering whether a mortar and pestle rather than a mill might be more effective for the initial crushing phase. More grain at a time could be crushed more quickly and with less physical effort in a mortar compared to a saddle quern. It is a widespread assumption in the literature that the mortar and pestle was involved in ancient Egyptian flour production.

This was probably not the case, at least in ancient Egypt. Domestic mortars excavated from New Kingdom village sites such as Deir el-Medina and the Amarna Workmen's village are made of limestone and are mostly surprisingly shallow. The internal depth of a typical mortar from Amarna is only about 250 mm, and the inner diameter of the rim is 300 mm (Samuel 1989: 259). We know such mortars were used to process cereal, because of closely associated cereal remains beside one *in-situ* mortar within a village house (Samuel 1989: 280). Multiple lines of evidence strongly support the view that these mortars were used for stripping the tightly enveloping chaff from emmer wheat grains (Samuel 2000: 560–62). Experiments on grain crushing, which have involved both an ancient excavated mortar and a modern stone mortar of somewhat smaller dimensions, show that grain cannot be easily fractured with these tools. With the application of any force on the pestle, much of the grain flies out of the bowl. If the pestle is pounded gently enough to stop the grain spilling out, the grain is not crushed (Samuel 2000: 562).

There is ethnographic evidence to support the suggestion that a two- (or more) stage grinding process is an effective way to produce fine meal with a saddle quern. In the northern Darfur region of Sudan where, as in Egypt, wood is scarce, millet meal is produced with a two-part grinding process using two different grades of quern (Schön and Holter 1990: 362). In Sudan, fine sorghum meal is produced with two separate grindings on the same quern (Dirar 1993: 75). Several authors, summarised by Adams, have described the living tradition of multiple grinding stations used by women for grinding maize in the U.S. southwest (Adams 2002: 116). At these installations, there is a progression of grinding. The first woman cracks and coarsely grinds the grains, and passes this coarse meal to the next grinder, who reduces the meal to a finer texture, and so on until the finest grade of meal is obtained.

In areas where deep mortars were made, most likely from wood, a preliminary grain-crushing step is possible, but might not have been necessary or even very efficient. As described above, pp. 458–59, cracking whole grains on the quern with the handstone is quite rapid and can be immediately followed by grinding proper. This might be easier to carry out than a separate pounding step, which requires several repetitions to process a given batch quantity of grain, and takes time and effort to transfer each batch in and out of the mortar. This system might also lead to unacceptable losses during transfer, or to slowing down processing too much in order to prevent losses.

Time taken to grind

It seems logical to assume that the harder the grain, the longer it would take to grind. To test this assumption, three separate 10 g lots samples of for each selected wheat samples variety were milled to coarse and fine meal. The wheats selected were emmer Zimmerhackl (very hard), emmer Garfagnana (soft), durum wheat Duilio (hard) and bread wheat Centauro (very soft). The time taken from beginning of the first pass to end of the last pass was recorded. These timings therefore do not include placing grain on the quern or removing the meal, which are not affected by grain texture. Replications were carried out on at least two separate occasions for each sample. These timed lots samples were not included in the particle size distribution analysis. Table 4 shows the results of the timed experiments.

Timing the grinding process can only give general indications of differences, because there are several possible reasons for variation in the amount of time each batch might take to process. For example, random differences in the amount of spilled grain, adjustments to body position and small pressure variations could all alter the overall grinding time. For large grain batches, the time taken to grind can be expected to increase as the miller tires.

Overall, the differences in time to grind the various wheat samples are slight. Even accumulated over 2 kg, a quantity sufficient to make a reasonable amount of bread, the difference between the hardest and softest emmer only amounts to about 20 minutes. If meal fineness were important and hard grains were ground, then increased time and effort would have been needed to reduce the particle size. Although hardness has an important influence on timing, it is not the sole factor. Grain shape as suggested above also seems to play a role: rounded Duilio was longest to grind of the hard wheats. The difficulties of grinding the very soft wheat Centauro have already been discussed.

Extrapolating from the timed trials, it would take about 2 hours and 30 minutes for 2 kg of the hardest emmer Zimmerhackl to be ground on the quern. If about half an hour to three quarters of an hour is added for sweeping the flour off the stone, placing more grain on the stone ready for grinding, gathering up fallen particles, slowing down as the miller tires, and simply stretching and re-positioning the body, then 2 kg might take 3 to 3½ hours to mill on the experimental equipment used for these experiments. With a less artificial, combined cracking-and-grinding technique, less time might be needed. During earlier grinding experiments with a replica New Kingdom quern emplacement, an authentic ancient Egyptian saddle quern and a small ancient basalt handstone, I took just under two hours to grind 1.2 kg of emmer grain (Samuel 1994: 160). This is the same as or longer than for my ground-based milling experiments. The difference in level of experience must be taken into account, as well as the form of the handstone, which was probably not of the type used for ancient cereal grinding.

