Physical Characteristics of Mammoth Ivory and their Implications for Ivory Work in the Upper Paleolithic

Claire Heckel
Department of Anthropology
New York University
ceheckel@gmail.com

Abstract: *Mammoth ivory was a significant raw material for the production of representational objects and personal ornaments in the early Upper Paleolithic. Archaeological approaches to these objects are enriched by an improved understanding of the relationship between the physical characteristics of ivory and its properties as a raw material. Drawing on physical science research, experimental archaeology, and microscopic analysis, this article offers a synthesis of quantitative and qualitative research and observations on the nature of ivory as a unique natural material. These observations are then applied to the subject of ivory work in the Upper Paleolithic, and the relationship between material exigency and cultural choice in prehistoric production processes is explored.*
Keywords: *Swabian Jura, Southwestern France, Aurignacian, ivory working, personal ornaments, art objects, experimental archaeology*

Die Materialeigenschaften von Mammutelfenbein und ihre Bedeutung für die Elfenbeinbearbeitung im Jungpaläolithikum

Zusammenfassung: Mammutelfenbein ist ein bedeutendes Rohmaterial, das im Jungpaläolithikum in besonderer Weise zur Herstellung bedeutender Objekte wie Schmuck und Kunstgegenstände verwendet wurde. Man schätzte die besonderen Materialeigenschaften wie Dichte und Feinkörnigkeit und den Glanz, den man auf der Oberfläche durch Polieren erzeugen konnte. Besonders das Aurignacien der Schwäbischen Alb zeichnet sich durch eine ungeheure Fülle an Gegenständen aus Elfenbein aus, und auch in vielen aurignacienzeitlichen Fundstellen in Südwestfrankreich ist eine Vielfalt an Elfenbeinobjekten sichtbar. Die Elfenbeinbearbeitung im Paläolithikum beschränkt sich weder auf das Aurignacien noch auf West- und Mitteleuropa, doch um der Gefahr zu entgehen, nennenswerte kulturelle, zeitliche oder geographische Unterschiede in der Elfenbeinbearbeitung zu vermischen und dadurch eine direkte Vergleichbarkeit zu verhindern, konzentriert sich der Beitrag auf die frühesten bekannten Belege für Elfenbeinbearbeitung im Aurignacien der Schwäbischen Alb und Südwestfrankreichs.
Um den Rohstoff Elfenbein aus einer archäologischen Perspektive heraus zu verstehen, bedarf es eines zweigeteilten Ansatzes. Zunächst muss das Material aus einer wissenschaftlich-technischen Sicht betrachtet werden. Dies ist notwendig, um zu verstehen, wie seine chemischen und strukturellen Eigenschaften die Materialeigenschaften als Ganzes beeinflussen und um von daher wiederum die Informationsmenge zu vergrößern, die wir den Elfenbeingegenständen aus archäologsichen Zusammenhängen entnehmen können. Um diese eher technischen Erkenntnisse für archäologische Zwecke nutzbar zu machen, ist es aber in gleicher Weise notwendig, Elfenbein auf einer praktischen und ästhetischen Ebene zu begreifen. Man muss wissen, wie Elfenbein aussieht, wie es sich anfühlt und wie es auf verschiedene Bearbeitungsmethoden reagiert. Im Anschluss an die eher theoretischen Grundlagen zum Verständnis des Werkstoffes Elfenbein werden im Beitrag ausführlich eigene Bearbeitungsexperimente präsentiert.
Für die Experimente wurde ein zylindrisches Stoßzahnfragment verwendet, das in den 1920er Jahren im Permafrost in Alaska geborgen wurde und das ein Alter von etwa 28.000 Jahren hat. Ein erster Arbeitsschritt bestand darin, ein für die Herstellung eines figürlichen Elfenbeinobjektes von der Größe her geeignetes Stück Elfenbein zu gewinnen. Indirekter Schlag mit einem meißelartigen Zwischenstück erwies sich als ungeeignet. Erst mit etwa einem Dutzend wiederholter, harter direkter Schläge mit einem Schlagstein gelang es, ein Bruchstück von der Seite des Stoßzahnfragmentes abzutrennen. Da es für den vorgesehenen Zweck noch zu groß war, musste es in einem weitern Schritt weiter zerteilt werden. Dies gelang erst unter Verwendung eines steinernen Ambosses sowie eines Schlagsteines. Schließlich lag ein für die Herstellung einer Elfenbeinfigur geeignetes Stück vor. Bei der eigentlichen Schnitzarbeit zeigte sich, dass es selbst mit scharfen, kräftigen Klingen nicht gelang, bei trockenem Elfenbein mehr als feinen Staub von der Oberfläche abzuschaben. Erst bei wiederholtem Wässern der Oberfläche gelang es, nen-

nenswerte Späne abzuheben. Mehrfaches Wässern und Trocknen führte allerdings dazu, dass natürliche Risse im Elfenbein sich weiteten. Dieser Effekt ließ sich durch die Zugabe einer fetthaltigen Substanz, im konkreten Fall Olivenöl, minimieren. Bei der weiteren Vorbereitung des Rohlings wurden verschiedene Techniken angewandt: Schnitzen und Schaben mit Steinklingen und Abschlagen kleiner unerwünschter Vorsprünge mit dem Ende einer besonders kräftigen Klinge. Die Oberfläche wurde mit einem Kalksteinstück vorgeglättet. Anschließend konnte die eigentliche Herausformung der Figurine beginnen, die grob dem Mammut aus den Nachgrabungen am Vogelherd nachempfunden ist. Das Schnitzen mit ungeschäfteten Steinwerkzeugen erwies sich als sehr mühselig und zeitaufwändig, da der nötige Druck die Hände sehr stark belastete. Während des gesamten Formungsprozesses wurde die Oberfläche des Stückes immer wieder mikroskopisch untersucht und fotografiert, um die bei den verschiedenen Arbeitsgängen entstandenen Arbeitsspuren zu dokumentieren. Abgeschlossen wurde der Herstellungsprozess durch Polieren der Oberfläche mit einem mit feuchtem Hämatitpulver getränkten Stück Tierhaut.
Die Beobachtungen und Erkenntnisse, die bei der experimentellen Herstellung einer Elfenbeinfigur gewonnen wurden, werden schließlich mit den aus den archäologischen Funden erschließbaren Hinweisen zur Elfenbeinbearbeitung im Paläolithikum verglichen, und es wird die Beziehung zwischen Materialanforderungen und kulturell bedingten Rohmaterialpräferenzen im Paläolithikum untersucht.
Schlagwörter: Schwäbische Alb, Südwestfrankreich, Aurignacien, Elfenbeinbearbeitung, Schmuck, Kunstgegenstände, Experimentelle Archäologie

Introduction

Ivory is an osseous raw material widely recognized for its fine qualities: density, fineness of grain, potential luster when polished, weight, and warmth of texture. In the early Upper Paleolithic of Western Europe, we find the first examples of an appreciation for ivory as a raw material in the production of symbolic and/or representational objects. Artifacts of mammoth ivory abound in Aurignacian deposits in the Swabian Jura of Germany (at sites such as Vogelherd, Hohlenstein-Stadel, Geißenklösterle and Hohle Fels). These objects include small, uniform beads in several forms, as well as zoomorphic and anthropomorphic figurines and pendants. Sites in southwestern France (including Abri Castanet, Abri Blanchard, Isturitz and Brassempouy) have collectively yielded nearly two thousand uniform "basket-shaped" beads in Aurignacian contexts as well as other small pendants in ivory. Upper Paleolithic ivory work is certainly not limited to the early Aurignacian or to Western Europe: impressive ivory artifacts have been found in later Upper Paleolithic contexts in these regions and in Upper Paleolithic deposits in Eastern Europe and Eurasia. To avoid collapsing significant cultural, temporal, and geographic differences in ivory use, however, the present discussion is limited to the earliest known ivory work, which occurs in the Aurignacian of southwestern France and Germany.

