ALUTIIQ ENGINEERING: THE MECHANICS AND DESIGN OF SKELETAL TECHNOLOGIES IN ALASKA'S KODIAK ARCHIPELAGO

by

Amy Vlassia Margaris

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As members of the Dissertation Committee, we certify that we have read the dissertation

prepared by Amy Vlassia Margaris

entitled "Alutiiq Engineering: The Mechanics and Design of Skeletal Technologies in Alaska's Kodiak Archipelago"

and recommend that it be accepted as fulfilling the dissertation requirement for the

Degree of Doctor of Philosophy

____ Date: 10/18/06
Steven L. Kuhn

____ Date: 10/18/06
Mary C. Stiner

____ Date: 10/18/06
Michael B. Schiffer

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copies of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

____ Date: 10/18/06
Steven L. Kuhn

STATEMENT BY AUTHOR

Signed: Amy Vlassia Margaris

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ABSTRACT

This dissertation expands current theoretical and practical knowledge of variability in the technological strategies practiced by past forager societies. Specifically, it examines the interplay between raw material innate and working properties, and tool design as they relate to skeletal media and technologies. Data were synthesized from existing biomedical literature on the structure and mechanical properties of technologically-relevant osseous media, including bird and cetacean bone, and antler. Original laboratory tests were then conducted to determine the mechanical properties of Young's modulus (intrinsic stiffness), intrinsic strength, and fracture resistance of the compact tissue of reindeer antler, cervid long bones, and the limb bones of the California sea lion. Cervid compact limb tissue is stiff, strong, and brittle, while reindeer antler is flexible and highly fracture-resistant (tough). Air-drying hardens all skeletal tissues, and greatly increases investment times for creating tool blanks of both antler and cervid limb bone. Water - soaking can soften dry antler, but may have little effect on the workability of previously-dried land mammal limb bone. Finally, data on the mechanical and working properties of osseous tissues were applied to an analysis of the raw material selection and tool design strategies practiced by protohistoric Alutiiq foragers of Alaska's Kodiak region. Drawing on a sample of over 300 osseous tools and tool blanks, the engineering designs of five tool types were investigated: unbarbed arrows, barbed sea mammal harpoons, fishing harpoon tips, woodworking wedges, and awls. By employing multiple analytical scales, the study points to multiple design pathways toward a generalized goal of maximizing tool longevity, or circulation time. Tool fracture potential can be reduced through raw

material selection and stress-reducing structural design. Alutiiq designs for longevity include nested fish harpoon valves, and the off-set line holes on unilaterally barbed harpoons. Also, both tool types were created most frequently from tough but non-local antler. Tool recycling and conservation to avoid drying and fracture can likewise increase tool use-lives. For osseous tools, maximizing longevity might offset high initial tool production investments. The results are applicable to processes of technology transfer in many protohistoric contexts and the Upper Paleolithic of Eurasia.

CHAPTER 1:
INTRODUCTION

Forager Technological Strategies in Wider Perspective

This dissertation expands current theoretical and practical knowledge of variability in the technological strategies practiced by past forager societies. Behavioral and organizational approaches to the study of prehistoric technologies focus on tool life histories, as a materially-centered means for illuminating the choices individuals made regarding raw material selection, tool design and manufacture, and tool use, recycling, and discard. In hunter-gatherer studies, organizational and behavioral theories have been applied primarily to the study of lithic materials and technologies (Bamforth 1986, 1990; Bamforth and Bleed 1997; Binford 1979; Bousman 1993; Gero 1991; Jelinek 1976; Kuhn 1991, 1994; Sackett 1982; Shott 1989; Torrence 1983, 1989).

Our understanding of the technological decisions made by foragers can be significantly widened, however, by focusing attention on under-studied types of technological resources whose innate properties lay outside the range of those of brittle stone. This is because the innate, mechanical properties of materials, including their strength, stiffness, and resistance to fracture (toughness) place ultimate limits on how the materials can be worked and used, thus affecting most facets of tool use-lives. This study makes a unique contribution by showing how forager technological strategies played out in the realm of osseous tools and materials. As the “hard parts” of animal bodies, antler and other bony tissues form in biological rather than geological environments. Although as a class, osseous materials tend to be tough rather than brittle, each has evolved in response to different selective pressures, resulting in considerable variation in their composition, structure, and mechanical properties. An analysis of the innate properties and performance of particular osseous tools and materials can thus broaden our understanding of technological strategies in general to a degree not possible by focusing on a single raw material class.

The first step in such a project is to assess the extent of variability in the mechanical properties possessed by different types of osseous tissues, such as their strength and impact resistance. A second is to evaluate the comparative time or labor investments required for working materials towards specific ends. Because mechanical and working properties place constraints on how the materials can be used and the costs of producing artifacts from them, exploration of these two properties provide a necessary starting place for exploring how and why various materials were chosen for use in specific contexts.

An understanding of the physical limitations of various kinds of skeletal tissues allows researchers to formulate predictions about optimal use in tool-making with respect to economy of time or tool performance. For instance, high-impact tools should be constructed of materials that are highly fracture-resistant -- i.e., tough. Because tough materials are normally particularly difficult and time-consuming to work, however, superior tool performance is gained at the expense of high production costs. In the best of all possible worlds, tool designs would be perfectly suited to all needs, but compromises are instead unavoidable, as no one material or artifact design can embody all desirable performance characteristics. What is more, the performance characteristics of tools carry variable weight to different individuals, groups, or segments of a society (Bijker 1995; McGuire and Schiffer 1983), as well as in different contexts of use (Skibo and Schiffer 2001). Departures from optimality-based predictions can provide clues to the other constraints that influence tool design, from the limited availability of certain materials, to culturally-imposed restrictions that have patterned material correlates but that might otherwise be indecipherable to present-day researchers (e.g., McGhee 1977).

Technology Transfers and Culture Contact

Incorporating osseous technologies in wider theoretical perspectives would particularly benefit the study of indigenous groups around the time of European contact, as osseous and lithic materials have often played central roles in the technological shifts that followed contact and colonization. The archaeology of protohistoric forager groups was until recently relatively unexplored, falling between the traditional realms of inquiry of prehistorians and historical archaeologists (Lightfoot 1995). Moreover, studies of culture change in response to colonialism have tended to stress either acculturation in the sense of near-complete assimilation on the part of Native groups, or case-specific particularism (Leonard 1993). This divide underscores the need for a framework for investigating the adoption – or rejection – of new technologies which is both widely applicable and sensitive to cultural context and historical contingency. To this end, it is essential to have a solid understanding of the mechanics of the materials and tools at hand, and of how they might fit into larger technological and social systems (Schiffer 2002), as specific context is key to determining when and how new technologies are adopted and employed (Schiffer 1992, 2002).

