3. Firing Clay, Breaking Glass, and the Past Futures of Ceramics

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Abstract

This chapter follows from the previous chapter on earthy materials to consider the entanglements of transforming clay into glass and other substances. Introduced is the concept of *operational sequence*, or the process by which affordances of both materials and societies are assembled and disassembled as things are made, used, and discarded. Contrasted with the firing of clay to produce true ceramics is the breakage of glass-like rock, such as obsidian and flint. The operational sequence for making an Ice Age spear point illustrates the contingent relationships of physical and social acts in making things, while also showcasing the evolutionary conditions under which ancestral humans developed the cognitive, motor, and social skills to achieve particular outcomes from an array of possibilities. The application of thermal energy to first stone and then clay introduced additional affordances, as well as constraints, that inform our understanding of the potential for ceramic materials of the future to enhance the means by which energy can be generated and stored at lower costs and with lesser negative impacts than conventional technologies.

3.1 Introduction

Ceramics are among the premier materials connecting the distant past with futures. From the first pottery vessels of ancient China to the bone implants and fuel cells of tomorrow, ceramics have been developed to solve human problems for over 20,000 years. With such a long history of R&D, ceramics embody many impacts of materials on society. Since their beginning, ceramic materials served social needs, such as preparing a meal to share with others or decorating a place of ritual gathering. Future applications in communications, medicine, and energy production ensure that ceramics will remain integral to human societies for generations to come. As has long been the case, innovations in ceramics arise from the novel interplay of the properties of different substances—clay, temper, water, flux—and the application of heat. But they also arise from changing relationships between producers and consumers, experts and novices, and men and women. Before we delve into these sorts of issues we might first ask, what exactly is a ceramic?

3.2. What Makes Something a Ceramic Material?

That plate in your kitchen sink and tiles on your bathroom floor are most likely ceramic. So too are the insulators of your light bulbs, components of your microelectronics, the brake linings of your car, and maybe even the crown of your tooth. The array of applications of the past and those of the future make it difficult to define ceramics in simple terms. We can agree that ceramics are inorganic and nonmetallic materials, and we might add that they are a refractory, that is, a substance resistant to heat. Ironically, it takes a great deal of heat to make a true ceramic, and some ancient ceramic vessels were designed to convey heat efficiently, as with the wet cooking of foods like corn and barley that required prolonged simmering.

To sort through the array of materials broadly classified as ceramic, it is useful to distinguish between *traditional* and *technical* or *functional* forms. Traditional ceramics include objects made from clay. A by-product of weathered rock, clay is a fine-grained material consisting of alumina silicates (more specifically hydrous aluminum phyllosilicates, or wet, sheet-like minerals) with traces of metal oxides and organic matter. To reiterate key properties of clay noted in Chapter 2: (1) the water content of clay makes it plastic, capable of being molded while still wet; (2) dried and fired clay becomes hard and brittle; and (3) most clays shrink when dried, causing cracks to form at surfaces and requiring temper to prevent cracking. The utility of clay for humans depends on how its properties are recognized and manipulated, including combing it with others substances (water, temper), and usually subjecting it to heat.

A clay can become a ceramic only if subjected to temperatures in excess of about 1,200 degrees C. The outcome is known as *vitrification*, the transformation of clay into glass. The first potters to achieve this goal lived in ancient China, under the Han Dynasty (ca. 200 BC–AD 220), whose early porcelain was not only glassy in composition but also translucent because they used white kaolin clay. Pottery making for millennia before and since the dawn of porcelain involved the production of terra cottas, earthenwares, and other forms of *subceramics*, meaning they were not vitrified in the firing process. As you read about in the previous chapter, clay could simply be sunbaked to achieve a relatively durable form for purposes such as hot-rock cooking or house construction.

Technical forms of ceramic (functional ceramics) go well beyond the vitrification of clay to include carbides, pure oxides, and nitrides, among other materials. Glass itself is a technical ceramic, and includes nonsilicate glass (e.g., chalcogenides, tellurites, gallates, germanates, heavy metal oxide glass). A naturally occurring glass known as obsidian that was used for millennia as raw material for stone tools is not usually considered a ceramic. In fact, archaeologists generally do not lump glass and ceramic together, as each has a distinct culture history.

For the purpose of this chapter, we will focus not on the physical or chemical composition of ceramics but instead on their production and use. We are most concerned here with the transformation of matter, a process that entailed the harnessing of energy, which, as we will see, also entailed hidden costs and unintended consequences for societies of all sorts.

3.3. Operational Sequences

A useful way to begin discussion of the impact of ceramic materials on society is to examine the production process. Here we mean production processes in general, not any particular one. All such processes have *operational sequences*, or simply a series of decisions and actions that lead to intended goals. We of course follow operational sequences in many of the things we do, from cooking food, to painting a room, to repairing a bicycle tire. And we all know, from experience, what happens when a sequence is enacted out of order, especially when processes have irreversible outcomes.

From a humanistic perspective, there is much more to operational sequences than the step-by-step procedure for getting something done. Doing work and making things involve the interplay between persons and matter, notably the bodily and social acts involved in production. Anthropologists often employ the concept of *chaîne opératoire* (French for operational sequence) to describe how the technical, bodily, and social acts of production are mutually dependent and collectively the basis for innovation and change. In this sense, we might say that society is made as things are made, or that production involves *entanglements* that reach deep into the fabric of society and its cultures (see Chapter 2).