Ivory's appeal as a raw material is often attributed to its aesthetic qualities and its unique properties as a medium for carving and sculpting. These qualities were evidently valued in some way by early Upper Paleolithic peoples, as there is a clear preference shown for ivory over other osseous materials in the production of Aurignacian beads, ornaments, and figurines (White 1993, 1997). This preference for ivory is not evident in the production of tools and utilitarian objects, which are rarely found in ivory in these contexts. Precisely how ivory was valued in Paleolithic societies may never be known, as the cultural and aesthetic values of Paleolithic societies cannot be divined from the archaeological record. For example, the early peoples of the Swabian Jura who encountered woolly mammoths in their landscapes probably had a different understanding of and approach to the material than did the early peoples of southwestern France, who inhabited an ecosystem that no longer supported populations of mammoths.

Nonetheless, people in both regions began to produce ivory objects of a symbolic and ornamental nature shortly after their documented arrivals in their respective landscapes.

Understanding ivory from an archaeological perspective requires a twofold approach. It is necessary to approach the material from a scientific perspective: to understand how its chemical and structural properties contribute to its overall material properties, and to maximize the amount of information that can be derived from ivory recovered from the archaeological record. In order to properly contextualize this scientific information for archaeological purposes, it is equally important to understand ivory on an experiential and aesthetic level: to know how ivory looks, feels, and responds to different production processes. The synthesis of these approaches has shaped my own attempts to explore and clarify those qualities of ivory that are significant to its use as a raw material in the Upper Paleolithic. To this end, I have engaged in the experimental fracture and sculpture of mammoth ivory and subsequent microscopic analyses, combined with interdisciplinary research on physical scientific literature relevant to the study of ivory in Paleolithic archaeological contexts. Here, I present some initial findings and observations that the synthesis of these studies has yielded, as well as some implications for the study of ivory work in the early Upper Paleolithic of Western Europe.

Scientific Foundations

The term ”ivory” is frequently employed to refer to many animal dental materials of commercial value. This broad use of the term masks significant differences between true ivory and other ”ivories” (Saunders 1979; Trapani and Fisher 2003). True ivory occurs only in the form of proboscidean tusks: the enlarged, ever-growing incisors of extant elephants and their extinct relatives such as mammoths and mastodonts. The distinction between true ivory and other ”ivories” is not simply a matter of semantics. The differences in chemistry and internal architecture that distinguish true ivory from other dental materials are the sources of its singularity as a raw material. The sheer size of mammoth tusks required a remarkable structural composition in order to bear the weight of the material itself and to resist the various impacts and stresses to which the tusks might have been subjected during an animal’s lifetime. Mammoth tusks have been known to reach a length of up to four meters and a weight of up to 400 kilograms for a single tusk (Saunders 1979). Such size and weight in dental material is unparalleled in the Pleistocene, and the structure of mammoth tusks is accordingly unique.

The chemical and structural composition of mammoth ivory is quite complex (Locke 2008; Heckel 2009) and a detailed discussion exceeds the scope of this article. In materials science terms, ivory is a rigid biological composite, which means that it is composed of a rigid matrix reinforced by elastic fibers (Roylance 2000-2001). The rigid matrix material of ivory is, generally speaking, a crystalline lattice of hydroxyapatite. Hydroxyapatite is a calcium phosphate and is the primary inorganic component of most mammalian osseous materials. Discontinuous collagen fibers reinforce the inorganic matrix and lend elasticity to the material. It is this combination of rigid and elastic materials that lends biological composites the necessary material properties of both components. Ivory is especially known for its combined strength and elasticity: ”The most outstanding and most unique attribute of ivory is its *elasticity* – its ability to bend under force and rebound, often resoundingly, when that force is removed. It is this single property that has so wonderfully suited tusks for a great variety of uses" (Saunders 1979, 57). It is the relative qualitative characteristic of elasticity that is referenced here, rather than elasticity in the more strictly-defined sense applied in physics and materials science (Heckel 2009).

Ivory's strength and resilience exceeds that of many other rigid biological composites because of its unique structure. Locke (2008) has aptly described the internal structure of ivory as a "complex three-dimensional architecture." This description adequately captures the system of interlocking structural features that lend the material its notable tenacity. Structural formations on the macroscopic and microscopic levels interweave on multiple planes (transverse, radial, and axial) to reinforce the tusk (Locke 2008; Heckel 2009). The most clearly visible manifestation of this complex architecture is the Schreger pattern, visible to the unaided eye in transverse sections of the tusk (Fig. 1). The Schreger pattern is unique to proboscidean tusks, and the angles of the pattern differ among proboscidean taxa to the extent that one can often distinguish between mammoth, mastodont and modern elephant tusks on its basis alone (Espinoza and Mann 1993; Trapani and Fisher 2003).

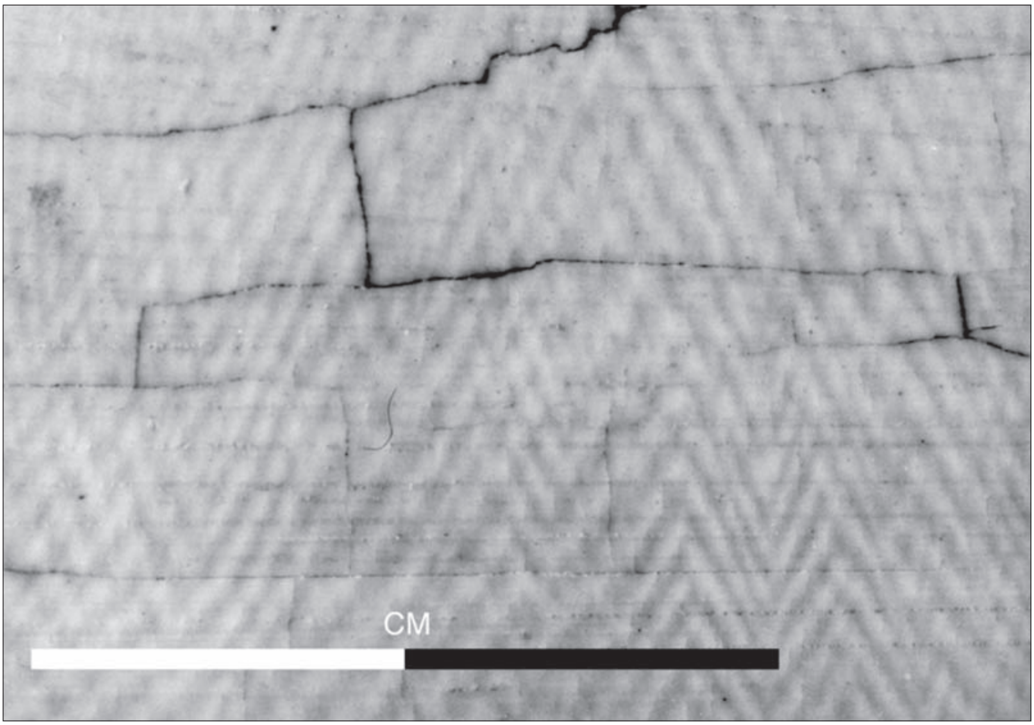

Fig. 1: *This image of the cross section of the mammoth tusk used in experimental carving research at New York University illustrates the interlocking structural features of ivory. Horizontal lines visible are the Lines of Owen, or growth rings. Vertical cracks represent separation along the radial microlaminae. Cross-cutting both of these features is the Schreger pattern, visible as interlocking diagonal lines. Photo: R. White.*

While the complex internal architecture of ivory makes it a remarkably strong material, its unique composition and structure also lend it other qualities that make it an ideal medium for carving and sculpting. A proboscidean tusk is composed nearly entirely of dentine, coated with a thin layer of cementum. The tip of the tusk is coated with enamel, but this coating usually wears away within the first five years of the tusk-bearer's life (Fig. 2). The material significance of this composition lies in the relative softness of