Despite claims to the contrary, for example, researchers have shown that metal did not arrive in Alaska first with European explorers to the region (Collins 1937; Larsen and Rainey 1948), and that it was not necessarily coveted by indigenous peoples as a replacement for bone or antler. The widely divergent formal properties and performance characteristics of metal and osseous tissues, such as toughness, ability to hold a sharp edge, and susceptibility to corrosion or decay, render them more or less useful for certain types of tasks. The importance of each property is not inherent, but is dependent on how the materials are intended to be used, and by whom.

Neandertals and Modern Humans

Finally, a more nuanced understanding of the mechanics of skeletal materials and technologies may shed light on one of the most compelling but least understood examples of culture contact, the interaction of Neandertals and anatomically modern humans in Eurasia. The punctuated appearance of ornaments and formal tools with osseous components in Aurignacian and contemporary industries across Europe and Western Asia stands in stark contrast to the lack or near absence of such objects found in association with Neandertals (d'Errico et al. 1998). Although this trend is often cited as one hallmark of the emergence of modern cognitive capacities, it is far from clear what new capabilities the construction of bone, antler, and ivory implements might represent from a technical perspective.

Composite spear technologies were in place at least as early as the Middle Paleolithic, and hominids have had wide access to bone as a byproduct of hunting or scavenging for much longer. Perhaps their earlier constructions were precluded not by the availability of the raw materials, or even lack of the necessary skills required to work tough bone, in contrast with brittle stone, but in the high labor costs required for creating even simple tools of bone or antler. What is more, once exposed to the open air, antler and bone are subject to drying and other post-mortem processes that may affect their ease of working, creating further scheduling constraints potentially in competition with those imposed by other important tasks. A deeper understanding of the performance characteristics of the raw materials with respect to their initial working and to tool maintenance would provide important functional grounding to current arguments regarding their use and evolutionary significance.

The Research Project

Cultural norms and raw material availability are central but highly contextual factors which influence when and how various raw materials can be incorporated into technological systems. Yet raw material selection, tool use, recycling, and discard decisions may also give weight to the labor investment required to produce tools, which stem in part from the properties of the underlying raw materials.

While no single dissertation could address the multiplicity of roles that bone or antler tools might play in cross-cultural interactions, or the entirety of reasons behind their earliest uses in Eurasia or Africa, this dissertation lays some groundwork by investigating osseous tool strategies from the bottom up. In particular, it asks:

1. What adaptive functions have antler, marine mammal bone, avian wing and terrestrial mammal limb bones evolved to fulfill *in vivo*, and how have the *in vivo* functions of these skeletal tissues shaped their mechanical properties at the material or structural scales?
2. To what extent do the distinctly different mechanical properties of antler and cervid limb bone affect the efficiency with which they can be worked by human hands, using a simple lithic-based toolkit?
3. How might the workability of these same materials be affected by *external* forces, especially drying, and can the effects of drying be mitigated in order to preserve desirable performance characteristics of an osseous tool?

4. Finally, what osseous tool design strategies are evidenced in actual archaeological tool assemblages, and in what ways do these strategies exemplify, conflict with, or contribute new insight into the mechanical and working considerations outlined above?

As a case study, data on the mechanical and working properties of osseous tissues were brought to bear on an analysis of the raw material selection and tool design strategies practiced by protohistoric Alutiiq foragers of the Kodiak region of southern Alaska. The Alutiiq assemblages are rich in artifacts constructed from an array of osseous raw material types. The collections thus provided an excellent context in which to study the links between raw material use and practical tool design and use, aided by the fact that early Russian clergy and explorers who visited Kodiak penned accounts of how many of the osseous tools now in museum collections were once used. The results shed light on Alutiiq economic decisions regarding tool construction before and following Russian control of the Kodiak region, while also greatly expanding our understanding of the more general interplay between tool use-lives and the innate mechanical properties of their materials of manufacture.

Chapter 2 reviews some of the known formal and mechanical properties of several types of bony tissues selected for tool-making by forager groups in the past. The data draw largely from medical, biological, and materials science literatures, focusing on the types of tissues and their properties most relevant to technological interests. Cervid limb bones, for instance, tend to have a relatively high mineral volume fraction, making cervid compact bone quite stiff. Avian wing bones are also tubular elements, and their structural solution to torsional and bending forces encountered during flight make them ideally suited for the production of some types of tool and instruments, although gross size places ultimate limits on their usefulness. Special attention is given to the bones of marine mammals, which were incorporated into the toolkits of coastal forager groups from the Arctic to the tip of South America. Although all marine mammals claim terrestrial ancestries, their skeletal adaptations to aquatic locomotion are diverse. Whale bone was a key element in Alutiiq technological repertoires but little is known of its mechanical properties, save that its porosity likely lends it a low degree of stiffness at the tissue scale.

Chapter 3 presents the results of original mechanical tests to determine the strength, stiffness, and fracture resistance of compact bone samples from the California sea lion (*Zalophus californianus*), reindeer antler, and limb bones of two species of cervids. The compact bone of the California sea lion is shown to be mechanically similar to that of cervids, despite the sea lion's adaptation to semi-aquatic life. The results also underscore the unique mechanical properties of antler, particularly its extreme resistance to fracture. Mechanical testing of the cancellous tissue of which cetaceans bones are primarily comprised requires procedures that are distinct from and more difficult than those typically employed for compact bone mechanical studies. Only limited mechanical studies have been undertaken on cetacean bones; lack of available whale bone tissue precluded its inclusion in this study. (While the need for such studies forms a clear avenue for future research, unique insights into the likely properties of marine mammal bones arise from analysis of the Alutiiq osseous assemblages, described in Chapter 6.)