In their study of artifacts, archaeologists develop models of operational sequences to characterize the production of stone and bone tools, pottery, and rock art, among other things. According to archaeologist Peter Bleed[1], such models take two general forms. Some simply describe the sequence of operations towards a predetermined goal, much like recipes in a cookbook. Others emphasize the potential for variation in sequences by looking at the dynamic interaction between conditions and variables, both technical and social. This latter approach reveals how change occurs and thus provides some basis for imagining how future innovations in ceramics and glass may impact societies. Let's take a look at possible futures by first looking back to the ancient past.

3.4. Breaking Ancestral Glass

Any variety of organic and inorganic substances were manipulated by our ancestors since the beginning of human time, but things made from stone comprise the oldest archaeological evidence for making things. Stones used for early tools were more durable than other substances humans modified, so by default stone tools archive the beginnings of human engineering. We have in the archaeological record of Africa, for instance, evidence for the making and using of flaked stone tools going back over three million years, well before the appearance of fully modern humans.[2]

To call a stone tool a *flaked* stone tool is to indicate it was made by the removal of flakes from a parent core of rock. Flakes can be removed from cores with either percussion (knocking them off) or pressure (pushing them off). Hit any hard stone with a hammer of at least equal hardness and you are liable to break something off. How the stone breaks depends on a number of things, most notably what geologists call *cleavage planes*: the planes of relative weakness in crystalline structures. Rocks differ in their type of cleavage. Halite and galena break into cubes, calcite breaks into rhomboids, others into prisms, and so on. All such tendencies for rock to fracture, or *part*, may offer technical applications for humans, but to achieve forms beyond what nature alone provides, rock lacking any predetermined breakage pattern is needed.

Worldwide, rocks that lend themselves to "unnatural" breakage consist of microcrystalline quartz (silica), such as chert, flint, jasper, agate, and chalcedony, as well as a variety of lesser materials like quartzite and rhyolite.[3] In a class unto itself is *obsidian*, a glass-like rock that forms when felsic lava (feldspar and quartz) is cooled rapidly after being spewed from a volcano. Rapid cooling minimizes crystal growth, resulting in an extremely fine-grained, isotropic rock. With the right application of force or pressure, obsidian can be flaked to produce edges sharper than the sharpest surgical scalpels.[4] Like the finest of the fine-grained silicates, obsidian can be manipulated to produce virtually any shape.

3.4.1 Sequencing the Production of a Clovis Point

So let's pick a traditional shape of stone tool and run through the operational sequence for its production. Our shape of choice is a Clovis point (Figure 3.1), a lance-shaped blade that was flaked on both sides (making it a *biface*) to achieve a thin, lenticular cross-section and then *fluted* from the base to afford its attachment to a handle or shaft. Clovis points were made in North America from about 13,200 to 12,900 years ago by hunters of mammoth, mastodon, and other Ice Age creatures.[5] Modern flintknappers (that is, persons who flake, or knap, stone) have replicated Clovis technology and attest to the high level of skill involved, particularly in removing the distinctive flutes on either face, a final, risky step in the process that is successfully executed only if all other steps are followed in proper sequence (watch Jeff Boudreau make a Clovis Point: https://www.youtube.com/watch?v=jRax_a8t4C4).

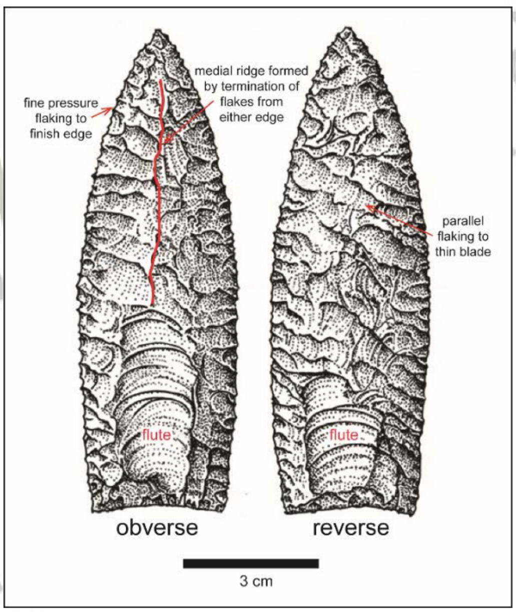

Figure 3.1. Drawing of two sides of a replicated Clovis point, showing some of the diagnostic features mentioned in the text (adapted from drawing by Melanie Diedrich of replica made by Scott Williams (http://amipbot.com/illustrations.html).

3.4.1.1 Acquire Raw Material

It goes without saying that the first step in the production of Clovis point must be the acquisition of raw material, in this case stone. But as discussed above and in the sidebar below, not any old stone will do. The technical requirements for Clovis points demand the highest-quality raw materials. North America is blessed with all sorts of quality toolstone, including obsidian, but geological sources are scattered, and some locations that were excellent for hunting and dwelling were devoid of stone. Thus, for Clovis tool makers, getting rock meant traveling to sources, either directly from places of dwelling or in the course of moving from place to place over the year. Many of the points made by Clovis hunters were displaced from the geological sources of their raw materials by hundreds of kilometers.