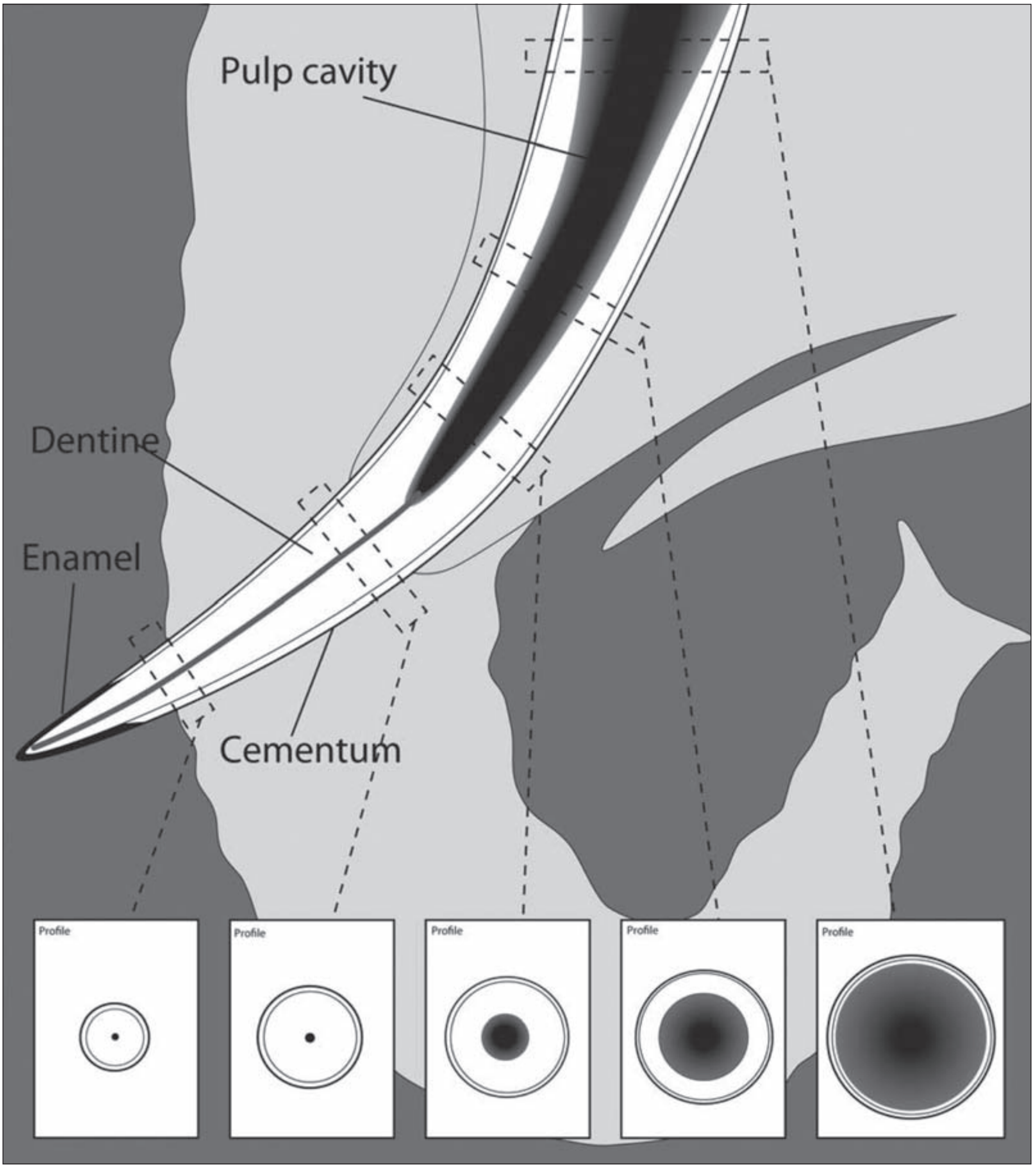

Fig. 2: *Diagram of tusk morphology indicating pulp cavity, dentine, cementum, and enamel as well as cross sectional images at various points on the tusk. Illustration: R. White.*

dentine when compared with other dental materials. Dentine is seventy percent rigid inorganic material, ten percent water, and fifteen to twenty percent collagen and lipids. In contrast, enamel is ninety-five percent rigid inorganic material, which renders it strong but quite brittle. Because they are large and composed almost entirely of dentine, mammoth tusks present large bodies of relatively soft dental material ideal for sculpting. The lustrous polish that one can achieve on ivory surfaces mimics the brilliance of more brittle surfaces like tooth enamel and shell. White (1993, 1997) has suggested that the use of ivory in the Paleolithic was in part an effort to achieve lustrous tactile and visual properties.

The dentine that composes a proboscidean tusk is chemically and structurally unique when compared to other types of dentine, including the dentine that composes proboscidean molars. About ten percent of the calcium in the hydroxyapatite that forms tusk dentine has been replaced by magnesium (Su and Cui 1997, 1198). Paleolithic archaeological applications for the magnesium content of mammoth ivory have been explored in some detail by Christensen (1995, 1999; also Christensen et al. 1992). The hydroxyapatite crystals in ivory are also smaller than those found in other types of dentine (Su and Cui 1997, 1198). Ivory is often described as a finer or denser material than bone or other teeth, and the fine nature of the hydroxyapatite matrix lends scientific support to these observations. A further reason for ivory's material fineness lies in the nature of its formation and formational infrastructure. In all teeth, dentine is laid down by dentinal tubules, which in tusks run from the tusk axis to the external surface of the dentine (known as the dentine-cementum junction). In true ivory, the dentinal tubules are smaller and more closely packed than in other types of dentine (Saunders 1979), which again renders it finer in texture.

Scientific observations of the sort summarized here support the aesthetic observations often made about ivory and are of great importance to the study of ivory in archaeological contexts. In order to better understand the role of mammoth ivory in Paleolithic societies, however, it is essential to build experiential knowledge upon a scientific foundation. To know that ivory is a rigid biological composite and that its microstructure is the source of many of its material properties is significant to us as academics, but it was assuredly not an awareness of this sort of information that drew Paleolithic people to ivory as a medium for sculpture and ornamentation. While experimental archaeology cannot reveal the entire cultural context of ivory work in the Paleolithic, it does offer significant insights of a more tacit and experiential nature.

Having offered an overview of the science behind ivory's unique material characteristics, I turn now to the more personal insights I have gained through experimental ivory work.

Qualitative Experience

In scientific discussions of ivory as a Paleolithic raw material, an important aspect of the archaeological record often disappears. A focus on materials and finished products obscures the human creative acts that produced these objects. Behind every bead and figurine recovered from Aurignacian deposits is a deliberate action informed by culture, cognition, and material exigency. Ivory's material characteristics present both possibilities and limitations, and it is only by working ivory with the tools and techniques indicated in the archaeological record that one can truly appreciate the relationship between material and creative process. I have engaged in experiments in the fracture of mammoth ivory by direct percussion and in the sculpting of mammoth ivory with stone tools common in the Aurignacian.

White's (1995, 1997) work on the reconstruction of production processes for ivory ornaments in the early Upper Paleolithic offers both theoretical and practical foundations for the research presented here. On a theoretical level, I follow White (1997, 94) in situating production processes and manufacturing techniques within Leroi-Gourhan's *chaîne opératoire* as active "constituents of culture" rather than as passive byproducts of material processes. Likewise, I more broadly frame the study of Paleolithic production processes as "an integration of technology and social dynamics through which we might gain access to the culturally-embedded technological production sequences from which socially meaningful decorative styles emerge" (White 1995, 30). Essential to this approach to material culture is the recognition that a Western art-historical approach to meaning in prehistory impedes an archaeologically-grounded, anthropological understanding of the social function of representative forms in the Paleolithic (Conkey 1985, 1993; White 1992, 1995, 1997, 2000).