The mechanical properties of antler and the limb bones of terrestrial species are widely divergent, and it is possible that differences in their working properties follow suit. Chapter 4 is an attempt to get at some of these working properties through a series of timed, semi-formal experiments using traditional techniques of abrading, groove and splinter, and saw and snap in order to create and finely shape tool blanks of cervid limb bone and antler. Consistent with previous studies, drying was found to have a profound influence on workability. The results, combined with those of other researchers, lead to a hypothesis regarding the optimal timing of bone and antler tool blank production based on the mechanical properties of these materials when worked wet versus dry.

Finally, the mechanical data and insights on the working properties of osseous media are brought to bear on actual tool design strategies used by protohistoric Alutiiq foragers, inhabitants of the Kodiak Archipelago in the Gulf of Alaska. Over three hundred bone and antler tools were examined from two prehistoric sites, Karluk One and Settlement Point, and one Russian-period site, the Afognak Artel, which was occupied by Russian fur traders and conscripted Alutiiq workers. Chapter 5 provides an overview of the study region, an introduction to Alutiiq culture around the time of Russian contact, and a description of the three archaeological sites, portions of whose osseous assemblages formed the basis of the artifact study. Five tool components from these sites were chosen for analysis: unbarbed arrows, barbed harpoons used for taking large sea mammals, ingeniously designed two or three piece toggling fish harpoons for shallow-water fishing, wood-working wedges, and a final loose category of awls. Unlike artifacts recovered from more ancient contexts, the uses of these artifacts are fairly well documented, and are also described in Chapter 5.

Based on the types of stresses each artifact type would be expected to undergo during use, predictions are made in Chapter 6 about which raw materials should be selected to optimize their mechanical performance. The mechanically-based predictions are then tested by analyzing patterns of raw material selection by artifact type. Breakage patterns were also noted, providing evidence of the actual stresses the tool components encountered during use. The results reveal that in the construction of some types of tool components, Alutiiq toolmakers sought to maximize impact resistance by selecting antler, despite its availability only through mainland trade. Impact resistance for other tool types proved less crucial or unimportant, and a wider range of raw materials was selected.

One of these materials is whale bone, which was frequently used to create wedges for woodworking. Simultaneously dense and porous, its properties have largely eluded scientists, but Alutiiq technical choices involving whale bone yield unique insights which help to circumscribe the range of its mechanical limitations. In particular, whale bone's toughness (fracture resistance) probably lies between those of antler and of land mammal limb bone, both of which are well documented. Mechanical tests conducted on other types of cancellous tissues also strongly suggest that fresh or wet whale bone accrues additional strength through compressive loading, as woodworking wedges would regularly undergo. Taken together, the laboratory and collections data shed unexpected light on one of the least well-understood maritime forager osseous resources.

The results also contribute to a much wider body of technology theory. In particular, laboratory and tool replication experiments, analysis of Alutiiq collections, and insights from ethnohistoric texts combine synergistically to demonstrate how osseous materials vary radically from brittle stone resources. Consequently, the two material classes can be utilized to fulfill very different technological goals.

Bone and antler technologies contrast sharply with those of stone because while stone is inherently a brittle material, most skeletal media are tough. Toughness, as it applies to tool life histories, translates into *durability* during use, as tools or tool components that are durable are able to withstand battering to an extent not possible for rigid, brittle tools. The great emphasis Alutiiqs placed on tool durability is evidenced by the fact that it was incorporated into their tool construction plans not only through their choice of raw materials, but at multiple design scales. Both fishing harpoons and barbed sea mammal harpoons, for instance, were expected to make sharp impacts during the course of their routine uses. The fracturing of tool tips used in aquatic hunting and fishing contexts would result in the almost certain loss of prey, so that durability would be of primary importance to the users of these tools. Not surprisingly, both sea mammal and fish harpoon tips were constructed principally from antler – despite its being attainable only through trade.

In the Alutiiq case, durability through raw material selection was echoed in the larger, structural design of these same harpoons, where, in modern terms, materials science and engineering meet. Examples include the "telescoping" heads of interlocking fishing tips, and the coordinated placement of line hole and barbs in unilaterally barbed sea mammal harpoon, which directed stresses to the region of the harpoon most equipped to withstand them. In some cases then, tool engineers choose to coordinate material and structural properties, such as durability.

In other cases, a raw material was selected whose properties were in some way less than ideal; the deleterious mechanical effects could be dampened through the design of the entire tool's "architecture." Alutiiq woodworking wedges were created most commonly from large segments of whale bone, a tissue which is intrinsically low in stiffness and strength. But because whale bone is available in large packages, the stiffness and strength required for well-functioning wedges could still be achieved by "building big", lending the tools strength at the structural, if not tissue scale.

Design for durability is only one means for attaining a larger goal of maximizing a tool's *longevity*, or use-life. Research conducted for this study and by others suggests that the labor investments required to produce tools from tough, osseous materials are relatively great. High initial labor costs associated with the manufacture of skeletal technologies, however, may be offset by the potential long circulation periods of these technologies in systemic context. Three, interrelated strategies for maximizing tool use lives are evidenced in the Alutiiq osseous assemblages.

The first is the selection of raw materials best equipped to handle the stresses encountered in particular contexts of use – in other words, selecting for durability, exemplified in the design of interlocking fish harpoon valves, each constructed from tough antler. The second is the design of osseous tool components with morphologies amenable to recycling and reworking, so that even when these parts become broken or worn, their use-lives can be extended. Great variability in the lengths of birding arrows and fish harpoon tips suggests these artifacts were likely resharpened time and time again. The complex contours of barbed sea mammal harpoons precluded their easy resharpening, yet the use-lives of many (presumably broken) barbed harpoons were extended by their recycling into a number of other tool forms. Finally, the longevity of osseous tools can be maximized through tool conservation measures aimed at locking in moisture as skeletal materials age, thereby preventing drying and fracture. Ethnographic accounts from different parts of the world describe the addition of fats or oils to maintain desirable performance characteristics of bone and antler tools. Special concavities located along the face of some Alutiiq woodworking wedges are credited for this same purpose, and their storage of lubricating fat would help to prevent buckling and fracture associated with dry trabecular tissue loaded in compression.

In sum, the analysis demonstrates that investigations of tool design must be undertaken at multiple scales. The innate mechanical properties of raw materials provide an essential starting point from which to investigate increasingly higher and interrelated levels of structural design, from individual tool components, to entire tools or technological systems (*sensu* Bleed 1986; Schiffer 2005). The mechanical properties of any given material are also innate, wholly objective, and thus applicable to all contexts in which the materials are used, without temporal or geographic strictures.