How Can You Tell an Actual Stone Tool from Some Old Rock?

The late-20th-century comic strip *Calvin and Hobbes* occasionally featured the efforts of its human protagonist to make big discoveries by digging into the earth. The few dirty rocks Calvin found in the strip above were treasure to him, but were they artifacts, that is, objects of human modification? In the case of flaked stone tools, the evidence for human agency is distinctive. Fine-grained rocks that are isotropic or amorphous are usually shaped by removing flakes from the surfaces that converge at edges. When force or pressure is applied perpendicular to an edge and towards the core of the rock, a fracture is initiated and then propagated radially, much like the ripples that form in a pool of water. If you exert force perpendicular to a flat surface, the resulting fracture truly is radial, in the shape of a cone. You may have seen a fracture like this in a windshield hit by a stone. But if you apply that same force to an edge you drive off a flake from one of more surfaces that is elongated, and potentially very thin. Experts in flake-stone tool manufacture (flintknappers) can manipulate the shape of the edge and angle of applied force to essentially "sculpt" the surface of a core, one flake at a time. Archaeologists are trained to recognize the attributes of controlled reduction and can therefore distinguish manufactured tools from "a few dirty rocks," as well as the by-products of manufacture, notable the many flakes that are removed in sequence to achieve a desired end. Sure, rocks occasionally break in ways that mimic human agency, as when cobbles of chert or obsidian impact other stones during a landslide, for instance. But the more steps involved in the reduction of a core the less the chance a particular fracture pattern could be mimicked by natural agents. For example, the making of Mesoamerica obsidian blades involved a carefully orchestrated operational sequence whose outputs (both products and by-products) were the distinctive mark of incredibly skilled persons. Moreover, distinctive forms of stone tools can reveal historical connections across times and places for how tools should be made, used, maintained, and even discarded and recycled. For these and many more reasons, the "treasure" archaeologists find in stone tools is the capacity they have for revealing so much about human societies of the ancient past.

3.4.1.2 Prepare Raw Material for Transport

If you have to travel far from home to get rock, you don't want to carry back useless material. Archaeologist Charlotte Beck and colleagues researched the costs of transporting rock from quarries to places of habitation and, not surprisingly, found that ancient toolmakers minimized the costs by reducing raw nodules of rock into cores of useful material.[6] The greater the distance between source and home, they found, the greater the effort to remove mass of limited value. Minimally, this entailed removing the cortex of the rock, which is not terribly conducive to flaking, as well as proturberances and other irregularities.

3.4.1.3 Prepare Core for Reduction

Once you acquire rock of acceptable quality and transport it home, it is time to shape it into a core of appropriate form and size. At this stage of reduction the primary objective is to "preform" the final product, or simply "rough it out." It will take a hammerstone or *billet* (i.e., an antler or bone hammer) to achieve this objective, along with good planning and motor skills. If the nodule of rock is large enough, a large flake can be struck from its surface and used as a preform for your Clovis point. Otherwise, the preform resides inside the nodule, in the core itself, and can be revealed only through the careful removal of multiple flakes from across the surface. This is hardly a random or haphazard process, but instead one whose successive steps are contingent on previous steps.

3.4.1.4 Shape and Thin Biface

The contingencies of core reduction become even more critical as you approach the final shape of the intended product. Like many flaked stone knives and projectiles, Clovis points are thin in cross-section—they have to be not only because an acute edge is needed to cut and pierce animal tissue, but because a thin cross-section is conducive to edge maintenance, that is, resharpening. Clovis flintknappers often used an "overshot" technique to drive flakes across the entire face of a core, a decidedly tricky move. Ultimately, however, they had to leave a ridge along the midline of each face of the tool, the location of flutes yet to come. To do this they had to terminate flakes halfway across the surface, an outcome that could be best achieved by applying pressure to the edge of the tool with an antler tip or some such implement to remove thin, narrow flakes.

3.4.1.5 Remove Flutes

Now comes the fateful moment, when the distinctive flutes of Clovis points are removed from the base of the tool on either side. Fluting will only be possible if the bifacial core has been prepared to precise tolerances. It is risky business indeed, and few modern flintknappers have mastered the technique. Experiments in percussion, pressure, and even the use of levers show that flutes can be removed in a variety of ways. Most impressive perhaps is when a flintknapper holds the biface in his or her palm and drives off a flute with the free swing of a hammer.

3.4.1.6 Finalize Edges

Now the edges have to be finalized by removing small flakes along the margins from either side. This too is done with pressure, or what is known as "pressure flaking." Holding the tool in the palm of one's hand, an antler tine is applied to the edge to remove flakes in succession, from base to tip, or tip to base. The result is an incredibly sharp edge, serrated if the tool maker desires. This same technique will be used to resharpen the tool as its edges become dull through use.

3.4.1.7 Grind Basal Margins

Now, before we can attach our finished product to a handle or shaft, its basal edges must be ground. This will prevent the edges from tearing into the materials used to bind the tool to its handle. An abrasive stone is good for this task, perhaps the same one used to prepare edges for flaking.