As Menasanch and colleagues point out, grinding times very much depend on the type of equipment and grain, as well as the ability of the operator. They gathered a range of saddle quern grinding timingstimes, based on experimental, documentary, and ethnographic sources (Menasanch et al. 2002: 98). Together with the results presented here, it seems reasonable to estimate that in ancient Egypt, milling flour on the ground for domestic production might have taken about three hours a day. The advent of the quern emplacement greatly improved ease of milling (see below, Inferences for ancient Egyptian grinding), and may have reduced this time. Throughout Pharaonic times, millers working for large estates or in temple grinderies may well have had to work longer.

Quern surface wear and handstone shape

In 1992, I undertook a site survey at Amarna to whichthat recovered over 700 quern stones and other stone artefacts exposed by previous excavation. The querns were made from granite or quartzitic sandstone. A preliminary analysis of a sample of 136 querns showsed that nearly half of them have a slightly convex curve across the width of the working surface (fig. 2, and see Samuel 1989: 262, fig. 12.4). Of the other querns in the sample, more have a flat surface in transverse section than a slightly concave surface (table 5). This result was unexpected, because intuition would suggest that a quern is more likely to be shaped with or to develop a concave surface, in order to prevent the material being ground from falling off. Experiments by Adams indicated that flat grinding stones were unsuitable for dry kernels because the seeds kept falling off the surface (Adams 2002: 68). Her recording forms do not allow for convex surface (Adams 2002: 253), suggesting in the US southwest, convex surfaces are never found. At south-eastern Spanish sites dating to the 3rd third and 2nd second millennia BC, long narrow quern stones similar in form to ancient Egyptian querns were recovered. Many of these also have convex transverse sections. The marked convexity working surfaces of these querns also puzzled Menasanch et al. (2002: 83).

In part, the difference in form between these Old World querns, compared to the southwest US querns, might be explained by the nature of the foodstuffs which were processed. Adams' comments on loss of seed from the flat querns relates specifically to dry maize kernels. Characteristics such as shape and size of the kernels, as well as hardness, compared with Old World wheat and barley grains, are likely to play a role in their behaviour on the grinding surface. The grinding of these very different cereals probably cannot be meaningfully compared.

Menasanch and colleagues constructed experimental querns closely modelled on the ancient examples, including the convex transverse working surface. They used wheat of an unspecified type and 'dressed barley' (possibly pearled barley, i.e. with the adhering chaff removed by modern mechanical abrasion). When they used the experimental querns to grind wheat, they found that flour did not fall off the sides of the stone, but stayed in the central area, while the light bran moved down the curved surface. The effect was even more pronounced for barley. They state that the vibration of the mill concentrated the flour in the centre, helping to separate out the bran (Menasanch et al. 2002: 95). The effects that they observed may well be relevant to ancient processing, but the cereals they used are possibly not analogous to the ancient third and second millennium grains. The vibration of the quern that they observed may not have been a feature of grinding after the First Intermediate Period in Egypt, once the quern emplacement was in use, as the quern stone was cradled in the emplacement surface. Whether the vibration effect occurred when the Egyptians used querns placed on the ground needs further investigation.

Both Menasanch et al. (2002: 83) and Adams (2002:100) have pointed out that the use of and wear on the saddle quern is intimately affected by the form of the handstone. Adams' research benefits from the study of a living tradition, as well as the recovery of both parts of the grinding tool. In contrast, the study of both the Amarna and the southeast Spanish querns is hampered by a marked lack of ancient handstones. This fact needs further investigation and explanation. Menasanch and colleagues prepared experimental handstones from different materials (stone and wood) and with working surfaces of differing shapes (Menasanch et al. 2002: 90–91). As far as shape is concerned, they found that when using an experimental handstone with a flat working surface, the handstone rolled over the hard grains. As a result, crushing required considerable effort because strong pressure had to be used on the grains. The fact that a regular grinding rhythm could not be maintained added to the difficulty in grinding. A handstone with a slight convex curve on the working surface allowed a rocking movement as well as a back-and-forth movement, which resulted in the grain being crushed with less effort (Menasanch et al. 2002: 98).

The degree to which the handstone is curved is important. The cylindrical handstone used for the experiments reported here was too rounded to allow really efficient cracking in the early stages of grinding, and might be best suited to smaller grains and seeds. If a handstone with a less pronounced curve to the working surface was the tool of choice in ancient Egypt, it would have been easier to rock and push down and thus fracture the grain, and more at a time could be processed, compared to the cylindrical handstone used for these experiments. Adams points out that the handstone working surface can be altered throughout its lifetime of use on a flat saddle quern, creating a range of profiles on the handstone (2002: 103ff). It is likely that the curve of the handstone, together with the way it is manipulated during grinding, will have an effect on the wear of the quern surface. It is also probable that the exact configuration of handstone, as well as quern stone, is in part dictated by the nature of the foodstuffs that are ground.

As well as the curve of the working surface, the width of the handstone may have an effect on the pattern of quern wear. I found that grinding with a narrow, flat experimental quern and a slightly wider handstone meant that grain has to be kept the centre of the stone in order to avoid losing too much grain or meal over the sides. The meal acts as a cushion between the stones in the centre of the quern, but the long edges of the quern had a great deal of stone-to-stone contact.