One of the many contexts in which these insights can be applied is the dynamics of technology transfer that accompanied inter-group interactions. Although relatively few of the artifacts including in this study were recovered from the Alutiiq Artel, where conscripted Alutiiqs labored for Russian fur traders, the *artel* assemblage nonetheless provides a window onto some of the changes and continuities in Alutiiq tool repertoires that accompanied sustained and forced Russian contact. In short, the bone and antler components of sea mammal hunting assemblies, including barbed harpoons, sea otter dart tips, and bone sockets, continued to be produced by Alutiiq workers, but to do so, Alutiiqs selected to use newly-introduced, sharp-edged metal manufacturing implements. In other words, it was the tools designed for maximum longevity, and used in aqueous contexts in which the toughness, or durability, of bone and antler are greatest, that Alutiiqs continued to produce well into the Russian era.

CHAPTER 2:
THE STRUCTURE AND KNOWN PROPERTIES OF SOME BONY TISSUES

Introduction

Archaeologists are frequently guilty of referring to the wide array of skeletal materials that exist in the natural world as simply "bone." On one hand, the conflation is somewhat just because as the hard parts of vertebrate bodies, bony tissues are all biologically-based composites of protein, mineral, and water. On the other hand, biomineralized tissues serve many roles: as internal scaffolding, protective armor for the inner organs, and a source of mineral reserves, or to support feeding, competitive behaviors, and auditory functions. Compositional fine-tuning and variation in the form and properties of these bony tissues reflect the many adaptive functions they have evolved to fulfill.

This dissertation examines osseous materials from yet another perspective, that of a technological resource for human groups in the prehistoric past. The full range of reasons behind an individual's technological choices can perhaps never be fully known, but a reasonable starting place is an analysis of the properties of the materials themselves, as these help to circumscribe the limits of their use. Thus, this chapter begins with a description of "generalized" bone, as a prelude to a discussion of more specialized types of bony structures and their mechanical properties as far as they are currently known, including strength, stiffness, and resistance to fracture. (These three properties are formally defined and discussed in greater detail in Chapter 3.) Rather than attempting to provide a complete compendium of the many osseous materials used by prehistoric peoples and their relevant properties, this chapter bridges gaps that exist in the current archaeological literature on this topic by drawing largely from disciplines outside archaeology. In this light, special focus is given to the bones of marine mammals, which vary in important ways from "standard" land mammal bone. The current paucity of data on the mechanical properties relevant to their technological potential belies their importance in the technological repertoires of many coastal forager groups. Ivory is not treated here owing to its rarity in the Kodiak region, but good descriptions of the macro- and microstructures of various forms of ivory can be found in Penniman (1952) and Krzyszkowska (1990). MacGregor (1985:Table 2.1) provides some data on the mechanical properties of elephant ivory. Research on the properties of walrus ivory would particularly benefit the study of high latitude forager technologies.

The following review of bony structures and their properties draws together information garnered from a number of disciplines. Featured prominently is the work of John Currey, a biologist with a keen interest in the comparative properties of bony tissues and whose research has been deeply influential in the field of biomechanics. The biomechanics literature is a largely untapped source of data for archaeologists interested in how the composition and structure of raw materials of any sort profoundly affect how they can be manipulated and used for human purposes. Much of the relevant information on terrestrial mammal bone can be found in journals devoted to the material as examined from a biomedical perspective, especially the *Journal of Biomechanics* and in Currey's highly-readable book *Bones: Structure and Mechanics* (2002).

Generalized Bone: Micro- to Macrostructure

At the heart of all bony structures lies the intimate association between collagen, the mineral carbonated apatite, and water molecules. Although a variety of non-collagenous proteins contribute minimally to the organic make-up of bone (Weiner and Wagner 1998:274-276), nearly all (85-90%) of the protein fraction is type I collagen, which is also found in skin, tendons, and tooth dentin (Currey 2002:5; Wainwright et al. 1982:82). A single type I, or tropocollagen, molecule is composed of three polypeptide chains, two identical in composition, and all three rich in the amino acids glycine, proline, and hydroxyproline. The individually twisted chains are closely packed and hydrogen bonded into a single, left-handed helical molecule (Vincent 1982:54).

At the next highest structural level, tropocollagen molecules are stacked end-to-end and cross-linked with neighboring molecules to form a three-dimensional array, or fibril. A gap punctuates the interface between stacked proteins, and in this linear direction the organization of collagen fibrils is well understood. How individual molecules are bound in other dimensions has been debated, but it is now believed that stacks of protein molecules are staggered so that adjacent gaps are slightly offset, and in three dimensions these spaces align to form continuous, diagonal channels within the fibril (Currey 2002:5; Vincent 1982:880-881; Weiner and Wagner 1998:277).

The mineral phase of bone is an impure form of hydroxyapatite in which carbonate frequently substitutes for phosphate groups ($Ca_5(PO_4, CO_3)_3(OH)$). This carbonated form of apatite, also called dahllite or bioapatite, forms exceedingly small, plate-shaped crystals, with an average length of only 50 nm. Their resulting large surface-area-to-volume ratio makes them highly reactive and hence difficult to study *in vivo* (Currey 2002:6; Weiner and Wagner 1998:276). Soon after the death of the organism, however, the crystals re-form to become larger and more thermodynamically stable (Nielson-Marsh et al. 2000). Collagen appears to act as a nucleating site for the mineral crystals, which form within and between fibrils, including in its stacking spaces. At this level of structural organization, the linear arrangement of collagen packed with mineral crystals and, to a lesser degree, the crystals themselves (Gibson and Ashby 1997:434) create a material that is highly anisotropic.

Finally, water is pervasive throughout bone tissue, inhabiting spaces within and between individual collagen molecules, fibrils, and fibers, so that its volume is inversely proportional to the bone's mineral content (Currey 1988a:138). Bone's aqueous component crucially affects its mechanical properties by lending some viscoelasticity, or tendency of the bone to flow very slightly under pressure. Material changes are associated with the loss of water in bone and are discussed at greater length in the section on antler, and in Chapter 4 in the context of working properties.