Following Mills (1957), White (2000) has adopted the concept of the "controlled qualitative experience" as a descriptor for human interactions with representational forms. This term captures the qualitative and experiential nature of the production and use of representational objects, but recognizes as well the significant cultural mediation of these experiences. Understandings of form and function, material and meaning, structure and suggestion, and the complex ways in which these phenomena interact are both neurologically-based and culturally-informed.

Some aspects of this experience (the sensation of a polished ivory surface or of a tool incising that surface) may be seen as more immediate and visceral experiences that I might share with people of many cultural and temporal contexts. Others (the nature of the creative act, mental associations with color or material) may be more culturally mediated and fundamentally different. With regard to my own experiences and those of prehistoric peoples, the extent to which qualitative experiences overlap or diverge is a mystery. In approaches to representational artifacts in the deep human past, it is essential to be mindful of the potential for both similarity and difference in individual experiences and conceptions of production, representation, and meaning. My own experiments with ivory have been an attempt to build a personal qualitative experience of the material that might serve as a foundation for the scientific study of objects made of ivory: to establish what Lorblanchet (1995) has evocatively called a "dialogue" with the medium.

On a practical level, White's experimentation with ivory offers some foundations for the experimental working of ivory. In my initial approach to the material, I was able to take as parameters some significant findings on the fracture and sculpture of ivory in the early Upper Paleolithic. For instance, there is no evidence in the archaeological record for the "groove and splinter" technique of ivory blank removal in the Aurignacian (White 1995, 36). Rather, techniques of percussion and splitting seem to have exploited the natural fissures presented by the partial delamination of sub-fossil ivory. While fresh mammoth ivory is clearly unavailable for experimental use today, White (1995, 1997) has securely established that working fresh ivory in the Aurignacian was highly unlikely, if not impossible. Experiments conducted at New York University have also demonstrated the utility of water and powdered hematite in abrading and polishing ivory, a claim that is substantiated by the frequent observation of ochre particles in the polishing striae on Aurignacian ivory beads from southwestern France (White 1995, 37).

In the experiment presented here, I have built upon previous findings to the exclusion of techniques deemed either ineffective or absent in the Aurignacian of Western Europe. I set out to produce a small zoomorphic figurine in mammoth ivory similar to those recovered from sites in the Lone and Ach Valleys in Swabia (Fig. 3). Rather than attempt to faithfully reproduce a specific figurine, the goal of this experiment was to explore the process of working ivory with stone tools, including the manner in which the material might dictate or influence form. This process included disengaging a piece of ivory of workable size from a larger tusk segment, shaping this piece into a blank suitable for sculpting, shaping the blank into a rough zoomorphic form, and polishing the figurine surface. In this section, I will present an account of the sculpting process illustrated with photographs and microphotographs.

Fig. 3: *Mammoth figurine from Vogelherd cave, Swabian Jura. Aurignacian, ca. 30-35,000 BP. Photo: H. Jensen. © Eberhard Karls Universität Tübingen.*

My experiments in ivory work took place at the Paleolithic Archaeology Research Facility, part of the Center for the Study of Human Origins at New York University. This facility presents a wealth of resources for experiments in Paleolithic technologies: ivory, antler, bone, hide, soapstone, flint and other stone tools, and powdered red and yellow hematite. Having such materials at hand is essential to the trial-and-error processes of experimental archaeology. One often approaches such experiments with an idea of how the process will play out, but as I and many of my colleagues have discovered, this initial plan rarely works out. Recourse to a variety of tools and materials is often necessary.

The mammoth ivory used in these experiments was taken from a cylindrical tusk segment with an estimated age of 28,000 years, recovered from Alaskan permafrost in the 1920s. The tusk segment was deaccessioned to the care of Randall White at New York University by the American Museum of Natural History. Each end had been cleanly cut with modern tools, presenting neat cross sections at the distal and proximal ends. As was discussed previously, the tusk had begun to delaminate, creating deep fissures in the material along the circumferential Lines of Owen, as well as radially (Fig. 4).

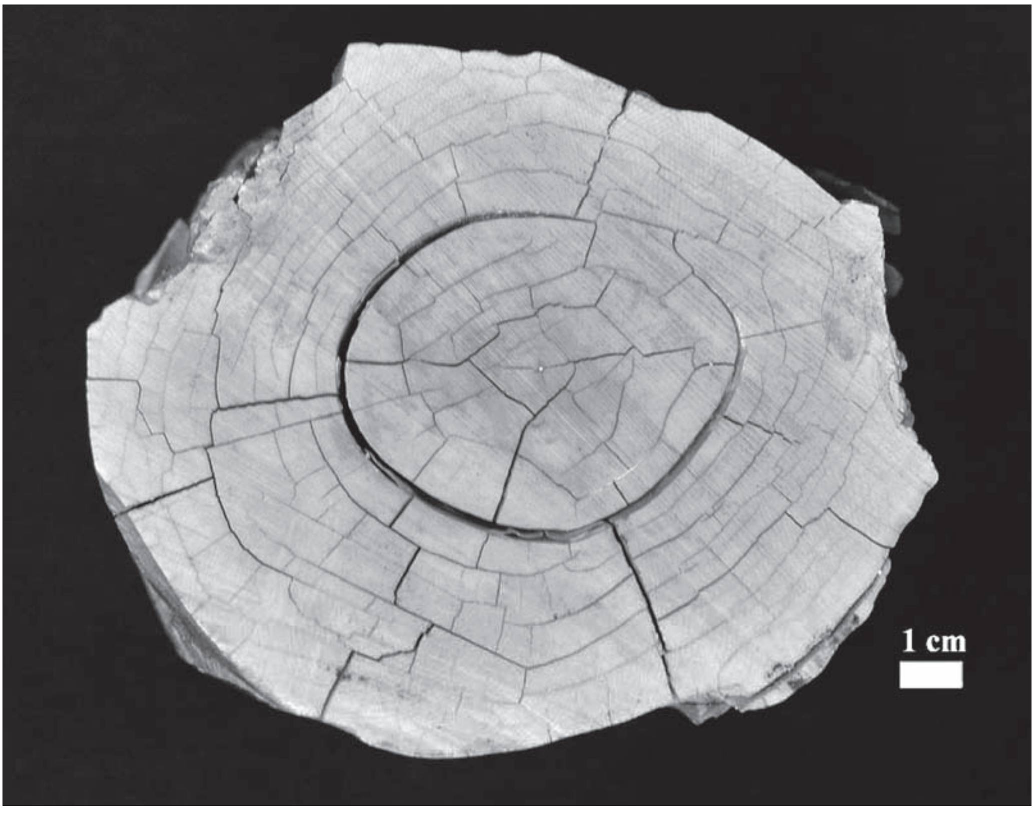

Fig. 4: *Cross section of the proximal end of the mammoth tusk used in the experimental research discussed in this article. This image clearly shows the delamination of a tusk that occurs along several planes with age and desiccation. Adapted from R. White. Visible lines running from top left to bottom right are tool traces from the modern blade used to section the tusk.*

The first step in the experimental process was to disengage a fragment of ivory of suitable size for carving a small figurine. As I was limited to the tools and techniques available during the Aurignacian, this in itself proved to be a challenging undertaking. Even after 28,000 years, the structural integrity of well-preserved mammoth ivory is remarkable, but delamination presents some points of entry for the removal of workable material. These networks of fracture caused by delamination present points of weakness that can be exploited through techniques documented in the Aurignacian such as direct percussion and splitting-and-wedging. Even so, these are points of relative weakness and do not present clear lines along which ivory *will* fracture so much as areas along which cracks *might* propagate under adequate force. Predicting the manner in which ivory will fracture under direct percussion is nearly impossible.