Although in need of more detailed investigation, it seems probable that stone-to-stone contact will result in more rapid wear than stone-to-grain-to-stone contact. It also seems likely that a narrower handstone would cause less stone-to-stone wear during grinding. The only Old World ethnographic study giving details about sizes, shapes and wear of quern stones of which I am aware is by Schön and Holter (1990: 362). They record that the nomadic tribes of the northern Darfur (Sudan) grind millet or sorghum with handstones that are always narrower than milling stones. The milling stones are made of gneiss or granite and become concave as a result of the milling process. The handstones are made of coarse or fine-textured gneiss, round or irregular, but the working surface remains flat even after extended used. The querns used by these women are larger than the experimental and ancient Egyptian querns (see table 6).

In the current absence of any clearly identifiable handstones from ancient Egypt, the artistic record may be of assistance at least for relative handstone width. Wall reliefs and paintings do not illustrate this type of detail, but most figurines are sufficiently well rendered to distinguish whether the handstone is longer or shorter than the quern width. Moritz states that the width of handstones in ancient Egyptian figurines is usually somewhat narrower than the width of the quern (Moritz 1958: 29). In contrast, the sufficiently clear illustrations of grinding statuettes and models which I have examined show handstones of the same width or wider than the corresponding quern stone. There are plenty of examples from the main Egyptian periods to show that this feature seems to be constant throughout Pharaonic times. Many Old Kingdom statuettes show the wider handstone - plainly (for example, see Breasted 1948). An excellent example from Giza is illustrated by Hassan and Darwish (1944: pl. xxv). Middle Kingdom models tend to be more schematic, but suggest the handstone is at least as wide as the quern. A very detailed model from the Middle Kingdom which definitely shows somewhat wider handstones comes from the tomb of Meketre, a high official of the early Twelfth Dynasty (Roehrig 2002: 11, fig. 10). The few New Kingdom statuettes of grinding are ritual in nature, but the wide handstone is very clearly depicted (Breasted 1948: pl. 23, 24).

This overview seems to show clear that, like the quern used in the experiments described here, ancient Egyptian querns were narrower than the attendant handstone. It is therefore probable that the lateral edges (the long sides) of ancient Pharaonic querns were exposed to extensive stone-to-stone contact. This might have caused a gradual reworking of the quern surface to a convex shape. If so, the range of profiles found on the Amarna querns, and the preponderance of convex widths, suggests that the transverse profile may be a function of the extent to which individual querns had been used. The more they had been used, the greater their working surfaces would have been altered. The pattern of wear is therefore an indicator of their life history (Adams 2002: 100). This possibility that convexity is equivalent to greater wear is intriguing, because it may present a route by which more information on the economics of ancient Egyptian cereal grinding can be obtained. It is clear that further work is needed on the Amarna quern surface profiles and their wear patterns.

Inferences for ancient Egyptian grinding

The experiments presented here show that saddle querns are easily used to produce meal free from whole grains or very large fragments. Since within limits it is easy to control the grade of meal quite precisely on a saddle quern, and therefore the inclusion of whole and cracked grain in many of the ancient Egyptian loaves must have been deliberate. There are several possible reasons: coarse meal is quicker to produce; many of the surviving loaves are funerary or ritual in origin and may have been made less carefully than bread for daily consumption, as it was intended only to be representative; and the coarser, presumably chewier texture may have been appreciated for its taste and mouth-feel, much as granary and multi-grain loaves are enjoyed by the modern Western consumer.

Strength and body position are amongst the factors that influence grinding speed and productivity. We can turn to the artistic record to provide some insights about changing body position for the millers of ancient Egypt. Throughout the Old Kingdom, statuettes and tomb paintings that illustrate the grinding process all show the millers kneeling on the ground (see amongst others the relevant statuettes illustrated in Breasted (1948); there are many other examples). By the Middle Kingdom millers are shown working at querns placed on raised platforms. The tomb paintings of Beni Hasan are amongst many depictions that show this (Garstang 1907).

I have described elsewhere experiments grinding on a saddle quern placed on a raised emplacement (Samuel 2000: 563). In summary, when working at a raised emplacement with the feet supported by a wall at the back, grinding is quite comfortable and the full weight of the upper body can be brought to bear without undue effort. The simple expedient of raising the quern off the ground in this fashion must have greatly increased the amount of flour one person could produce. Little strength is needed to grind because the weight of the upper body is used to apply force on the grain (Samuel 1994: 158). When grinding from a kneeling position, considerable effort is needed to push off from the toes, to bear down with the arms, and to support the body in the correct position, and stress is placed on the knees, wrists and lower dorsal vertebrae (Molleson 1989: 361).

The innovation may have had an influence on meal and bread texture. Since the changed body position makes it easier to grind for longer, a finer meal or a more consistently fine meal could be ground if desired. This strengthens the case for the deliberate inclusion of large grain particles in New Kingdom bread.