Increasingly higher levels in the organization of bone are recognized according to ways in which mineralized fibrils are juxtaposed, creating a diversity of forms whose properties vary accordingly. Woven bone consists of fairly random arrays of collagen fibrils. It forms quickly, such as after a fracture (Turner et al. 1990) as well as embryonically, and through time is usually replaced by a more ordered tissue form (Weiner and Wagner 1998:286). As might be imagined, its properties are more isotropic than those of bone tissue with axially aligned fibril arrays. The collagen fibrils of lamellar tissue, in contrast, are more neatly arranged into sets of parallel lamina, the orientations of which vary roughly every 30-100 μm (Wainwright et al. 1982:171).

These two basic tissue types are spatially extended or further elaborated in succeeding levels of structure, such as fibrolamellar (also called plexiform, or laminar bone), which features layers of both lamellar and woven bone (Vincent 1982:152), or the addition through remodeling of Haversian systems, or secondary osteons that contain vascular and neural networks. The possible mechanical advantages of Haversian systems, if any, are unknown (Currey 1984), but Liu and colleagues (2000) have shown that the two halves of fractured osteonal bone do not tend to separate completely as they do in unremodeled lamellar bone, a feature that would facilitate bone repair.

Just below the level of the individual skeletal element is the distinction between compact and cancellous (spongy) bone tissues. The absolute quantity and spatial arrangement of compact and cancellous tissues within skeletal elements have repercussions for how these bones can be used and perhaps worked as technological materials. Compact bone typically forms the solid shell of the skeleton and gives it its overall form. Cancellous bone is both light and shock-absorbent; these two functions vary in their importance depending on where the cancellous tissue is found, such as in the movable joints of long bones of terrestrial animals, as the “filling” in short bones, in cranial, rib, and other flat bones (Currey 1984:133), or as the major component of the limb bones of cetaceans (de Buffrénil and Schoevaert 1998; Felts and Spurrell 1965; Madar 1998). The most delicate spongy bone forms a lacy webbing of bony struts, or trabeculae. Denser tissue is formed in response to higher loads, wherein the trabeculae are found in the form walls or plates that surround open portals. Cancellous tissue is classified as bone with a relative density of less than 0.7 (Gibson and Ashby 1997:431; Keller et al. 1990:593), but porosity varies along a nearly continuous scale so that it is sometimes difficult to distinguish between compact and cancellous tissues, (Carter and Spengler 1978) such as in the region where cortical shell and dense webbing meet. The material compositions and densities of compact and spongy bone are similar (Gibson and Ashby 1997:434); it is only at the visual, tissue level of organization that their mechanical properties may greatly diverge.

Finally, the size and geometry of whole bones vary greatly by element and between species, placing limits on how particular skeletal elements can be worked and used.

Mechanical Properties of Compact Tissue

Bone is an adaptive tissue structured to suit the particular stresses placed upon it during the life of the organism. Its mechanical properties, such as strength and stiffness, can be viewed as the lowest-cost design suitable to the uses of a whole bone or bone portion though life (Currey 1984). A universal theme in bone is that the mineral portion confers hardness and rigidity, while the collagenous fibrils provide toughness and elasticity, together forming a rather unique fibrous composite. The elongate mineralized collagen fibrils also give bone a definite grain, just as in wood, which in long bones is aligned with the length of the element. The result is anisotropy, or variation in measured properties along different axes.

Wet or dry, compact bone is stronger when loaded along the grain than across it or obliquely (Martin and Boardman 1993; Yamada 1970). Dry bovid tibial bone is about twice as stiff and three times stronger loaded along rather than across the grain, and nearly six times more fracture resistant (MacGregor and Currey 1983). During day-to-day use, long bones are most often loaded in compression, and the design of compact bone ensures that loaded along the grain it is stronger in compression than it is in tension (Currey 1984:Table 2.2; Yamada 1970). When bones do break, it is most often in *bending*, which combines compressive loading on the concave side with tensile loading along the opposite region. Fracture most often initiates in this weaker, tension-loaded zone (Currey 1984:74; Wainwright et al. 1982:178). Anisotropy will affect how bony substances can most easily be worked, and their level of effectiveness as tool components that experience particular directions and magnitudes of loading during use.

Bone density can also vary by an organism's age (Ioannidou 2003) or nutritional status. High calcium demands or nutritional stress, including female pregnancy and lactation, can result in mineral loss (Baker and Brothwell 1980). There is a positive correlation between mineral content and the intrinsic stiffness of skeletal materials and, to a lesser extent, between bone density and strength in bending (Currey 1979, 1988b).

Mechanical Properties of Spongy Tissue

Cancellous tissue is structurally more complex and heterogeneous than compact tissue, and so mechanical testing is a less straightforward procedure (Keaveny et al. 1997; Linde and Hvid 2000). A good deal of literature exists on the problem; the spongy tissue that is present as “sandwich fillings” in flat bones such as vertebrae and the bones of the pelvis plays a significant role in osteoporosis, and in the efficacy of orthopedic implants (Cosman et al. 1992; Gibson and Ashby 1997:429; Saito et al. 2006; Szivek et al. 1993).

The ways in which porous tissues respond to mechanical stresses is important to this discussion for two reasons. First, many osseous tool components are constructed primarily of compact tissue, but raw material size or dimensional limitations -- or deliberate design choices -- can result in a worker’s incorporation of some spongy tissue into the piece, which will affect its mechanical properties as a heterogeneous structure. The retention of some of antler’s spongy core is seen in many Aurignacian points (H. Knecht 1991), and in some of the Kodiak material, especially along one face of sea mammal harpoons. Second, the marine mammal bone from which Alutiiq people constructed various tool components is primarily a macroporous tissue. Tools constructed from these bones would be expected to function quite differently from those comprised of compact bone when used for the same tasks.

While painstaking research has aimed to determine the mechanical properties of individual bone trabeculae (see references in Currey 2002:Table 5.1 and in Gibson and Ashby 1997:Table 11.2), the strength, stiffness, or resilience of these tiny structures in isolation is not of great interest to archaeologists or, in most cases, even to biomedical practitioners beyond its contribution to basic knowledge. Within any bony tool component or skeletal element networks of trabeculae act in concert, along with the negative space that they define, to create an entire load-bearing architecture. The spatial variation in trabecular orientation and macroscopic porosity can be great and has a profound effect on the mechanical properties of the overall tissue (see Gibson and Ashby 1997:Figures 11.7 and 11.8). It is at this scale that the properties become relevant to technological interests.