3.4.1.8 Affix to Handle or Shaft

Your finished product is not terribly useful without a handle (if it's a knife), or a shaft (if it's a projectile). Now that you have the basal margins ground you can fit it to a haft of some sort, but you'll need more materials and know-how. A split wooden handle will accept the fluted surface of your tool nicely, but there are other options available, some involving multiple parts. No matter the option chosen, you'll need some sort of binding material, such as sinew from a game animal, and perhaps some type of glue. Blood works well, as does pine resin. Bear in mind that you may want to remove your Clovis point when it breaks or is spent, because that handle was likely time-consuming and costly to make. Tool maintenance and replacement are foremost concerns.

3.4.2. Social Implications?

OK, we have followed an operational sequence for making a Clovis point, but so what? Could not a single individual follow this sequence alone, from beginning to end, and have a Clovis point to show for their effort? Sure, theoretically. But when we consider that Clovis points were used to dispatch mammoth and other megamammals, we understand that the *application* of these tools was inherently social: mammoth hunting was communal, a social affair, involving many persons, as was the processing and sharing of literally hundreds of pounds of meat, fat, bone marrow, hide, and other useful products.

Arguably, each step of the operational sequence for making Clovis points involved social acts too. Consider that in acquiring raw material from locations hundreds of kilometers from locations of manufacture, toolmakers crossed over land occupied by others. Alternatively, rock could have been acquired in the course of regional settlement moves, what archaeologist Lewis Binford called *embedded* procurement.[7] In that case acquisition was embedded in the movements of entire groups, not just individuals. Some archaeologists see the basis for group territories in growing dependencies people had for quality rock.

As we move on to the planned reduction of raw material into cores, the social acts involved cross generations of toolmakers in networks of learning. Flintknapping is a nuanced skill, one that is not readily assimilated without apprenticeship and mentoring. So too is knowledge of the locations of raw materials, what anthropologists call *landscape learning*. The operational sequence of flaking and the final form of the Clovis point were matters of longstanding tradition, the way things had been done for generations. Sure, innovations arose that led to regional variations in how fluted points were made and used, and over time—as Clovis disappeared as a tradition and was replaced by descendent traditions—ancient knowledge was lost to change. The upshot is that technical know-how in cultures without Google and other literary forms of information sharing was transmitted socially, from expert to novice. The process of learning was situated in the relationships people had to one another; change those relationships and you impact the content and process of learning. Likewise, changes in the content and process of learning impact the structure and function of society.

And finally, in the application of fluted points for communal hunting and food sharing, core principles of society are revealed. This is exemplified best at an archaeological site in Massachusetts, at a place called Bull Brook. From the distribution of lithic artifacts from this site, archaeologist Brian Robinson has reconstructed in detail a gathering of several dozen Paleoindian hunters and their families.[8] Family campsites were arrayed in the large circle. The raw materials for making fluted points and a variety of other stone tools came from various places across the region, signaling a gathering of communities that otherwise spent time apart from one another. They came together to hunt caribou, a migratory herd species that was targeted for communal hunts well after mammoth and mastodons went extinct. To prepare for the hunt, toolmakers crafted many fluted points. Evidently, the risky step of fluting was shared among toolmakers. They gathered in the center of the camp circle to remove flutes, presumably under the guidance of a ritual specialist, someone who knew how to minimize risk and enhance success through many years of experience. Around the perimeter of the camp circle were clusters of flaked-stone scrapers, tools used to process hides for clothing, bedding, and perhaps tent covers. Is the spatial distinction between locations of fluting and hide working indicative of a division of labor? Likely so, and most likely a division along lines of gender, given analogs with historic-era bison hunters of the Plains. Attributing particular tasks to particular genders has its pitfalls in archaeology, but such distinctions are nonetheless relevant to our understanding of the implications of materials on society, as is well illustrated in Chapter x on plastics.

3.4.3 Mind, Body, and Society in Evolutionary Terms

Our rather lengthy excursion into the operational sequence of a Clovis point can be put into long-term evolutionary perspective to understand how modern humans came to be different from other species, and how human societies were impacted by transforming matter into useful products. On the first count, the mental and physical ability to make a Clovis point was underpinned by a 3-million-year evolutionary history of human ancestry. If you know the classic film *2001: A Space Odyssey*, you will recall the initial attempts of protohumans to smash bones with hammers (Figure 3.2). Lacking a tradition for tool making and thus without knowledge of an operational sequence for achieving a particular form, the results were haphazard. Still, the connection between cause (application of force) and effect (breaking bone) was apparent to these early tool makers, and, with time—and lots of trial and error—our ancestors came to understand the process of weapons manufacture.

Figure 3.2. An ancestral human in the 1968 film *2001: A Space Odyssey* comes to realize through experimentation that the application of force through the instrument of a hammer results in bone breakage.

Captured in this gem of cinematic art is the process by which mind and body evolved in sync to produce a creature capable of not only applying energy (controlled force) to modify matter, but to also anticipate each step of an operational sequence to achieve desired outcomes. The cognitive and somatic developments behind this evolutionary history are beyond the scope of this chapter, but suffice to say that they arrived out of the interplay among planning, motor control, problem solving, knowledge transfer, and memory. But the time we get to the Clovis era—well beyond the advent of fully modern humans—the level of strategic planning is impressive, albeit hidden away in the design and use fluted points, among other tools. In this regard two aspects bear mentioning: (1) each step of the operational sequence was contingent on the prior step, and the sequence was irreversible, so the pressure was on to get it right; and (2) the costs of making a fluted point were so high that an adequate return on its investment entailed long-term maintenance and even incentives to recycle broken and work tools into other products, which was common at locations far from quarries.