The invention of the quern emplacement likely had an impact on domestic economy. In a more modern context, A.J. Bauer has eloquently highlighted the diversified household economy and varied diet in cultures where women were able to work other than for long hours at the grinding stone (Bauer 1990: 2–3). With a more efficient tool, and assuming the same amount of grain to be processed, ancient Egyptian millers would have had more time available, allowing them to do other things (Adams 1999: 483). They would also have been less tired to do them. Women may have been able to grind into older age, freeing the younger women in a household for other tasks. Older individuals were surely able to maintain the productivity of their meal production, since strength was no longer critical and wear on the body would have been very much reduced. (Molleson (1989) describes the damage to the body which can be inflicted by extensive ground-based saddle quern grinding.) Whatever other consequences it had, the advent of the quern emplacement must certainly have improved the lot of the ancient miller.

The artistic evidence offers a clue as to when this invention took place. Wooden models from First Intermediate Period Sedment show millers kneeling on the ground. This is perhaps most clearly depicted in a wooden model from tomb 2106 (now Ny Carlsberg Glyptotek, Copenhagen ÆIN 1571 – Jørgensen 1996: 108–109[40]). Another wooden model of the same period includes a kneeling miller (Breasted 1948: pl. 34). According to the artistic record, by the Middle Kingdom the quern raised on an emplacement was a standard installation throughout Egypt.

Did the ancient Egyptians use a multi-stage process to produce their finer meal, or was sieving more likely – or were both processes employed? The only other directly comparable ethnographic situation known to me is emmer grinding with saddle querns in Ethiopia. In this area, quern milling ceased about 20–25 years ago, but former practitioners emphasised that quern-ground emmer meal had to be sieved to remove impurities (D'Andrea and Haile 2002: 211). Information is not available on the factors that might have a bearing on this comparison, such as the type of sieve, the nature of the undesirable material, and whether the quern was raised or on the ground.

It is quite possible that the Egyptians did not always use a two-stage process for milling. The larger grain particles in the ancient bread may have come from grinding each grain batch on the quern just once. As described, it is possible to use the quern in a more sophisticated manner than with the experimental procedure used here. It is likely that the Egyptian millers sometimes used a relatively quick single-stage procedure leading to a less coarse meal, but incorporating a proportion of whole and partially broken grain. Those ancient loaves made of finer particle size meal were almost certainly milled using a multi-stage process, because with this equipment, large particles from the initial whole grains always get scattered off the stone and into the meal. Depending on the grade of meal produced with a single grinding, sieving these particles out may have been more difficult and time consuming to do than straightforward re-milling. This is not to say that the ancient Egyptians never sieved the meal; for the finest grade they may well have 'bolted' a finely ground meal through linen cloth for example. Nevertheless, sieving may not have been required to obtain the grade of fine meal observed in surviving loaves, and may not have been the standard procedure for emmer meal production.

The two-part milling method may not have been necessary for fine meal once the quern emplacement had been invented. Earlier experiments have shown that the manipulation of grain, cracked grain and flour are much easier on the raised quern stone (Samuel 1994: 159–60). As well as making the grinding process less tiring, this may have been another way in which the quern emplacement increased efficiency. More experiments are needed to investigate the details of quern emplacement grinding as opposed to floor-based grinding.

Results from this study indicate that the saddle quern is not suitable for milling grains whose endosperm fractures very finely and cereals for which the bran remains relatively intact. This implies that prior to the introduction and development of rotary milling, grains destined for milling did not resemble the soft modern bread wheats.

Nowadays, millers condition their grain through the controlled addition of moisture, increasing the water content in proportion to grain hardness (Kent and Evers 1994: 122). In addition to toughening the bran, this process decreases the endosperm strength, so that less force is needed to fracture the starchy endosperm. Due to the extreme hardness of durum wheat, the grain is tempered to a relatively high moisture content of 16% before grinding (Kent and Evers 1994: 154). Experiments with emmer and ancient Egyptian processing technology have indicated that whole spikelets were dampened prior to stripping the chaff with the mortar and pestle (Samuel 2000: 562). If spikelets were moistened for processing, it is probable that the Egyptians were aware of the effects of moistening grain for milling. Hard emmers may be notably easier to mill with the saddle quern if they are allowed to absorb limited amounts of water. This is an area that would repay experimental investigation.

The ethnographic literature of quern grinding highlights its arduous, time-consuming nature (e.g. D'Andrea and Haile 2002: 207; Bauer 1990: 10). This is borne out by experimental reconstruction (e.g. Menasanch 2002: 98). Meal would have been needed on a frequent and regular basis to make bread, the dietary staple of ancient Egypt. The ancient Egyptian millers must also have worked long and gruelling hours to supply that meal.

