Investigation of Ancient Egyptian Baking and Brewing Methods by Correlative Microscopy

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Ancient Egyptian methods of baking and brewing are investigated by optical and scanning electron microscopy of desiccated bread loaves and beer remains. The results suggest that current conceptions about ancient Egyptian bread and beer making should be modified. Bread was made not only with flour from raw grain, but sometimes also with malt and with yeast. Brewing blended cooked and uncooked malt with water; the mixture was strained free of husk before inoculation with yeast.

Food is fundamental for all human societies, not only for nutrition and health but also in economic, social, and ritual life. Information about prepared food is therefore critical for an understanding of ancient cultures, but examination of past food is extremely difficult. Food is normally consumed, and leftovers usually decay. Ancient food preparation is seldom studied, and modern descriptions of ancient cooking are sketchy. Typical examples of this problem are ancient Egyptian baking and brewing. Bread and beer were dietary staples throughout ancient Egyptian history (*1*). Microscopy evidence reported here, of desiccated loaves and beer residues, illustrates the complexity of ancient Egyptian cereal food processing.

Traditional descriptions of ancient Egyptian bread and beer rely on artistic depictions and written sources. Egyptologists have proposed various beer ingredients, such as dates and lupins, on the basis of documentary evidence (*2*). Translations differ, however (*3*). Documents contain little data on bread ingredients. The artistic record has been used almost exclusively to interpret baking and brewing methods. Standard descriptions suggest unsophisticated preparation: bread is said to have been made of coarsely milled wheat, well kneaded into dough but often full of chaff and grit (*4, 5*), and barley is considered to have been the preferred brewing cereal. It has been thought that well-leavened, lightly baked bread was crumbled, strained through sieves into vats with water, and fermented by yeast from the bread (*6–8*). Notable discrepancies in these interpretations persist, however, because the artistic evidence is not clear (*9*).

Remains of ancient Egyptian prepared food have been widely recovered from tombs and settlements dating throughout the Pharaonic period (approximately 3100 to 332 B.C.). Like other organic material, they are extremely well preserved in Egypt's arid climate. Analysis of these remains provides direct evidence for ingredients, and how they were prepared for consumption.

As early as 1905, starch was detected from ancient Egyptian bread by microscopy (*10*). Beer residues are not always recognizable, but have occasionally been identified (*11*). A few were examined by light microscopy in the 1920s, revealing plant tissues, starch granules, yeast, and other microorganisms (*12*). This pioneering work did not lead to a model for ancient Egyptian brewing and was not continued.

The present results are based on systematic analysis by microscopy of desiccated loaves and cereal residues. The bread derives from several sites that span approximately 2000 to 1200 B.C. The residues are from two sites: Deir el-Medina (1550 to 1307 B.C.), where workmen lived who built the tombs in the Valleys of the Kings and Queens, and the Workmen's village of Amarna (approximately 1350 B.C.) in middle Egypt. Nearly 70 loaves and more than 200 contents of pottery vessels were first examined optically. This method provides essential data about ingredients and their quantities, unintended inclusions, and texture.

Ancient Egyptian bread varies greatly in size, shape, and decoration. Loaf texture ranges from fine to coarse. Unlike modern spongy-textured bread, ancient Egyptian bread usually has a dense crumb. All loaves have thin crusts, darker above and paler on the base, which show that they were definitely baked. Large quantities of husk are rare. A few chaff fragments are usually incorporated into loaves, but some loaves are clean and fine-textured. Almost all examined loaves are made from emmer wheat (*Triticum dicoccum* Schübl.), as determined by the presence of these chaff fragments and embedded whole or broken grain. Occasionally, other ingredients, such as coriander and fig, are present.

In contrast, both emmer and barley (*Hordeum vulgare* L.) were used for brewing, sometimes separately and sometimes mixed together (*13*). No flavorings have so far been detected in beer residues (*14*). The texture of residues, like that of bread, ranges from fine to coarse. Unlike bread, large amounts of chaff are a common feature. Coarsely shredded husks occur in substantial quantities in large jars. In thin coatings, husk slivers are often embedded, along with small bran pieces (Fig. 1). Some small pottery cups contain such thin residues, which suggests that they were used for drinking beer.