Societies, like tools, were made in the process of transforming matter. Learning, sharing, cooperation and competition, territorialism, divisions of labor, gender roles, and the flows of goods, services, and personnel are all entangled in the operational sequence of making and using Clovis points. If a process can be this entangled 13,000 years ago among relatively simple, small-scale societies, imagine how much more entangled they are in complex, global-scale societies of the modern era. Conversely, perhaps we are not all that much different than these ancient toolmakers?

3.5 Harnessing Energy through Ceramics

Beyond the geothermal and geophysical energies that went into forming rock, the energy involved in making Clovis points was basically human energy: the application of controlled force through percussion, pressure, and abrasion. In certain times and places, thermal energy was used to improve the flaking qualities of siliceous rock. This apparently was not routinely done during Clovis times, when high-quality rock was used, nor was it ever the case with obsidian, which already was subject to extremely high temperature at the time of formation. Rather, thermal alteration of rock was common in the mid-Holocene of the eastern North American, roughly 8,000–5,000 years ago, when populations began to settle down into smaller territories, some of which did not include high quality toolstone. Archaeologists disagree on the physical changes that heat had on chert and flint, but the outcome was a more glass-like material, rock that behaved more like obsidian. In essence, the application of thermal energy expanded the utility of siliceous rock, making it possible for groups circumscribed in areas with low-quality sources to thrive in the age-old traditions of flaked stone technologies.

This gets us back to ceramics and the potential of ceramics to solve all sorts of human challenges. As discussed earlier, a traditional ceramic is vitrified clay, essentially clay that has been transformed into glass by heat of at least 1,200 degrees C. It takes a kiln or furnace to maintain temperatures this high; temperatures in an open-pit fire can exceed this threshold, but air circulation is such that average sustained temperatures rarely exceed 1,000 degrees C (Figure 3.3). Potters using open-pit firing could *sinter* clay into a hard, relatively durable substance without vitrifying it, with outcomes that we classify today as *subceramics*. Kilns of various design show up in several places across the globe as early as 10,000 years ago, but designs capable of vitrifying clay date to only the last 2,000 years, the earliest in China, Japan, and the Roman world. The long history of R&D from subceramics to ceramics is filled with twists and turns as potters "discovered" the latent affordances of clays, tempers, and other substances, playing off and instigating, in many cases, changes in society that inflected the demand for innovations.

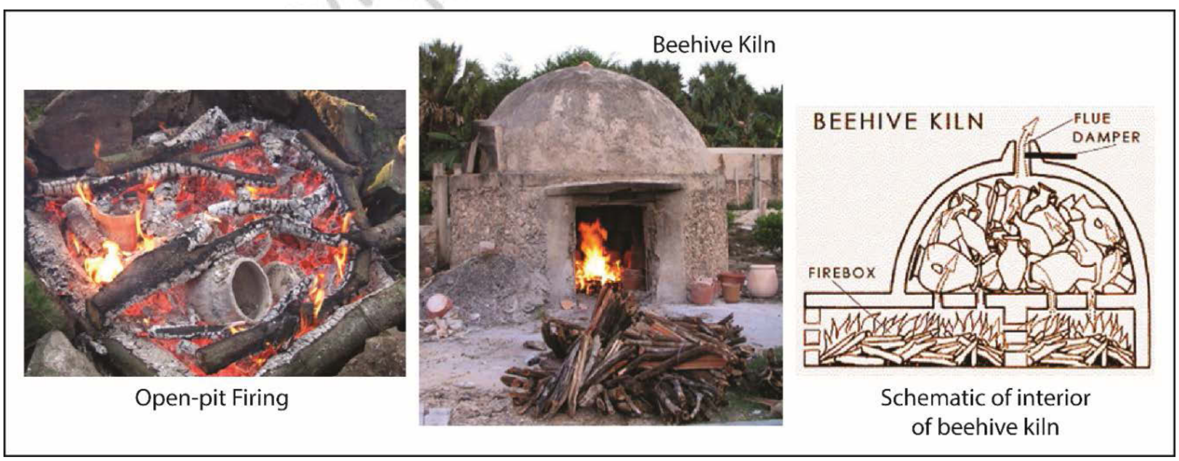

Figure 3.3 Example of open-pit firing of pottery (left; http://myhomeimprovement.org/home-remodel/pit-firing-clay), a beehive kiln (center; http://www.veniceclayartists.com/ceramics-pottery/), and a cross-section of a beehive kiln, showing the separation of a fire box from the chamber housing pottery vessels (right; http://seco.glendale.edu/~rkibler/kilns.html).

3.5.1 Pottery and Society at the Dawn of Agriculture

The entanglements of clay and society at Çatahöyük outlined in Chapter 2 were experienced under various circumstances by societies worldwide. Particularly impactful circumstances accompanied the advent of agriculture. In places where domesticated grain became the staple of agricultural economies, pottery was needed to realize its nutritional value, to render wild forms of wheat, barley, and rice palatable. Most often this entailed the process of prolonged boiling or simmering. Many such grains require 40 minutes or more of sustained boiling to absorb moisture and make them digestible. Pottery conducive to sustained boiling is tricky to make because one has to balance the need for thermal conductivity against the risk of thermal shock, plus pottery is generally a refractory, an insulator, not a great conductor of heat.