This study has focused primarily on the nature of the grain used for milling, an aspect rarely considered. Previous work on ancient food processing has mostly taken into account the important major morphological differences between cereal species (e.g. hulled vs. free-threshing wheats), the processing tools used for grinding (e.g. Menasanch et al. 2002), or most ambitiously, differences in seeds from widely varying taxa together with different processing tools (e.g. Adams 1999). This is hardly surprising. The stone tools are robust and easy to recognise and retrieve from the archaeological record. Archaeobotany has advanced sufficiently in recent years to allow much more precise identification of archaeological cereal remains to species level (Jacomet 2006). The more subtle qualities of the cereals used in antiquity, on the other hand, are harder to assess for ancient material.

I have shown here that the specific characteristics of cereals had an impact on ancient processing. In this study the effects of grain hardness have been considered in some detail, and the behaviour of the bran has been touched upon. Grain hardness, breakage patterns and grain shape can affect the milling process and its products. Indeed, these characteristics are important to wheat millers today (Campbell 2007, Campbell et al. 2007). The investigation of subtle physico-chemical features of cereal grain is challenging, but can lead to valuable insights into many aspects of ancient cereal food production.

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Wheat variety	Wheat species	Country of origin	SKCS hardness index	Relative hardness (texture)
Zimmerhackl (abbreviated to "Zimm")	Emmer wheat, *Triticum dicoccum*	Austria	94	Extra hard
Hucl	Emmer wheat, *T. dicoccum*	Canada	83	Very hard
Garfagnana (abbreviated to "Garf")	Emmer wheat, *T. dicoccum*	Italy	32	Soft
Duilio	Durum wheat *T. durum*	Italy	71	Hard
Centauro	Bread wheat, *T. aestivum*	Italy	23	Very soft

TABLE 1
The wheats used in the grinding experiments, together with country of origin, SKCS hardness index from an average of 300 grains, and Williams' hardness classification (Williams 1998).

Sieve size (mm)	Zimmer-hackl	Zimm 2nd	Hucl	Garf	Duilio	Centauro
1.400	33.5	34.3	28.3	33.6	39.7	30.7
1.000	10.9	9.1	10.2	30.4	5	4.4
0.710	2.5	2.7	3.9	13.4	1.7	2
0.500	0.9	1.3	2.3	6.8	1	2
0.355	0.4	0.7	1.4	3.8	0.6	1.4
0.250	0.3	0.6	1.2	2.8	0.5	1.4
0.180	0.3	0.4	0.9	2.4	0.4	1.3
Base pan	0.9	0.9	1.8	6.8	1	6.7
Total	49.7	50	50	100	49.9	49.9

TABLE 2.
Coarse meal sieved fraction weights in grams. For all wheats except Garfagnana, 50 g of coarse meal were sampled; for Garfagnana 100 g were sieved. All figures derive from single observations.

Sieve size (mm)	Zimm	Zimm 2nd	Zimm XF	Hucl	Garf	Duilio	Centauro
1.000	6.5	12.1	0.2	13	0.2	9.2	5.5
0.710	15.1	14.9	1.2	14.8	1.4	12.2	2.7
0.500	11.4	9.2	11.4	8.2	8.2	9.5	3.5
0.355	4.4	3.7	22.4	3.4	15.6	4.6	2.6
0.250	3.2	2.7	18.4	2.6	14.8	3.4	3.3
0.180	2.4	2.2	12.6	2	13.4	2.5	4.4
0.125	4.6	4.5	19.6	3.4	19.8	5.3	7.4
Base pan	2.2	1.1	14	2.4	26.8	3	19.3
Total	49.8	50.4	99.8	49.8	100.2	49.7	49.8

TABLE 3
Fine meal sieved fraction weights in grams. For all wheats except Garfagnana, 50 g of coarse meal were sampled; for Garfagnana 100 g were sieved. All figures derive from single observations.

Wheat variety	Wheat hardness	Time taken to mill coarse meal (s)	Time taken to mill fine meal (s)	Total fine meal time (s)
Zimmerhackl	very hard	18.3 +/- 1.5	27.7 +/- 2.5	46 +/- 3.5
Duilio	hard	22.3 +/- 2.5	29.3 +/- 2.1	51.7 +/- 3.8
Garfagnana	soft	17 +/- 1.7	23 +/- 3.5	40 +/- 4.6
Centauro	soft	23 +/- 1.7	33.7 +/- 2.5	56.7 +/- 4.2

TABLE 4
Average time to process 10 g samples of selected wheat varieties in seconds. Three separate samples were measured for each variety. Coarse meal time is the time taken for 10 passes of the hand stone beginning with whole grains. Fine meal time is the time taken for 20 passes of the hand stone beginning with coarse meal. Total fine meal is the sum of the average coarse and fine meal times. The average of three replicates and the standard deviation are presented.

Transverse profile	Numbers	Percentage
slightly convex	67	49
flat	41	30
slightly concave	28	21

TABLE 5
A comparison of the transverse profile of a representative sample of 136 saddle querns recovered from a surface survey of Amarna.