Individual trabeculae are, however, of interest when analyzing the way in which spongy tissue responds to compressive stress, as tools used for a variety of functions would undergo. The rods or plates bend elastically (as opposed to permanently) in response to small compressive stresses such as those routinely encountered in the body. Large loads create damage by causing thin struts to buckle, while thicker struts or plates respond slightly differently to damaging forces depending on whether they are wet or dry. If the tissue is moist the trabeculae will form micro-cracks, while dry trabeculae will fracture catastrophically (Gibson and Ashby 1997:439). Outside of the body bone is a dead tissue incapable of repair, but greasing or soaking the tissue may lengthen the use-life of tools subject to compressive forces.

Although irreparable, even the collapse of dry trabeculae need not signal the demise of all tools constructed from porous bone. The measured strength of the entire porous tissue remains constant through a certain amount of compressive loading as the individual “cells” or porous spaces are packed closer, and when crushing has totally eliminated open pore spaces there is a steep *rise* in the strength of the denser, compressed tissue (Gibson and Ashby 1997:439). Changes in other mechanical properties surely ensue; whether these are deleterious or beneficial from a technological standpoint depends on how the bone is intended to be used.

Variations on the Theme

Ungulate Limb Bones

Next to human skeletal elements, the tubular, marrow-filled limb bones of ungulates come closest to the ideal, or generalized bone described above. Artiodactyls (even-toed ungulates) are typically fast runners and have tapering limbs in order to decrease the inertia of limb movement (Biewener and Bertram 1991:69; Lieberman and Pearson 2001). Mass can also be reduced through the fusion of adjacent elements (Biewener and Bertram 1991:69), such as metapodials among artiodacyls, and the radius and ulna of horses (perissodacyls). The benefits of decreased mass do not come without cost, however, as it increases the likelihood of fracture, especially during violent movement such as sudden accelerations (Currey 1984:224). The shortening and straightening of the most distal elements of equids help to decrease bending moments (Lieberman and Pearson 2001:270). Artiodacyl limbs, in contrast, are relatively long and curved. While promoting bending stresses (Biewener and Bertram 1991:71), Bertram and Biewener (1988) believe this design may also increase the predictability of loading. Cervid limb bones tend to have a relatively high mineral volume fraction and associated stiffness, which perhaps compensates for the limb curvature. An axis deer femur and fallow deer tibia each contain about 16% more mineral than an adult human femur, for instance, and are about 43% stiffer (Currey 2002:Table 4.3), demonstrating that even small adjustments in the composition of bone material can effect major variation in its mechanical properties.

<u>Bird Bone</u>

"…birds are the only vertebrate class globally adapted to both bipedalism and flying (Cubo and Casinos 2000b:113)."

Bird bone has often been utilized in its natural tubular shape. Its structural as well as material properties are thus relevant to its technological uses. The mass of avian long bones decreases distally (Currey 1984:227) and long bones generally contain gases rather than marrow in central cavities (MacGregor1985:9), especially in the humerus (Cubo and Casinos 2000a:503). Gulls and terns (order Charadriiform), which were utilized by Alutiiq groups (Fitzhugh 2003:Table 2.2) are unusual in that all of the limb bones are marrow-filled rather than pneumatized (Cubo and Casinos 1998:Table 1). Both gas- and marrow-filled long bones of flying birds have thin walls (Currey 2002:Figure7.8). However, marrow-filled bones tend to have thicker cortices than gas-filled ones (Cubo and Casinos 2000a:Table 2; Currey 1984) and as *whole bones* also tend to be stiffer and stronger (Cubo and Casinos 2000b:Figure 2). Cubo and Casinos (2000b:Figure 2) claim that the stiffness of some marrow-containing avian bones rivals that of the bone materials of the highly mineralized whale rostrum and auditory bulla (discussed below)!

The existing literature has not yielded many clear functional explanations for the observed variation in whole bone properties, including patterns of marrow distribution. This probably owes to the great variation in the style and duration of flight and other locomotory activities exhibited between species, and perhaps reluctance on the part of researchers to match laboratory and detailed field data on animal behavior. The connection is clearer among flightless birds whose bones do not need to be as light as those of flying species, and tend to have R/t ratios (relative amount of cortex versus medullary space across a transverse plane measured mid-shaft) similar to those of land mammals (Currey 2002:Figure 7.8).

Prototypical fliers, birds may engage in other habitual types of movement, including bipedal walking, swimming, and flight take-off and landing motions. The associated stresses affect different regions of the body, such as weight-bearing in leg bones versus aerodynamic stresses placed on wing elements during flight. These would influence each bone's structural properties as well as their overall size and shape. For instance, the movement of a splayed pigeon's wing during flight creates considerable torsional and bending stresses in the humerus and radius-ulna (Pennycuick 1967). The adaptive advantage in being able to withstand stresses in these directions extends to tubular bird bone awls, used to press or twist their way through materials.

Bird bone shafts are thus strong, slim cylinders, and are lightly supported with internal struts to prevent buckling (e.g., Pennycuick 1967:Figure 3). This design reduces mass while allowing for a level of structural stiffness that exceeds that of a solid sliver of compact tissue of comparable cross-sectional diameter (Biewener 1982:298). The carry-through to their use as awls is again immediately apparent. Bird bones can also maintain sharp points with diameters sized appropriately for creating holes in skins and hides. Finally, the fact that bird bones are both hollow and thin-walled has also been exploited in the past, making them convenient, portable containers for storing needles or pigments and an acoustically ideal medium for constructing flutes and whistles.

Pinniped Limb Bones

Non-terrestrial bone was a central medium in the toolkits of many coastal forager groups, including Alutiiq groups, who have traditionally shaped a variety of hunting, fishing, and domestic equipment from the bones of marine mammals (D. Clark 1974, 1979; Crowell et al. 2001; Heizer 1956; Jordan and Knecht 1988; Wake 1997, 1999).