In my initial approach to the tusk, I began by selecting an area at one of the cross-sectional surfaces close to the outside edge of the tusk that presented substantial fissures of delamination. Ivory in the outer margins of the tusk is more subject to splitting and spalling, whereas the ivory closest to the tusk axis is much more compact and difficult to fracture. There is strong evidence in both the French and German archaeological records for the preferential use of the ivory nearest the outside of the tusk and near or in the dentine-cementum junction (Hahn 1987; White 1993, 1997). Attempts at disengaging a piece of mammoth ivory through indirect percussion were unsuccessful, resulting only in the shatter of the intermediate materials (both a flint wedge and an ivory wedge), with almost no effect on the tusk. After the failure of indirect percussion, I abandoned the use of wedges of any sort and continued with direct percussion. Around a dozen repeated, heavy blows with a hammerstone were necessary to disengage a wedge of ivory from the side of the tusk segment, and these blows left surprisingly few scars on the cross-sectional surface. The disengaged wedge was thickest at the cross-sectional surface, and tapered to a point at the end opposite this surface. This is probably due to the manner in which ivory's structure diffuses force, which will be discussed in more detail later.

This chunk of ivory was larger than I desired, so my next task was to break it into several smaller pieces. This, too, proved challenging in spite of the numerous deep fissures that ran through the material in several directions. My first attempts involved striking the ivory with a hammerstone without the use of an anvil. These heavy blows had very little effect on the ivory, aside from causing it to occasionally slip from my hands and fly across the room at a rather substantial velocity. Frustrated in these attempts, I searched in the lab for an appropriate anvil, selecting a cube of marble measuring about 15 cm in each dimension. I delivered several more blows to the ivory with the hammerstone and noted that the surface of the ivory was holding up much better than that of the marble beneath it, which had begun to chip. The cracks in the ivory did begin to propagate, and I eventually had several smaller pieces of ivory suitable for my carving experiment. I selected one of them for carving (Fig. 5) and set the rest aside for future use such as the microscopic study that will be discussed in the section that follows.

Having procured a piece of ivory of roughly the desired size, I began to experiment with the actual carving. The first goal was to create a blank for sculpting: to smooth and shape the irregular edges in order to have a more regular surface to carve. During this process, I was also able to select the stone tools that seemed to work best for carving ivory. I found that a particular set of characteristics was necessary for effective carving. The blades of course needed to have a sharp cutting edge, but a particular mass was also required. Carving ivory takes a great amount of pressure, under which thin blades frequently break. Because I did not haft any of my blades, they also had to present a large enough surface to be held firmly in my hand as I generated the required pressure. This decision was made for the simplicity of a first attempt at carving and does not reflect an opinion on the use of hafted tools in Aurignacian ivory work. Handheld blades, however, did offer a level of control that I found ideal for the creation of a small and detailed object. An increased contact between my hands, the tool, and the ivory blank allowed for very precise manipulation of the material.

Even with sharp and substantial blades, working dry ivory resulted only in the removal of a fine dust from the outer surface. Upon wetting the ivory with water, I found I was able to remove somewhat larger shavings, though these remained quite small, generally measuring under three millimeters in length. Because wetting the ivory worked so well, I left my carving blank to soak in water overnight, hoping that this would soften the surface a bit further. Upon resuming carving the next day, I found that once the very outer surface was removed, the ivory beneath was completely dry. This was not entirely unexpected, as it has been noted that ivory does not absorb water beyond a superficial level. Wetting the ivory also added another dimension to the experiential component of my work: that of smell. Well-preserved fossil ivory retains a very organic scent, akin to what one might expect from a barnyard. When the ivory is wet this scent becomes quite pervasive.

Over the course of the carving experiment, repeated wetting and drying of the ivory exacerbated natural cracks in the material. These cracks never propagated to the extent of disengaging from the carving surface, but were a source of concern. White suggested adding a lipid of some sort (noting that animal fat may have been used in Aurignacian contexts), and I found that a coating of olive oil did indeed diminish the negative effects of wetting and

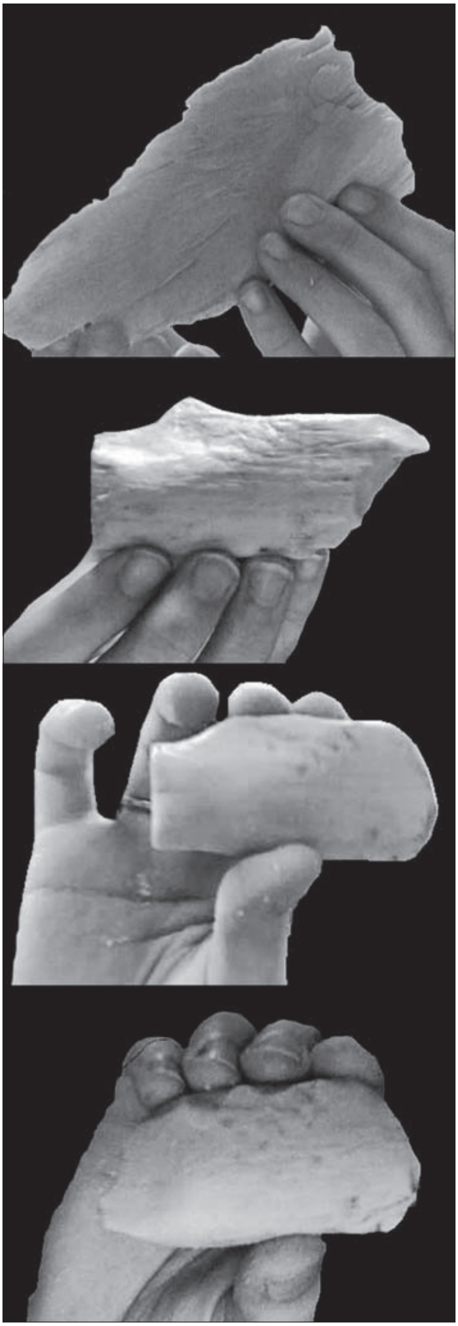

Fig. 5: *Several stages of blank reduction, from the initial chunk of ivory disengaged through percussion (top) to the carving blank produced by scraping, abrasion and "knapping" (bottom).*

drying. Cracks of substantial surface size but minimal severity may be observed in a variety of Upper Paleolithic ivory figurines. These cracks seem to have been present at the time of carving and appear not to have propagated substantially over tens of thousands of years. Repeated fluctuations in temperature and humidity can be quite detrimental to ivory objects, however, once they have been recovered from archaeological deposits (personal observation; Lafontaine and Wood 1986). The tusk fragment used in this experiment underwent substantial delamination through desiccation over a period of about one decade after it was removed from a climate controlled environment. This suggests that it may have been possible for Paleolithic peoples to produce delamination through material processes rather than rely solely on subfossil ivory occurring in their environments (White, personal communication).

In forming a carving blank, I employed several techniques for removing undesired bits of ivory. In addition to scraping and carving with stone blades, I attempted ”knapping” and abrasion. One end of my blank presented several jagged projections that I wished to remove before sculpting the figurine. I decided to try to remove these bits by striking them with the blunt end of a rather thick flint blade. Several blows were necessary for the removal of small bits of ivory that had been bilaterally thinned by carving, and again I found the patterns of fracture difficult to predict or control. I abandoned ”knapping” when a blow to a rather thin projection of ivory snapped the flint blade in half without affecting the ivory.

Through carving and knapping, I had achieved a fairly regular surface with only a few irregular projections. I decided to remove these through abrasion on a slab of rough limestone, a material that would have been readily available to Aurignacian peoples living in limestone rock shelters and caves. Dry abrasion had some effect on the ivory, but again, adding water and hematite powder to the limestone made abrasion much more effective. I noted that abrasion might be an excellent technique for detailed shaping toward the end of the process. Fellow researchers at New York University have found the addition of a secondary abrasive such as limestone dust or powdered steatite to the water and hematite mixture an even more effective aid to abrasion (Ranlett 2009, 40).