Optical microscopy is not sufficient to gain detailed insight into how these ancient cereal foods were processed. Scanning electron microscopy (SEM) of modern cereal foods has established that starch alters in recognizable ways according to processing conditions (*15–18*). When starch granules are heated in water they swell, fold, and eventually merge into one another completely. If moisture is limited, the granules are not completely dispersed and, although swollen or distorted, retain their individual boundaries. Enzymes in sprouting cereals break down starch to dextrins and simple sugars, creating typical surface pitting and interior channeling of starch granules (*19, 20*). Museums permitted samples to be taken from 14 ancient Egyptian loaves and 40 vessel residues, which were investigated by SEM to detect starch granule changes. The specimens were naturally desiccated, and therefore no special preparation was required. Several crumbs measuring about 0.1 to 1 mm in diameter from each sample were mounted on a standard aluminum stub with double-sided sticky tape, grounded with silver dag paint, and sputter-coated with about 30 nm of gold-palladium.

The microstructure of Egyptian bread loaves and beer residues, which are thousands of years old, is remarkably similar to that of modern cereal foods. The same morphological changes known from modern processing are observed in ancient starch granules. These include swollen, folded, and merged granules, undistorted starch, and pitted and channeled granules. In general,

Fig. 1. Desiccated organic residue adhering to the interior of a pottery vessel fragment. The residue (TAVR92-79) is a thin, cracked crust, with small shreds of cereal chaff (arrowheads) embedded in it. From the Workmen's village, Amarna. Scale is in millimeters.

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changes in starch granules are more pronounced and show a greater range of forms in the ancient Egyptian beer remains than in the bread.

The best explanation for these observations is that the same enzymatic and cooking processes known to affect starch today caused changes in ancient starch morphology. Other possibilities are aging, insect attack, or microbial activity. Aging can be ruled out by the large numbers of ancient starch granules that are morphologically unaltered compared to modern starch granules. Bread is sometimes heavily infested by insects, but there is virtually no sign of insect attack in beer residues. Insects therefore cannot be the cause of the pronounced morphological alterations seen in starch granules from ancient beer. Microbial alteration is more difficult to rule out because microorganisms may be present but difficult to detect visually. If microorganisms had played a role, their effects would have to have been highly inconsistent. For example, fungal hyphae often run over starch granules that show no morphological signs of swelling or enzymatic action (Fig. 2). It is therefore valid to use analogies of starch granule morphology from modern cereal foods to infer ancient Egyptian baking and brewing processes.

Starch in ancient loaves has generally not merged completely, and granule boundaries are often visible (Fig. 3). Some starch granules are unfused (Fig. 2). Air pockets are lined by swollen or distorted but distinct starch granules (Fig. 3). The lack of starch fusion is expected in a baked product, in which the water to starch ratio is relatively low. Much of the examined ancient bread microstructure is that of fairly merged starch (Figs. 3 and 4), the result of a moist rather than a dry dough. The presence of unfused starch pockets indicates incomplete mixing of the dough, suggesting that kneading was not extensive.

Some loaves contain a few starch granules that are hollow; others are deeply channeled (Fig. 4). These changes are consistent with enzyme action. Preharvest or storage sprouting is precluded by the dry climate. Deliberately germinated grain—that is, malt—must therefore have been used for some types of ancient Egyptian bread. Fermenting microorganisms such as yeast are often used by modern and past bakers. Because emmer bread is dense, it is hard to see yeast cells by means of scanning electron microscopy. Nevertheless, a few have been observed. It thus seems likely that at least these particular loaves were leavened.

As with baking, the brewing sequence has been investigated by examination of beer residue microstructure. The extreme range in starch morphology, from undistorted but pitted granules to thoroughly fused starch (Fig. 5), shows that ancient Egyptians brewed using a two-part process of coarsely ground, well-heated malt or grain and unheated malt (*13*, *14*). This technique explains well the morphology of starch in ancient Egyptian beer residues. The process does not resemble modern brewing, and the microstructural data do not match the use of lightly baked bread for brewing. Although partially cooked bread made of malt would contain unblistered, undistorted, and pitted starch granules, it would not contribute the extensive quantities of well-fused starch seen in the residues. If very moist bread had been baked long enough to create large amounts of completely merged starch, few unblistered and undistorted starch granules would remain.