The skeletal adaptations of marine mammals are tangential to the clinical and engineering inquiries that drive current bone research, but interest in the topic has slowly been mounting since William Felts and Francis Spurrell wrote the following in 1965:

> The overwhelming majority of studies on orientation, density and the mechanical significance of bone structure have dealt with tubular bones of terrestrial mammals…At the same time, however, there has been scant advance along similar lines in comparative skeletal structure…This disparity is critical, for the comparative approach is necessary in order to distinguish species specific from more general structural characteristics, and to develop some insight into common mandatory relationships which must exist between function, size, gross and microstructure, and density, composition and the physical strength of skeletal elements (Felts and Spurrell 1965:171-172).

Pinnipeds (seals, walruses and sea lions), sirenia (manatees, dugongs, and the now extinct Steller's sea cow) , and cetaceans (whales, porpoises and dolphins) are secondarily adapted to aquatic life, and possess special adaptations for swimming and diving to counteract the positive buoyancy caused by air-filled lungs. Their bodies are insulated with a thick layer of blubber and a streamlined morphology reduces drag in the water. Static weight-bearing requirements are reduced, and a primary concern instead is the ability to maintain neutral buoyancy -- one that requires no special energy expenditure -- at depths below the water surface (Madar 1998:354). The skeletal solutions to this problem are diverse, and will be explored separately for the three taxonomic orders.

There is some disagreement over the degree of relatedness between Phocid (earless) seals versus the Otariids (eared seals and sea lions) and Odobenidae (walruses) (Nowak 2003:65). The pinnipeds as a group nonetheless share physiological strategies for conserving oxygen that enable sustained periods of submersion underwater. These include an ability to dramatically decrease heart rate ("bradycardia") and to reduce blood circulation to the outer extremities during dives (Nowak 2003:67). Neutral buoyancy at various depths can be achieved by expelling air from the lungs before descent (REF) and additional depths maintained through continuous swimming (Taylor 1994).

Aquatic locomotion poses different mechanical challenges to skeletal elements than those encountered on land, resulting in limb elements with grossly different architecture than those of terrestrial mammals. Phocid seals propel themselves in the water through lateral movement of their rear flippers, while otariids move their wide front flippers in small arc motions, pressing their smaller hind flippers together to act as a rudder (Harrison and King 1965:116-117; Versaggi 1981:6-7). Otariids have the added ability to rotate their hind limbs forward which allows them to "walk" on land.

The proximal limbs are foreshortened but robust, with large muscle-attachment sites related to rotational and lateral movements (Versaggi 1981). Among terrestrial mammals the ratio of mid-limb radius to cortical thickness (R/r) (a measure of how "filled in" an element is, with a score of 1 = fully filled) falls within a fairly tight range (Madar

1998:Table III) as do actual limb bone densities (Wall 1983). The structural densities of pinniped limb elements are more scattered by species, and probably reflect a range of specific feeding and locomotory adaptations. Like tapirs, hippopotami, and other habitual swimmers, sea lion limb elements have relatively thick cortices and spongy tissue-filled marrow cavities (Madar 1998:361). This differs from the cancellous tissue embraced by only a thin veneer of cortex that composes the majority of each elephant seal limb bone. For reasons that are not well understood, a feature unifying all of the secondarily aquatic adapted mammalian taxa, including cetaceans, is the lack of an open medullary cavity. The cancellous tissue filling of limb shafts is often very dense in appearance and can grade imperceptibly into the outer cortical region.

Finally, pinnipeds are among the several taxa possessing an *os penis*, or baculum, which can reach over two feet in length. Known as *oosiks* throughout Alaska, these bones are slightly curved and extraordinarily dense. They are often seen worked into knife handles for the tourist trade by modern Alaska Natives, but it is likely they had other practical uses prehistorically. At least one and possibly two socket pieces from the Kodiak collections were almost certainly constructed from *oosiks*, which would have added considerable weight near the front of a weapon assembly to aid in its propulsion. A third very dense piece with a sharpened tip is likely made from an *oosik* or a fragment of bone from a Steller's sea cow.

Bones of the Sirenia

Sirenia exhibit anatomical streamlining features similar to those of cetaceans, including a loss of the rear limbs and a torpedo shaped body (Harrison and King 1965), but are not built for dynamic locomotion. Gentle vegetarians who live in relatively shallow waters, positive buoyancy among the sirenia is balanced hydrostatically through the special adaptation of pachyostosis, or "heavy bones" characterized by the thickening of compact tissue. In the case of sirenia, this thickening is created at the expense of spongy bone, a concomitant condition known as osteosclerosis (Domning and de Buffrénil 1991). The structural densities of the effected elements are thus very high (Wall 1983). Unlike the systemic condition seen in many aquatic reptiles (Wall 1983) and some early archaeocetes (Madar 1998), bone thickening in the sirenia is centered on the forelimb and ribs (Fawcett 1942) which is near the center of balance, and may help the creatures maintain a horizontal posture in the water (Domning and de Buffrénil 1991).

Pachyostosis may be linked to a paucity of osteoclasts, or bone-resorbing cells (Fawcett 1942), so that the typical balance between bone growth and resorption seen in other mammals is not maintained. This adaptation would be impractical for more dynamic swimmers who must feed at various ocean depths (Madar 1998: 355) but the permanent ballast that heavy bones provide apparently is an evolutionarily acceptable strategy of buoyancy control for slow-moving species who feed at a more consistent depths. The north Pacific dwelling Steller's sea cow (*Hydrodamalis stelleri*) would have provided a dense raw material perhaps similar to that of the ivory of walruses, which are rare in the waters near Kodiak. Sadly, after the explorer Vitus Bering recorded the first

European observations of the creatures in 1741, it took only 27 years for the sea cow to be hunted to extinction (Nishiwaki 1972:193).

Cetacean Bone

"…cetaceans, whether large or small, possess characteristics of body, limb and skeleton that afford maximum contrast with terrestrial forms (Felts and Spurrell 1965:172)."

Sea mammal bone was a prized resource for many prehistoric groups living at northern latitudes, both as large architectural elements (e.g., Black 1987; McCartney 1979; Savelle 1997) and to create portable tools, including weaponry and woodworking equipment (D. Clark 1974, 1979; Crowell et al. 2001; Heizer 1956; Jordan and Knecht 1988; Steffian 1992; Wake 1997, 1999). Its usefulness in these cases may well stem from the great size of skeletal elements and the fact that it could be scavenged on-shore as well as obtained fresh, in addition to any special biomechanical properties it may possess.