Quern origin	ancient Egyptian	experimental	northern Darfur

Single example or range	single example	single example	range
Quern length	40	28	35 – 68
Quern width	18	19.5	21.5 - 41
Handstone width (diameter)	Unknown	5.2	12 – 16
Handstone length	Unknown	20.4	13-23.5

TABLE 6
Ancient, experimental, and Northern Darfur ethnographic quern stone and handstone dimensions, in centimeters. Northern Darfur data is taken from Schön and Holter (1990: 362). Handstone width refers to front to back of the stone in working position; handstone length refers to side to side of the stone in working position.

FIG. 1
The modern granite quern used for the grinding experiments.
The scale bar is 40 mm.

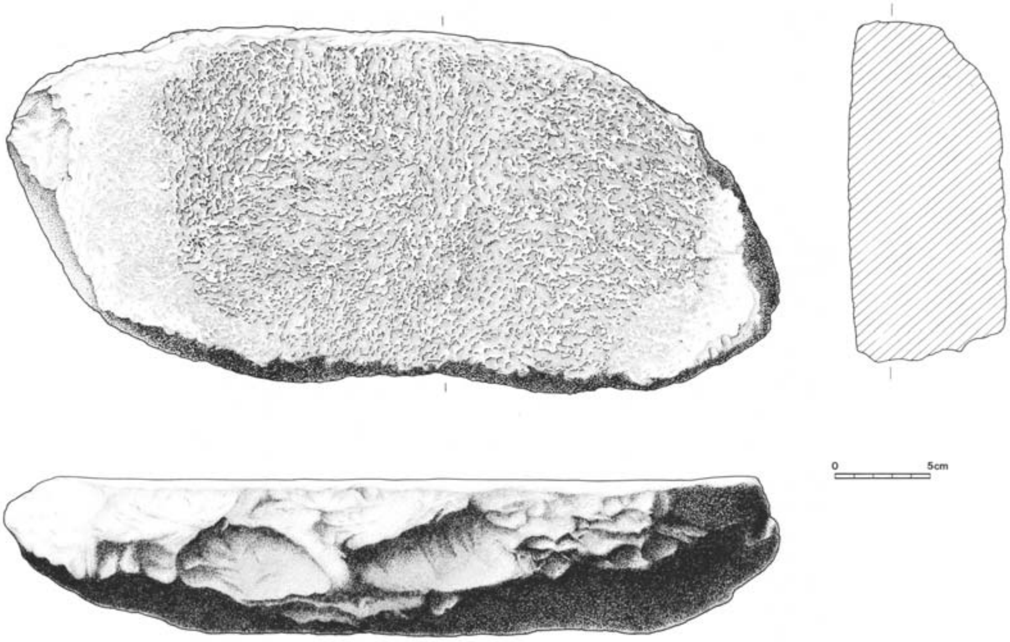

FIG. 2
Illustration of an ancient Egyptian granite saddle quern recovered from the site of Amarna. Note the slightly concave longitudinal surface and the slightly convex width. The centre of the stone is relatively rough while the ends are smoothed.
A. Boyce, from Samuel 1989: 262, fig. 12.4; courtesy EES.