The fermentation stage of brewing may be deduced on the basis of the presence or absence of yeast (Fig. 6) in different residues. Nearly all the large cereal-based contents of whole jars have no trace of yeast. Large pieces of chaff and coarse fragments of grain predominate. The microstructure is composed of morphologically unaltered starch granules, pitted and channeled but undistorted starch granules, and fused starch. This would be characteristic of a

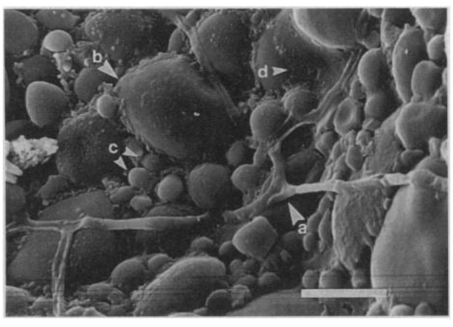

Fig. 2. Microstructure of a bread fragment (Inv. 048), with fungal hyphae (a) running over the surface of the crumb. The crumb has distinct large (b) and small (c) starch granules and traces of a protein matrix (d). The starch granules show little distortion and no sign of pitting or channeling. Surface blistering is apparent on many granules, indicative of exposure to dry heat. From an ancient Egyptian tomb loaf, Deir el-Medina. Bar, 10 μm.

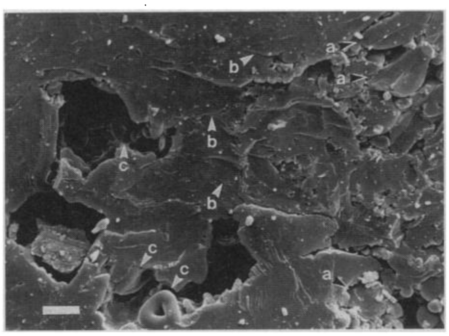

Fig. 3. A typical example of the microstructure of ancient Egyptian bread (Inv. 048). In some areas, individual starch granules are apparent (a), although much of the crumb is made up of partially fused starch that still retains the boundaries of individual starch granules (b). Air pockets are lined with distinct but distorted starch granules (c). Bar, 10 μm.

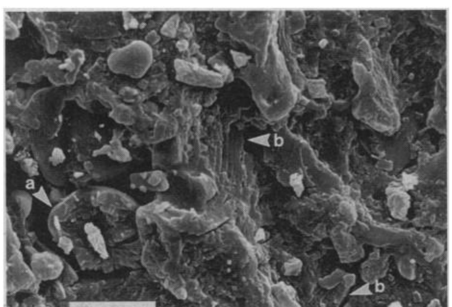

Fig. 4. Evidence for ancient Egyptian bread made from sprouted grain. The microstructure shows a hollowed starch granule (a) and channeled fragments of starch (b). From a tomb loaf, Deir el-Medina (Inv. 049). Bar, 10 μm.

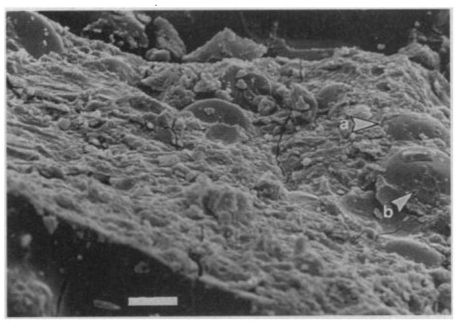

Fig. 5. Whole starch granules, some of which are pitted (a), are embedded in a mass of well-fused starch. The indentations on one starch granule (b) are caused by the tight packing of granules in the interior of the cereal grain. Their clarity indicates that this starch granule had not been exposed to distortion by heating. From residue on a pottery fragment from the Amarna Workmen's village (TAVR92-58). Bar, 10 μm.

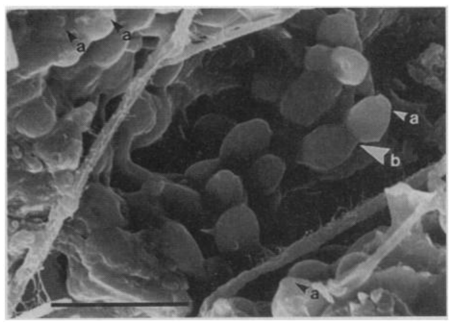

Fig. 6. Yeast cells from an ancient Egyptian brewing residue in a tomb pottery vessel, Deir el-Medina (Inv. 043). Bud scars (a) are apparent on a number of cells. Some cells (b) are in the process of budding, indicating active growth at the time of desiccation. Bar, 10 μm.

mixture of coarsely ground cooked and uncooked malt. The high proportion of chaff and lack of yeast suggest that these contents are spent grain, that is, the residues that are left after rinsing sugars, dextrins, and starch from processed malt. The large quantities of starch remaining are evidence of the relative inefficiency of the process, but such spent grains may have been re-used to make weaker beer. These findings suggest that fermentation was initiated in the rinsed sugar- and starch-rich liquid obtained after straining out the bulk of cereal husk.