As we learned in Chapter 2, before there was pottery at Çatahöyük there were clay balls. Similar technology was used in the American Southeast about 5,000 years ago, before clay pots were invented, and even afterwards for several centuries. The first pottery in the Southeast was designed for hot rock (and clay ball) cooking, and was thus intentionally thick-walled, to insulate internal heat. Similar technology appeared in the American Midwest a millennium later, where local communities began to consume in earnest the wild versions of weedy plants with starchy seeds, one of which (*Chenopodium*) is related to the *quinoa* that is gaining popularity today as a gluten-free grain. Thick-walled subceramics were just fine for traditional, hot-rock cooking, but if wild grains were to find a foothold in the economy, and be set on the pathway to domestication, pots that could be set directly over a fire were needed, and that meant overcoming the limitations of clay's insulating qualities.

Archaeologist David Braun documented the steps Midwestern potters took to unleash the potential of early pottery for prolonged boiling.[9] New operational sequences arose, all bent towards improving the thermal conductivity of pottery while reducing the risk of thermal shock, manifested most commonly in cracked pots. Local clays were sufficient, but increasingly added to clay was fine quartz sand, a substance not only with decent thermal conductivity, but also with a coefficient of thermal expansion slightly greater than most clays, which left, after firing, microscopic voids in the fabric of the pottery walls that arrested cracks before they propagated. Thinner walls also challenged traditional forming techniques, which included simply molding clay into a vessel by hand, or assembling slabs into a vessel shape. A *coiling* technique proved effective, where walls were assembled gradually from bottom to top, like the courses of brick in a building. The walls were then compressed by paddling. The paste had to be neither too wet nor too dry to make this work. Likewise, traditional forms would no longer cut it. Jars and pots with angular bases or shoulders gave way to globular vessels whose lack of angles reduced thermal shock, and whose slightly restricted orifices minimized evaporative heat loss (Figure 3.4).

Social changes attending the rise of agriculture are legion. Communities became less mobile, tethered now to patches of land they modified and to the plants they cultivated. Populations grew as both the demand for labor rose and constraints on fertility waned. Concepts like property and inheritance emerged to foster multigenerational connections among persons, things, and land. Senses of time were altered to accommodate the delayed return on investments that come from farming and food storage. Greater divisions of labor appeared to meet the increasingly specialized demands of production and distribution.

Figure 3.4 An ideal cookpot, in this case from the Intermediate Bronze Age of the southern Levant of the Middle East (http://apd.farli.org/the-southern-levant/The-Intermediate-Bronze-Age/Intermediate-Bronze-Age-cooking-pots).

3.5.2 Intensify!

Above all, conditions were in place for what anthropologists call *intensification*, which basically means increased production, but at increased unit costs, which is ultimately unsustainable. Pottery was at the forefront of intensification, with numerous innovations addressing the growing demands of larger and more sedentary populations. Beyond the drive to process food for consumption—to literally feed more mouths—were the incentives for diverting food surpluses into bigger projects, like public works, military capacity, and institutions of government and religion. Eventually, with the rise of markets and commerce, the production of pottery, like so many other commodities, became specialized. Operational sequences not only became more complex—with the addition of more steps and more substances, like glazes and fluxes—but also segmented and distributed among different people, places, and schedules. Gender roles and relations, in some cases, were most directly affected, as in the commodification of pottery outlined in the sidebar below.

Some of the costs of intensification are hidden, leaving unsuspecting persons with the appearance that "progress" is made with every innovation that increases productive capacity. But the real question is: Does an innovation lead to greater *efficiency* in production, a *relative,* not absolute measure of benefit? Sure, more pottery can be produced through specialized processes such as wheel throwing and kiln firing, but at what unit cost?

SIDEBAR: Changing Gender Relations and the Commodification of Pottery

Visit Acoma Pueblo in New Mexico and you can buy a traditional, coil-made pot from one of the elder women. It'll cost you, but it'll be worth it. Or, you could spend a lot less money on a knock-off. At Acoma, younger potters, many of which are men, offer for sale pots that were molded, not coiled. It is not easy to tell the difference, beyond the price, that is. What is remarkable from an anthropological standpoint is how the commercialization of pottery has changed gender relations. Worldwide, in societies were pottery was made exclusively for domestic use, women were almost always the potters. Men may have helped with clay mining or finding temper, but women formed, fired, and used vessels nearly to the exclusion of men. Commercialization changed that, not only at Acoma Pueblo, but worldwide, as market economies transformed ancient ways of life.

Changing gender roles in pottery making did not have to await the arrival of capitalist markets. Consider the case of Lapita pottery from Polynesia. The presumed ancestors of many Pacific cultures, people of Lapita culture began to migrate eastward across the Pacific Ocean at about 1500 B.C., reaching Tonga and Samoa by about 1000 B.C. They were consummate seafaring people, colonizing islands separated by hundreds of miles of open water. Their pottery was a distinctive ware, decorated with repeating geometric patterns of dentate stamping. Anthropologist Yvonne Marshall believes that pots were made exclusively by women in traditional Lapita communities.[10] However, over time men got involved. Why? For Marshall, the answer traces of trade and ceremonialism. As the Lapita world expanded across the Pacific, networks of exchange between islands arose to feed a growing political economy. Ocean-going trade and its associated rituals were the purview of men, mostly, but they incorporated the labor and products of women, namely pots. Increasingly, pottery production became geared towards nondomestic uses, with the more elaborate vessels funneled into exchanges controlled by men. Among some communities, men may have usurped production, as well as distribution. Eventually, intensification of production broke down, ornate decoration disappeared, and other materials supplanted pottery as a medium of ritual and exchange. Throughout this period of change, plain pottery continued to be made by local communities (presumably women) for domestic uses.