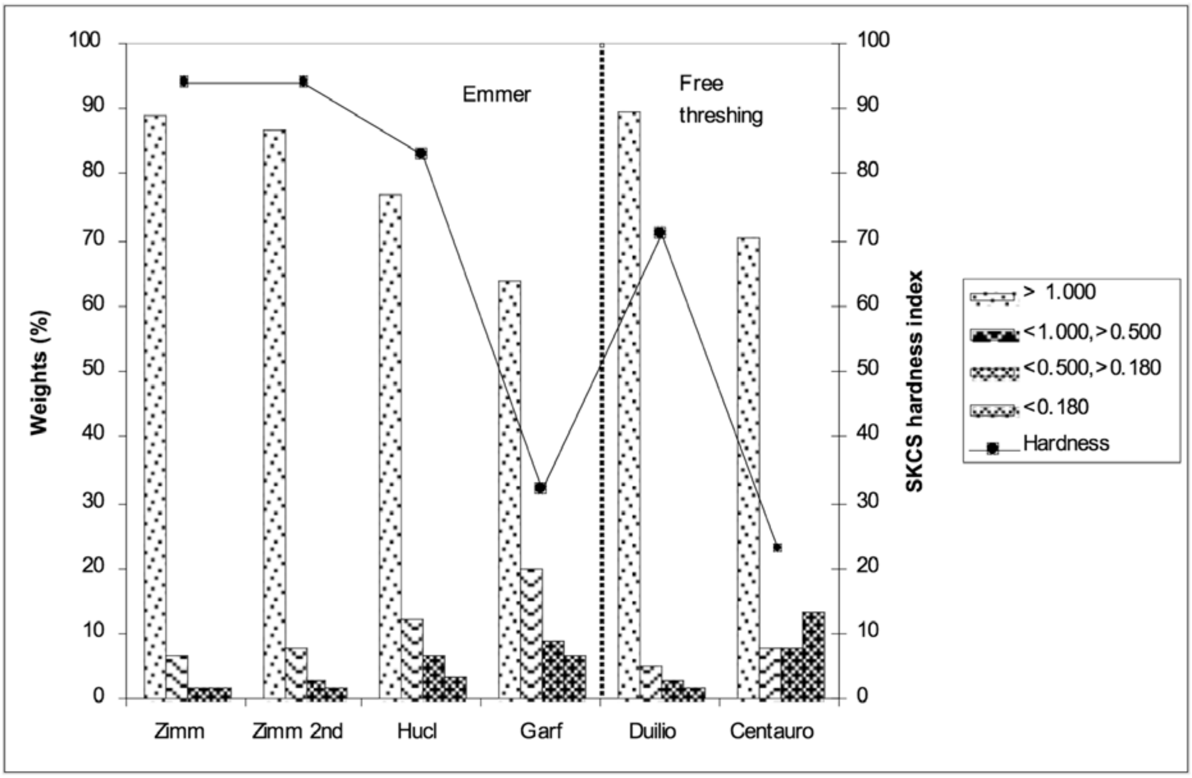

FIG. 3
Distributions of coarsely ground meal particles, by pooled weight percentages from a series of test sieves. Sieve sizes (in boxed legend) are in mm. Emmer wheats and free threshing wheats are grouped separately in order of hardness.

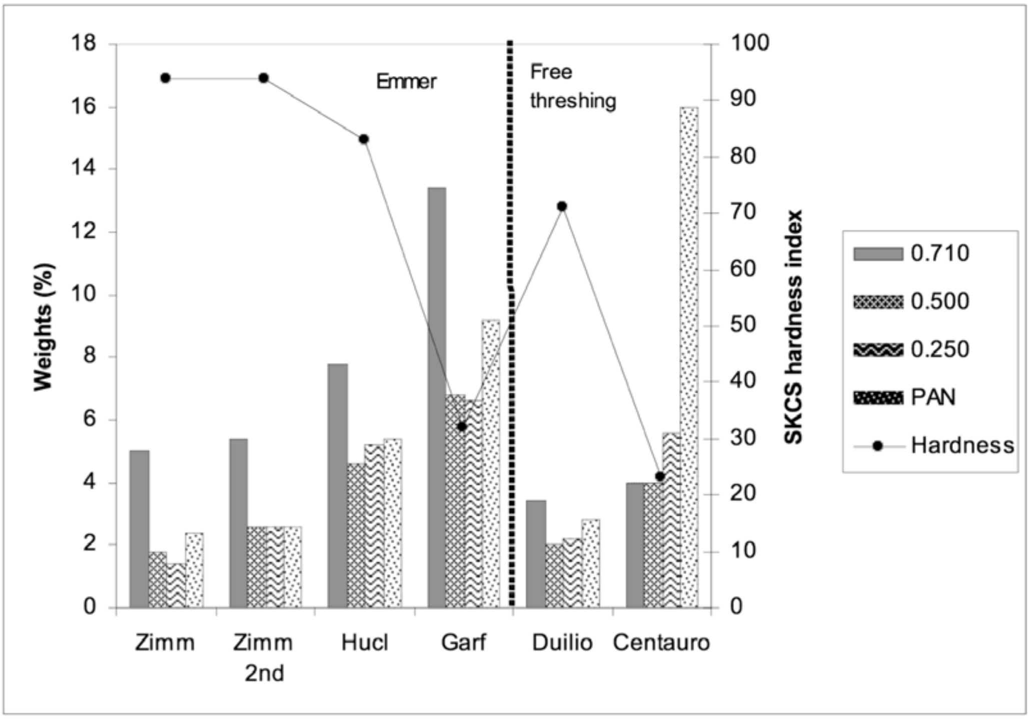

FIG. 4
Distributions of the finer particle sizes generated from coarsely ground meal, by pooled weight percentages from a series of test sieves. Sieve sizes (in boxed legend) are in mm. 'PAN' refers to material smaller than 0.250 mm, and thus similar in size range to modern flour. Emmer wheats and free threshing wheats are grouped separately in order of hardness. Note change of 'Weights (%)' scale compared to fig. 3.