The use of microscopy to investigate macro- and microstructure of desiccated foods has led to new proposals for how ancient Egyptians baked and brewed. The proposals can be tested by experiments in which ancient Egyptian food processing tools and authentic modern cereals (*9*, *21*) are used to replicate the processes described. The replicate foods are now being compared to the ancient specimens by SEM.

The implications of this research extend beyond ancient Egyptian methods of food preparation. Because starch morphology is stable over time in very dry conditions, there is great potential to analyze preparation techniques of other ancient starch-based foods from arid zones throughout the world. Although these regions contain a minority of the global archaeological record, they may serve as a model for ancient food-processing methods in regions where tools and ingredients were similar but organic preservation is much poorer. Microstructural preservation in dry areas is probably not limited to starchy foods. The unique record available from archaeological sites in arid areas provides an important opportunity to explore the development of prepared foods and evolution of food-making technologies.

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22. This work formed part of research for a Ph.D. thesis at the Department of Archaeology, University of Cambridge. It was funded by Scottish and Newcastle Breweries plc and the British Academy and supported by the Egypt Exploration Society. Sampling was carried out with permission of the Ashmolean Museum (Oxford), the British Museum (London), and the Musée du Louvre (Paris). Help was provided by P. Bolt, A. Burgess, C. Bridonneau, B. Chapman, N. Davies, W. V. Davies, P. Echlin, I. Forrest, M. Jones, B. Kemp, R. Mann, J. Merrington, M. Nesbitt, S. Quirke, R. Rose, D. Schofield, M. Serpico, and H. Whitehouse.

16 April 1996; accepted 7 June 1996

Volatiles from the 1994 Eruptions of Rabaul: Understanding Large Caldera Systems

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The 1994 eruption of Rabaul, in Papua New Guinea, involved a small plinian eruption at Vulcan and a vulcanian eruption on the opposite side of the caldera at Tavurvur. Vulcan's ash leachates indicate seawater interaction that is consistent with earlier observations of low sulfur dioxide emissions and the presence of ice crystals in the initial plinian eruption cloud. In contrast, Tavurvur ash leachates indicate no seawater interaction, and later sulfur dioxide emissions remained high despite low-level eruptive activity. Silicic melt inclusions indicate that the andesitic melt contained about 2 weight percent water and negligible carbon dioxide. Mafic melt inclusions in Tavurvur ash have water and carbon dioxide contents that vary systematically over the course of the eruption. The mafic melt inclusions suggest that a mafic dike intruded from below the silicic chamber and provide further evidence that mafic intrusions drive caldera unrest.

Measurements of volatile elements are critical to our understanding of magmatic and volcanic processes because these elements influence magma evolution and drive explosive eruptions. Large caldera systems, such as Rabaul, in Papua New Guinea, are an important class of volcanoes that are capable of many styles of eruptive behavior. The 1994 eruption of Rabaul, which followed several decades of caldera unrest, provided a unique opportunity to learn more about an active caldera's magmatic system. We measured SO_2 in the eruptive column and H_2O, CO_2, S, and Cl in the eruptive products of the 1994 eruption of Rabaul to provide a temporal record of magmatic volatile concentrations. This record defined the short-lived dynamic processes of Rabaul, which could not be directly observed and are not preserved in the geologic record.

The 1994 eruption involved two volcanoes with different eruptive behavior on opposite sides of the caldera. The initial eruption began at 6:06 a.m. on 19 September 1994 at Tavurvur and gradually gained intensity over a period of 70 min. At 7:17 a.m., the activity shifted primarily to Vulcan, where a new vent on the northern flank produced an ~18- to 20-km-high plinian eruption column and small pyroclastic flows for 70 min. Activity then shifted back to Tavurvur and continued at a much lower intensity, with discrete explosions and an eruption column that reached heights of ~6 km. At the end of September, a small lava flow was noticed in the crater of Tavurvur (*1*). Vulcan produced light tan, highly vesiculated pumice and ash (0.26 km^3) (*1*) with minor scoria. Tavurvur ash (0.04 km^3) (*1*) is dark brown with common scoria and dense glass chips.

Total ozone mapping spectrometer (TOMS) measurements during the first day of the eruption were unable to detect SO_2 in Vulcan's plinian column (*2*, *3*). The low SO_2 content of Vulcan's plinian column and abnormalities in the advanced very high resolution radiometer images of the plinian cloud were attributed to possible seawater interaction and the presence of ice crystals (*2*). On subsequent days, the TOMS detected moderate SO_2 (30 to 80 kton; Fig. 1) in a low-altitude eruption cloud near the caldera that most likely represented the output of Tavurvur. Addition-

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