The Lapita case goes to show that any inducement to manufacture products beyond the level of domestic consumption introduces challenges to traditional operational sequences and their underlying social relationships. In this case, the expanding nondomestic "market" fueled demand for high-quality pots, while in the Acoma case it allowed for the development of cheap knock-offs. Despite the differences, both cases involved changes in gender roles and relations, reminding us of the impact that changing operational sequences can have on fundamental social dimensions.

Taking the long view on the history of traditional ceramics, many innovations effectively met short-term goals, but they also introduced unintended consequences and thus new problems. The first kilns helped to concentrate heat, but they had higher construction costs and required more specialized fuels than open-pit fires (kilns required hardwood and other slow-burning fuels to attain and maintain temperatures in excess of 1,200 degrees C). These costs were potentially offset by the longer use-lives of pots (if used in thermal applications, like cooking), but that would have dampened demand for new pots and thus thwarted the investment return of expensive infrastructure, notably the kiln itself. Over time innovations in kiln technology appeared—such as the Chinese climbing kiln (Figure 3.5), which optimized conduction—in some cases to address production demand, in others to decrease fuel costs. Clearly a major limit to production expansion for technologies involving enormous thermal energy was fuel. Until coal was introduced in the 19th-century Japanese ceramics industry, fuel consisted of wood or dung. Potting industries worldwide have contributed to local deforestation, and ultimately demand for more efficient kilns and alternative fuels, like coal and gas.

Unforeseen consequences beset the health of potters too, along with those who used their wares. Like their counterparts who manufactured gun flints centuries ago and unwittingly inhaled microscopic quartz, potters working with finely ground sand were prone to silicosis, a deadly lung disease. Likewise, British potters steeped in the tradition of lead glazing that fueled a worldwide demand for European tablewares routinely suffered from lead poisoning. Add to this the collateral damage of lead exposure by consumers using pottery to process, store, and consume food. The lead threat continues today, showing how the production of something so traditional invites social interventions over labor rights, public health, and fair trade. Intensification always has its costs, direct and indirect.

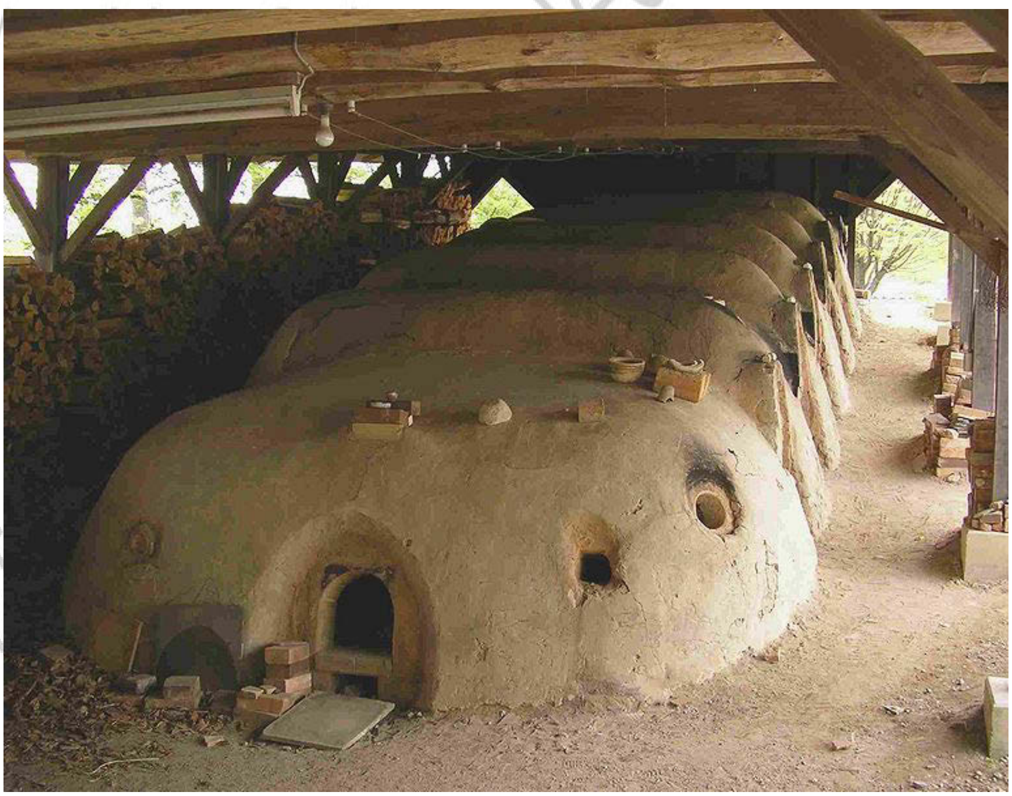

Figure 3.5 Chinese climbing kilns like the one shown here date back as early as 5th century A.D. (http://www.lowtechmagazine.com/2009/10/hoffmann-kilns-brick-and-tile-production.html)