Having produced a blank with a regular surface, I began to carve the ivory with the intent of shaping an animal of some sort. In the beginning, I did not have a particular animal in mind (though I did limit myself to the European Pleistocene), preferring to examine the possibilities while carving. I started following some of the contours presented by the blank, choosing an orientation by first selecting an area that vaguely suggested the feet and belly of an animal. The process of carving was a slow one, and progressed in one-hour sessions at first. The pressure required to carve ivory was certainly taxing on my hands, and it took about two weeks of carving daily or every other day before I was able to work in two-hour sessions, which then became the standard session length. Using un-hafted stone tools also required the buildup of substantial calluses, which took some time to develop. As the carving progressed, I designated the head and neck of the animal as well as the back and hindquarters by gouging and scraping rough-outs of these forms. The back and shoulders of the animal that began to emerge suggested a mammoth, and I then shaped the outline of what would become the trunk.

To shape the general features of the mammoth, I used primarily two carving motions. The first was a shallow, scraping/scooping motion, which removed ivory in shallow layers of small, curled shavings. After roughing out the general contours through scraping, I defined the feet, lower abdomen, shoulders, and trunk by gouging and incising. To shape more distinct features such as the legs and neck, a sharper slicing/sawing motion was sometimes required, followed by scraping and polishing to smooth the incised or sawed surfaces. Edges such as those of the feet and trunk and surfaces such as the flanks were scraped with stone tools and then abraded on limestone with wet hematite powder. In all, over one hundred hours went into the shaping of the figurine. Again, this experiment was exploratory in nature and this time investment is not meant to reflect the processing time of Aurignacian figurines.

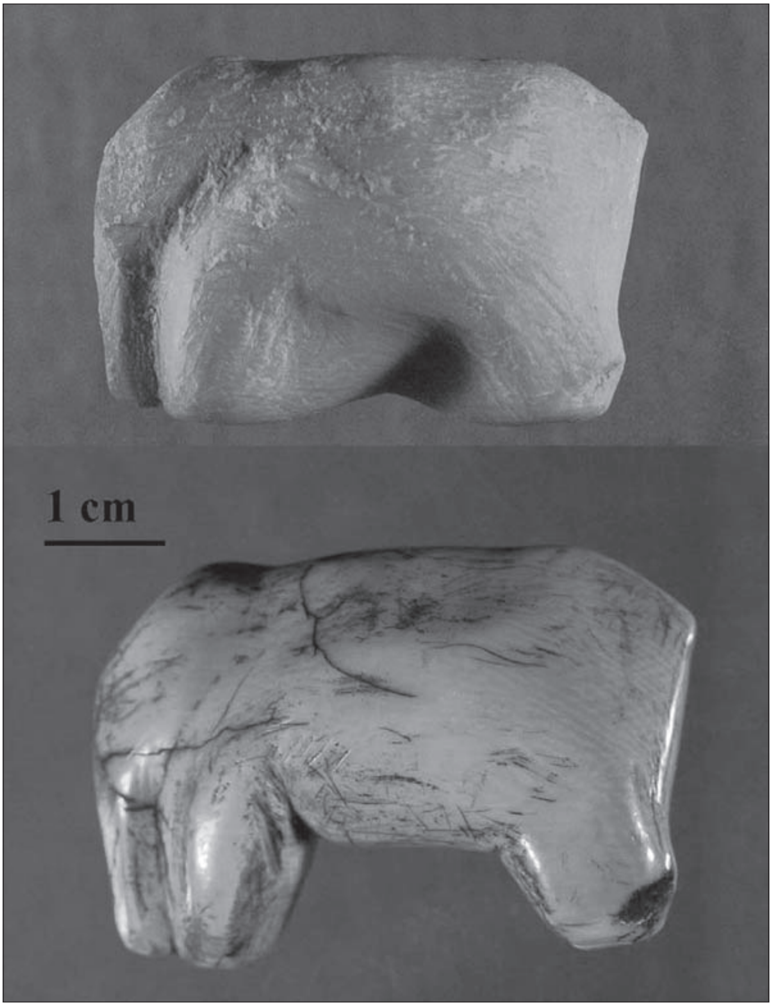

Fig. 6: *Two stages of carving, one before polishing with powdered hematite (top), the next following several hours of polishing (bottom).*

Once the general, rough shape of a mammoth was obtained (Fig. 6 top), I took photomicrographs of the carved surface. These images reflect the techniques and motions described above. Shallow scraping resulted in a surface covered in overlapping, multidirectional shallow striae (Fig. 7). Deeper gouging and scraping on more defined areas or in places where more material was removed resulted in deep grooves more uniform in orientation (Fig. 8). The incisions that defined features such as the trunk reflected repeated passes in a single direction to create a deep but narrow groove (Fig. 9). Abraded areas presented rougher surfaces due to abrasion striae (Fig. 10).

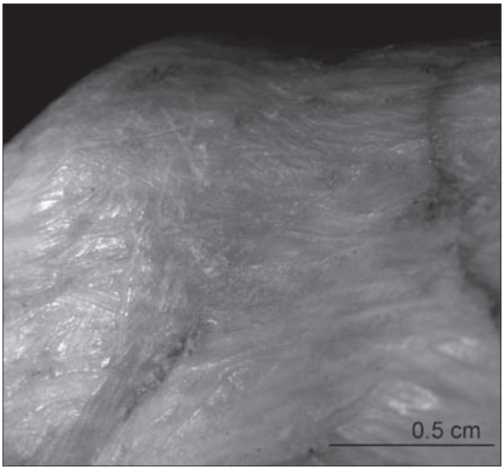

Fig. 7: *Shallow, multidirectional tool traces on unpolished figurine surface.*

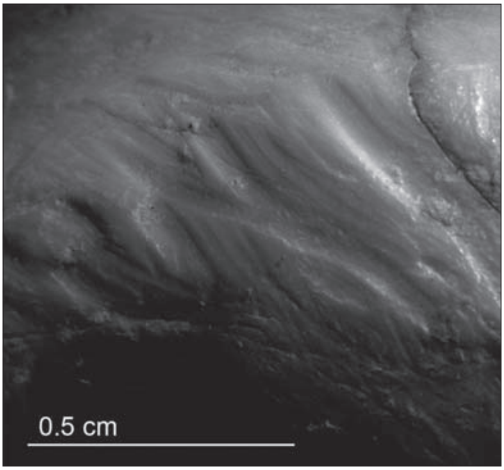

Fig. 8: *Deep, more unidirectional tool traces on a heavily scraped surface of the figurine.*

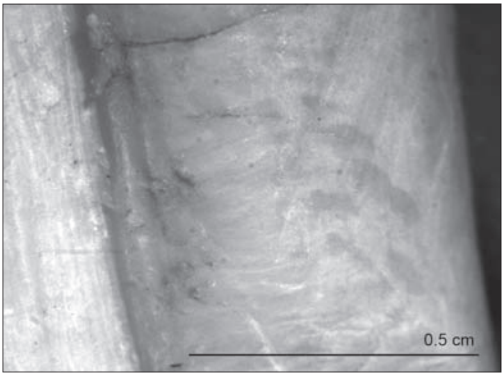

Fig. 9: *Deep, repeated gouges left by multiple incision-strokes with a flint point.*

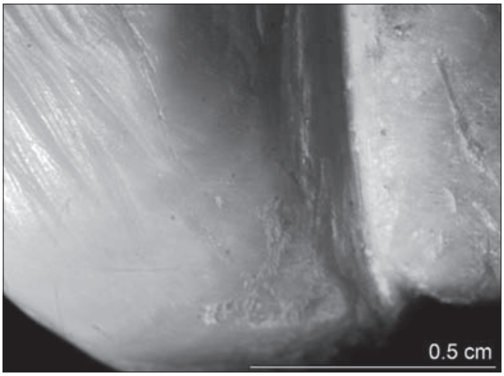

Fig. 10: *Images of the feet (left) and trunk (right), showing a variety of tool traces.*

Once I had studied the production traces left by scraping, gouging, incising, and abrading, I polished the surface of the ivory with a piece of animal hide covered in wet hematite powder. This polishing was time-consuming but highly effective. About twenty minutes of polishing on a small surface area resulted in the erasure of shallow tool striae and the attainment of a bright, smooth surface that was quite visually and texturally pleasing. Removing deeper striae required much heavier and more intensive polishing. While limestone may have reduced the time required to polish, polishing the undulations and grooves in the surface required the flexibility of animal hide. The surface obtained through polishing had a high luster and was quite smooth and pleasing to the touch (Fig. 6 bottom).