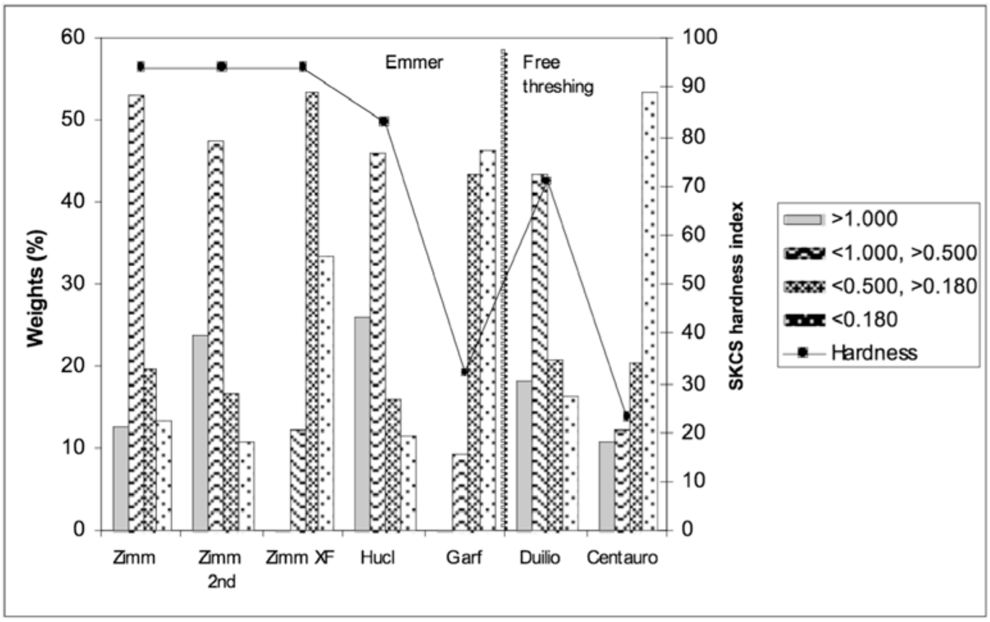

FIG. 5
Distributions of finely ground meal particles, by pooled weight percentages from a series of test sieves. Zimm XF = extra finely ground Zimmerhackl. Sieve sizes (in boxed legend) are in mm. Emmer wheats and free threshing wheats are grouped separately in order of hardness.

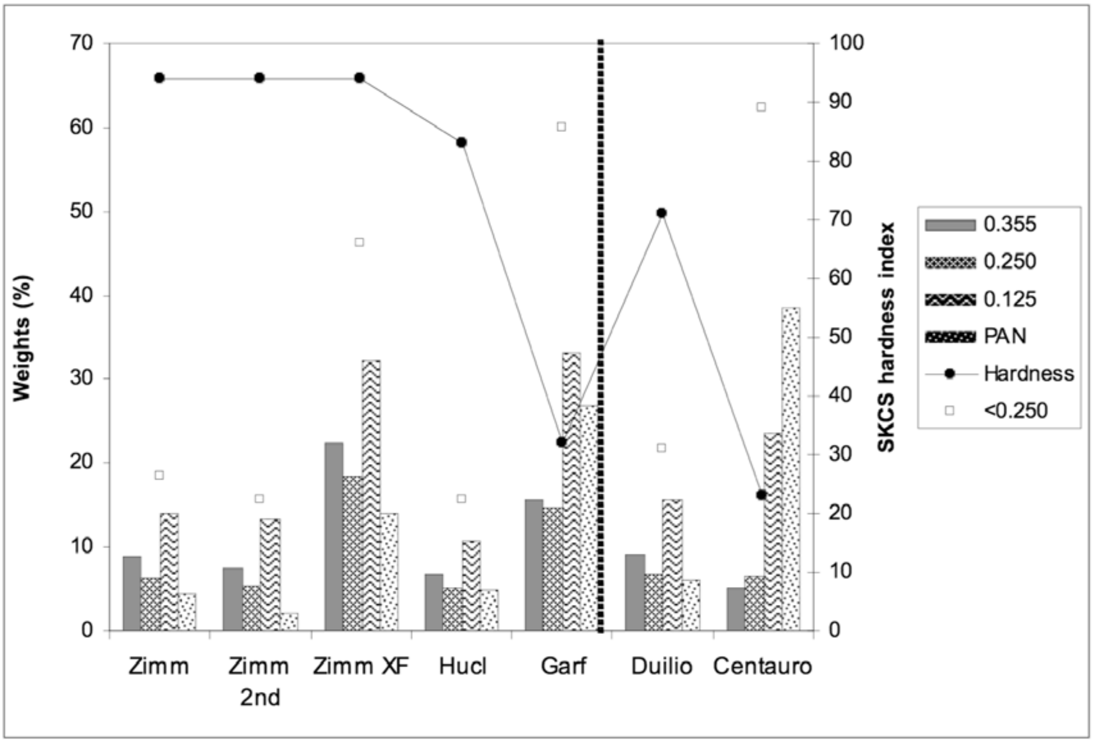

FIG. 6
Distributions of the finer particle sizes generated from finely ground meal, by pooled weight percentages from a series of test sieves. Sieve sizes (in boxed legend) are in mm. Zimm XF = extra finely ground Zimmerhackl. 'PAN' refers to particles smaller than 0.125 mm. The squares show the percent weights of all particles less than 0.250 mm. Emmer wheats and free threshing wheats are grouped separately in order of hardness. Wheats to the left of the dotted line are emmer; those to the left are free threshing. Note change of 'Weights (%)' scale compared to fig. 5.

FIG. 7
Millers and bakers from Meketre's model bakery, from the tomb of Meketre, Western Thebes, early Twelfth Dynasty (Metropolitan Museum of Art 20.3.12).
Courtesy Metropolitan Museum of Art, Rogers Fund and Edward S. Harkness Gift.