3.6 Generating and Storing Energy

In our examples of flaked stone and pottery, matter was transformed through the application of mechanical energy, mostly controlled human force. In the case of flaked stone, force and know-how was used to reduce rock from larger to smaller sizes and from amorphous to formalized shapes. In the case of pottery, force and know-how was used to assemble a variety of substances and manipulate their respective properties to form various things, finish their surfaces, and harden them with fire. This last step goes beyond human force to involve thermal energy. Applied to either rock or clay, heat altered the physical properties of substances in ways useful to people. It may seem ironic that efforts to make rock more like glass were aimed at making its breakage more predictable, while efforts to make clay more glass-like were to lessen the risk of breakage while increasing thermal conductivity.

3.6.1 Ceramic Fuel Cells

Is it ironic or poetic that glass-like substances offer affordances by alternately breaking them and not breaking them? Take this to the microscopic level of transformation and we begin to understand that putting things together and taking them apart are two sides of the same coin. That is, at the level of physiochemical change—as in the process of vitrification—energy is absorbed, stored, and released in microcosmic versions of operational sequences. Change the conditions under which these transfers of energy occur and you can produce different outcomes, create different products.

Ceramic fuel cells are among the more promising products that increase the efficiency of energy production and storage. Consider their application in domestic uses of energy. When electricity is produced at a centralized power plant and distributed to homes via a grid, the electricity has to be used quickly to maintain efficient use. However, a fuel cell that uses natural gas, for instance, produces power as it is needed, locally, in the home or is a refrigeration truck. It does this by using a solid oxide membrane to transport oxygen ions from one side of the fuel cell to the other. When these oxygen ions react with fuel such as hydrogen or carbon monoxide electrons are released and one produces a current.

Two limitations of solid oxide fuel cells must be overcome before this technology gains a better foothold in the competition for energy production. These cells can be extremely efficient at producing electricity however they must operate at high temperatures in order to help with the production and transport of the oxygen ions. So the search continues for better solid oxide membrane materials to help reduce this operating temperature.

The second limitation is that fossil fuels are still involved in the process. Sure, they are not being combusted like they are in a conventional generator, but we still have the costs and impacts of extraction to deal with. What if, instead, fuel that is used to generate electricity could be generated from another source, say, the sun. Obviously, solar energy has been converted to electricity for decades now, and we all know the limitations of this technology, especially in places on the earth and at times of the year where sunlight is limited. In addition, storage of solar energy is a major limitation as it is much less efficient than the chemical storage of energy in the refined fossil fuels on which much of our energy-making infrastructure is based.

A promising innovation is the use of a ceramic substance, cerium dioxide, to convert solar energy into methane. The promise is nicely summarized in a short lecture by California Institute of Technology Professor Sossina Haile (https://www.youtube.com/watch?v=gSIsc7xBX3A). In this lecture, Professor Haile notes that conventional solar panels use only a portion of the spectrum of sunlight and thus fall short of their full potential for energy production. If we can capture and concentrate all the light, much like we do with a magnifying glass, we can take advantage of the full spectrum and produce lots of heat, which then can be used to drive the chemistry of fuel production. The "magic" of cerium dioxide, as Professor Haile sees it, is that is can quickly "breath" oxygen at high temperatures. With nothing more than water, carbon dioxide, and solar heat, methane can be produced from the repetitive cycles of heating and cooling the ceramic surface. Not only is this sustainable from the standpoint of fuel production, but it helps to remove one the greenhouse gases that is generated from combustion of fossil fuels.

3.7 Conclusion

Revealed in operational sequences are the sorts of entanglements between materials and society you read about in Chapter 2. In a sense, operational sequences offer method for analyzing entanglements, so long as we allow that sequences involve bodily and social acts, not just technical steps. And this is no cookbook method any more than any operational sequence is merely technical steps in a production process. The broader historical, social, and cultural contexts of any process, at any point in time, is more than backdrop, but rather rationale, precedent, contradiction, aesthetic, creativity, and more.

We saw how the making of a Clovis point was entangled with the social structure of communal hunting, and how innovations in cooking pots were bound up in the emergence and growth of farming, and how the next generation of ceramic fuel cells are constrained by an existing infrastructure in chemical fuels, but capable of decentralizing locations of production and thus making households more self-sufficient. The intrinsic value of the analysis of operational sequences is insight on change that inheres in the potential relationships between materials and society. In the cases described here, heat was a common medium for changing relationships between people and things. In all cases heat enhanced or revealed affordances that were latent to the materials being manipulated by people. But the source of heat for realizing innovation had its limits and its hidden costs, as in the higher fuel costs of kiln firing or the environmental impacts of fossil fuel combustion. With such a long history of R&D, ceramic materials of the future will continue to offer alternatives to existing technologies. And with a history of impacting societies for millennia, the production and use of ceramic materials provide ample lessons for avoiding failures and enhancing successes.

3.8 Key Terms to Learn

Ceramic, cleavage plane, coiling, flaked stone, fluting, kiln, intensification, isotropic, operational sequence, subceramic, vitrification

3.9 For Further Reading

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3.10 Endnotes

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