Through this experiment in ivory carving, I gained a great deal of tacit, qualitative knowledge on ivory as a raw material. In spite of the difficulties presented by its tenacity, ivory is a pleasant medium to work with. It is a fine and smooth material, and the stone tools I used slid over it with little interruption once the requisite amount of pressure had been achieved. It offers an appealing tactile and visual experience, and the amount of time required to produce a figurine allowed me to become intimately familiar with the contours and characteristics of the specific blank I was working. I indeed had time to establish a dialogue with the material, and found myself responding to its surfaces and suggestions in many ways during the carving process. The process itself did not feel so much like an imposition of form upon the material, but more a collaborative process in which my own decisions were affected by the level of attention I paid to the intricacies of the material.

Here, I have presented qualitative observations on the process of forming a figurine in mammoth ivory. In the next section, I will offer some observations on structure and fracture gained through microscopic analysis. The conclusion of this article will present some implications of these studies for research on Upper Paleolithic ivory objects.

Microscopic Analysis: Structure and Fracture

Thus far, the complex structure of ivory has been discussed in scientific terms, and the fracture of ivory has been presented in a descriptive manner. In order to better understand the relationship of material structure to observed patterns of fracture, I engaged in the experimental fracture of ivory and bone and subsequent microscopic analysis of the resulting fragments. Bone offered a comparative sample that contrasted in many ways with the observations on ivory. The bone sample used (the diaphysis of a bovine femur) fractured fairly easily, requiring two to three direct, heavy blows with a hammerstone. Cracks in the bone did not propagate partially, but rather fractured completely upon percussion. In contrast, the ivory fragments required fifteen to twenty heavy, direct blows, and cracks frequently propagated without developing into full fractures. Pieces along the margins tended to disengage first, followed by the more central portions. It was the observation of these complex fracture-features that led me to investigate the relationship between ivory's strength, fracture-features, and internal architecture. The term fracture-features refers to the breakage patterns observable on fractured surfaces. The manner in which a larger piece fractures into smaller pieces is referenced by the term "fracture pattern." A manuscript in preparation explains the relationship of these phenomena in much greater detail, incorporating insights from the fields of physics, materials science, and chemistry.

Unique patterns of fracture and the presence of the Schreger pattern are diagnostic characteristics that can aid archaeologists in identifying ivory in the archaeological record. These characteristics are often visible to the naked eye or with the aid of a hand lens. Many archaeologists who recover ivory from archaeological contexts gain a tacit knowledge of these features through experience and observation. On a single fractured ivory surface, a number of distinctive fracture-features may be observable, as Figures 11 and 12 below indicate.

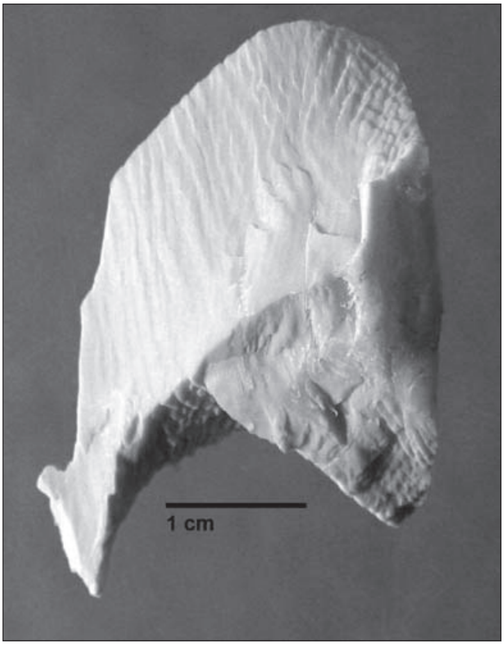

__Fig. 11:__ A piece of ivory that was broken from a larger fragment through direct percussion. Note the variety of features on the fractured surfaces.

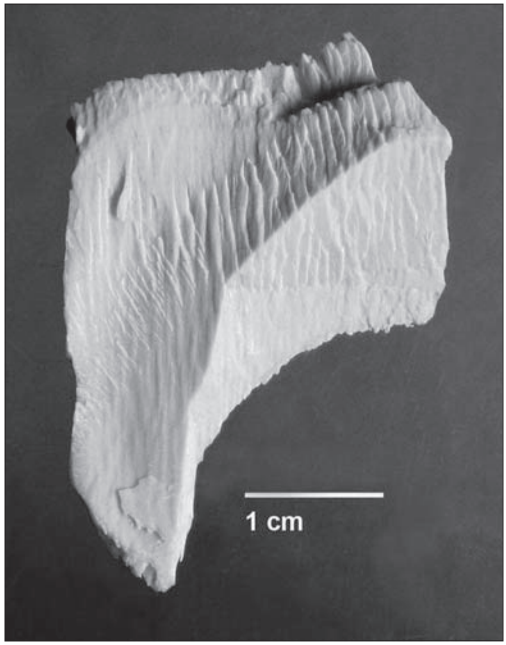

__Fig. 12:__ Another piece of ivory fragmented by direct percussion, again showing a variety of fracture-features on its surfaces.

The images above briefly illustrate the variety of fracture-features that regularly occur on fragments of ivory fractured by direct percussion. Another material characteristic of ivory that is related to its complex internal architecture is the frequent formation of cracks that tend not to propagate to full fracture. Examples of such partial fractures are illustrated in Figures 13 and 14.

The intricacy of ivory's internal architecture renders it a truly complex material, in its unpredictable patterns fracture, its tendency to partial fracture, and the variety of fracture-features to which it is prone. This material complexity has implications for the use of ivory as a raw material.

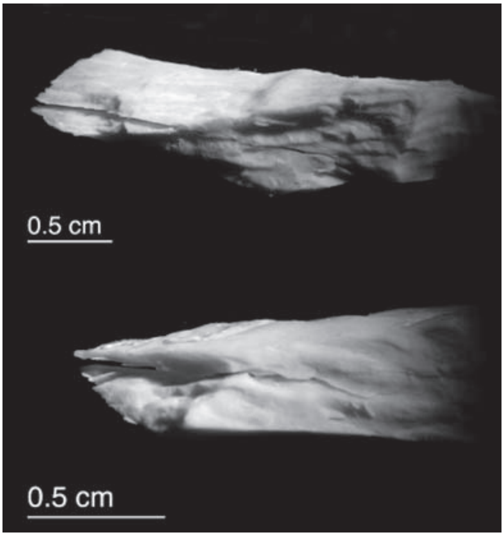

Fig. 13: *Opposing surfaces of a piece of ivory indicating a deep crack, longer on one side than the other, which did not propagate through the length of the sample.*

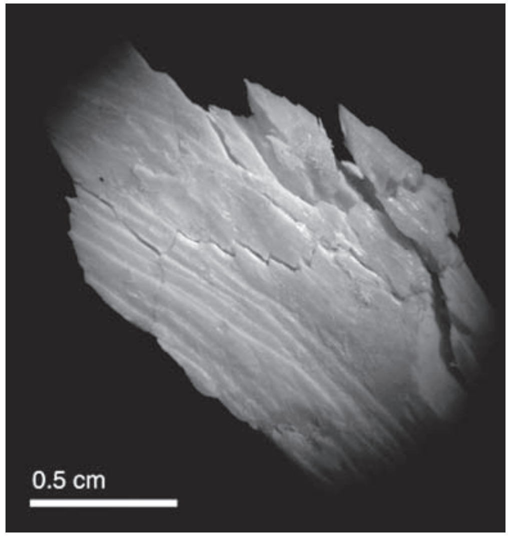

Fig. 14: *Another example of incomplete crack propagation in an ivory sample. The cracks here run in several directions, indicating the varied and unpredictable manner in which cracks propagate through ivory.*

Implications for research in the Paleolithic

Mammoth ivory was a preferred material for the production of representative or symbolic objects and personal ornaments in the Aurignacian of Western Europe. Understanding the cultural contexts of the production of these objects should be a central concern of archaeological approaches to early symbolic behavior in these regions. Leroi-Gourhan's model of the *chaîne opératoire* situates production processes and manufacturing techniques as active constituents of culture rather than as passive byproducts of material processes. As cited earlier, White has sought "an integration of technology and social dynamics through which we might gain access to the culturally-embedded technological production sequences from which socially meaningful decorative styles emerge" (White 1995, 30). Such an integration must be informed by scientific research on the structural characteristics and material properties of mammoth ivory. It must likewise be grounded in qualitative experiential knowledge of ivory as a raw material. These two approaches function best in combination: a scientific understanding of ivory's structural characteristics offers an explanation for observed material properties; experiential ivory work reveals the implications that these structural properties may have had for Paleolithic peoples who worked with the material. The research presented here was the result of an initial attempt at such a synthetic approach. While much research remains to be done in order to confirm and enrich these findings, several preliminary implications for ivory work in the Aurignacian of Western Europe may be drawn.

The complex fracture patterns and fracture-features observed on fragments of ivory can aid in the identification of ivory in the archaeological record, particularly in distinguishing ivory from bone. After long periods of exposure to post-depositional conditions, ivory and bone can appear quite similar. Laminar bone such as the long bones of mammals can delaminate with age much as ivory does. An intimate knowledge of ivory's structural characteristics and their visible manifestations can increase the range of distinguishing characteristics that might identify ivory and therefore increase the recovery and accurate identification of ivory in the archaeological record. Even those features illustrated above, however, are not so distinct in ivory recovered from Upper Paleolithic deposits. Further comparative research focused on the range and presence of fracture patterns and fracture-features on ivory fragments from archaeological contexts is necessary.

An additional benefit of scientifically informed experimental ivory work comes in the form of an expanded mental index of the evidence left by certain approaches to the material. Experimental work greatly enriches the amount of information that can be retrieved from ivory objects, as one can clearly see in tool traces and production debris the precise gestures and processes that went into the creation of an object. Whether incised markings on a figurine or nearly microscopic ivory shavings collected from production areas at archaeological sites (White 2007), such traces document processes that must be understood if we are to properly approach symbolic behavior in the Upper Paleolithic. Furthermore, qualitative experiential knowledge aids researchers in understanding that ”raw material choice indexes different auditory, olfactory, tactile, temporal and gestural experiences” (Ranlett 2009, 56). Through my own experiments with ivory, I have become familiar with a range of these experiences, which I apply in my approach to the archaeological record. As mammoth ivory is not in abundant supply, and many researchers may not be able to prioritize such time-consuming work, it is essential that qualitative and experiential observations feature in archaeological literature on ivory work, in concert with more physical scientific information and analysis of the archaeological record.

The experimental ivory work and observations on structure and fracture presented here also have more explicit implications for the processes and decisions involved in Upper Paleolithic ivory work. Available technologies and material exigency may have structured Aurignacian approaches to the material, including the formal attributes and range of the resulting products. It has already been established that Aurignacian peoples exploited ivory's natural structural properties by selecting ivory from the outer portions of the tusk, which are most subject to splitting through delamination and desiccation. The structural complexities discussed above and the manner in which they affect the percussive fracture of ivory may have similarly directed the removal of blanks and production of objects in the Aurignacian. It can be observed that strict regularity of form is limited to very small ivory objects, such as the small basket-shaped beads of southwestern France and the double-perforated beads of southwestern Germany. Larger ivory objects, such as the zoomorphic figurines of southwestern Germany, while displaying shared stylistic conventions, do not present a similar exactitude in repetition of form (Figs. 3 and 15). It is possible that this regularity of form was much easier to achieve on very small objects, while larger blanks were more subject to an irregularity of form that was better suited to formal variety. The culturally informed ”dialogue” that Aurignacians had with ivory as a raw material was probably quite complex, but its material bases may be more easily divined than its ideological ones and merit exploration.

Fig. 15: *Another mammoth figurine from Vogelherd cave, Swabian Jura. Aurignacian, ca. 30-35,000 BP. Photo: H. Jensen. © Eberhard Karls Universität Tübingen.*

The structural differences between ivory and bone may have also influenced decisions of which material to adapt to different purposes. The luster and tactile appeal of polished ivory cannot be achieved on bone, and were probably significant factors in the selection of ivory as a raw material for symbolic objects (White 1993, 1995, 1997). That ivory was routinely selected over bone and antler in the Aurignacian of Western Europe may reflect the recognition of these characteristics. Inversely, however, bone was highly favored in Western European Aurignacian contexts for the production of utilitarian objects.

The complexity and irregularity of ivory fracture has been discussed above, as has the enormous time investment necessary to disengage ivory blanks and shape ivory surfaces. Bone, in contrast, fractures fairly easily and regularly, and is easier to shape through carving and abrasion. These factors certainly would have been recognized by Aurignacian peoples, and may well have been a reason for the preference for bone in the production of tools such as *lisoirs* and r*etouchoirs*. Tartar's (2009) extensive analysis of bone tools from the French Aurignacian and her experimental production and use of such tools supports this hypothesis. Tartar indicated that there is much evidence in the archaeological record for the opportunistic use and reuse of bone fragments as tools. Fragments of ribs and long bones could be easily fractured and shaped to suit a variety of purposes. When broken in the course of use, these objects could again be easily fractured or shaped to produce another tool, either for the same purpose or for another. The experimental and scientific observations reported in this article indicate that such use of ivory would have been vastly time-consuming and ill suited to the production of tools that could quickly and easily be produced with whatever bones or bone fragments were on hand.

The observations and hypotheses offered here are not meant to discount ideological or cultural influences on raw material selection and use. Certainly, factors beyond technological possibilities and material exigency influence the use of materials. As human beings, we can each relate to the experience of being drawn to images, colors, and textures for reasons that are difficult to verbalize. Ivory, which has been a material of high value and demand throughout many time periods and in many places, is almost mystical in its appeal. The time investment required to produce polished objects in ivory and the scale of their production in Aurignacian contexts speaks to their cultural significance. Though the exact nature of this significance is beyond our reach, it is one that is resoundingly human and merits further research.

The implications presented above stand as examples of how a familiarity with both the qualitative experience of ivory work and the scientific understanding of ivory's structure might inform approaches to ivory and offer insights on its use in the Upper Paleolithic. Further experimental research and analysis of the archaeological record are necessary to the full development of this potential. It is my hope that the information here presented will serve to further such work and to enrich archaeological understandings of ivory as a raw material and of the objects produced in it during the early Upper Paleolithic. An approach that combines physical scientific research on ivory with experimental ivory work and thorough analysis of the archaeological record will greatly improve understandings of how the interrelated phenomena of technology, culture, and human experience shaped the development of stylistic and symbolic conventions and the objects that both influenced and reflected them.

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