The cetacean's hind limbs have been lost in the evolutionary transition to obligate aquatic locomotion and only a vestigial pelvic girdle remains (Harrison and King 1965:14). Cetaceans are similar to pinnipeds in that the humerus supports large muscle attachment sites and is the most greatly foreshortened of the limb elements, while those more distal tend to be larger or flatter to support fan-like flippers (Felts and Spurrell 1965:174).

Cetacean limb bones are composed of a complex mosaic of adjacent tissue regions which are characterized by different degrees of porosity (de Buffrenil and Schoevaert

1988; Felts and Spurrell 1965) so that the typical measures of R/r become meaningless (Currey 2002:207-208). Photodensitometry measurements from radiographs of the humeri of finback, beluga, and pilot whales show an amedullary core of porous bone tissue (Felts and Spurrell 1965). The density of the humeral bone tissue of the largest of these, the finback (*Balaenoptera physalus*), increases toward the edges of the bone but "even in the most dense regions, porosity (ranging up to 0.1 mm) is discernible to the naked eye" (Felts and Spurrell 1965:185).

Like antler, specific whale bone elements are perhaps best known in this context for qualities which apparently lie at the extreme limits of what is considered "normal" in osseous tissues: separate studies have explored the tympanic bulla of a fin whale (*Balaenoptera physalus*) (Currey 1979), which serves a purely acoustic function, and the rostrum of a toothed whale *(Mesoplodon densirostris)* (Zioupos et al. 1997), both of which are hyper-mineralized. They are extraordinarily stiff as a consequence, but are also somewhat weak. Although both stiffness and strength increase with mineral content to a certain point, very high mineral content results in a drop in strength (Currey 1969). The measured properties of these specialized structures are probably atypical of those of the overall skeletal systems of cetaceans, but due to the current lack of biomechanical data on other cetacean skeletal elements, it is difficult to state what "typical" truly would be.

Kabel and colleagues (Kabel et al. 1999) measured the intrinsic stiffness of sperm whale (*Physeter catadon*) vertebral bone in compression, arriving at a range of 5.6 +/- 0.2 GPa, which is on the low end for osseous tissues. Compression testing of porous materials is tricky because machining test specimens truncates some surficial pores, so that they are more easily compressed than intact pores. Due to edge effects, compression tests of cancellous tissue may systematically underestimate the true stiffness by as much as 20-40 % (Keaveny et al. 1997). This would put the true value of the vertebral bone in the range of 6.72 – 7.84 GPa, not accounting for random error; both ranges, however, are on par with those obtained here for intrinsic stiffness values obtained for *Rangifer* antler (Chapter 3), although the latter were obtained in bending and not compression. Significantly, seventy five percent of the variation in stiffness values obtained for the whale samples was explained by differences in the degree of porosity (Kabel et al. 1999:679).

Currey (1988a) tested anterior and posterior portions of a fresh Atlantic whale rib in bending and determined that the tissue is only slightly stiffer than that of dried and rehydrated *Rangifer* antler, and slightly less stiff than antler of the Asian muntjac deer (discussed below). Scheinsohn and Ferretti (1996) found that dry sperm whale clavicle samples had a low intrinsic stiffness compared to bird and camelid (guanaco) bone. The low stiffness could stem from a lower mineral content or mineral volume fraction (which is inversely proportional to porosity) than those of more "standard" terrestrial specimens such a bovid or cervid limb elements (Currey 1988a:Table 1). Using data obtained from a diverse set of animal bones Currey (1988a) has determined that material stiffness (Young's Modulus) of samples tested in bending is generally proportional to both mineral content and mineral volume fractions cubed.

<u>Antler</u>

Antler is an extraordinary and even bizarre type of osseous tissue that is unique to the family Cervidae and, with the exception of members of the genus *Rangifer*, to males. Antlers are the only mammalian appendage that can completely regenerate (Goss 1983:xiii) and because they develop and are shed annually, they form at an incredible rate: American elk (wapiti) antlers grow about a centimeter and a half *per day* (Goss 1983:3). They are paired, characteristically branching bony structures each of which extends from a pedicle -- a knobby protrusion of the frontal bone. Typical antler consists of a cortical sheath enveloping a completely trabecular- rather than marrow-filled interior. During growth, which proceeds from the tips (Goss 1983:153), antler is covered with a layer of velvet, a hairy, blood-vessel-rich skin which feeds and protects it from drying. Impressions of the velvet's arteries are left on the growing bone (Goss 1983:164; MacGregor 1985:12) giving the surface its familiar runneled appearance. Timing varies by species[1], but circulation through and surrounding the spongy bone core wanes as the trabeculae grow in diameter (Goss 1983:159) so that blood flow originating from pedicle is eventually halted altogether. When ossification is complete the vascularized velvet coating is shed, at which point the antlers are a dead tissue. Following the rut, each of an individual's paired antlers is cast off separately and the skeletal mineral reserves previously shunted to antler growth can begin to replenish if food supply permits (Brown 1990).

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[1] Male reindeer, for instance, typically shed their antler velvet in early fall, rut in October, and loose their antlers in December. White-tailed deer follow a slightly later schedule (Goss 1983:44).

Hasty development, a brief life span, and distinct mechanical requirements call for a type of structural organization in antler that is dissimilar to that of the prototypical "corporeal" bone described in the first section of this chapter. Antler cortex possesses the Haversian systems that result from bone remodeling (Currey 1989:471), but is relatively poorly organized, consisting of a porous fibrolamellar, or laminar bone (Currey 1989:471; MacGregor 1985:3) incorporating alternating layers of ordered lameller bone and the more chaotically structured woven bone (Vincent 1982:152). This type of microstructure can form more rapidly than lamellar bone (Currey 2002:17).

Although the direct relevance of antler to human clinical research is seemingly limited[2], the tissue has received a surprisingly large degree of attention in biomedical literature (Currey 1989; Mauch et al. 1992; Rajaram and Ramanathan 1982; Spatz et al. 1996, Sedman 1994**;** Zioupos et al. 1994), probably because its mechanical properties represent an extreme among those of bony tissues. Mechanical studies clearly show that antler has rather unique properties in relation to those of typical land mammal bone, but how these properties compare with those of the bones of marine mammals is so far not well understood. (Chapter 3 discusses mechanical tests performed to contribute to this dataset.)

Antler is neither stiff nor particularly strong as a material. Cortical tissue from a fresh bovid femur is about twice as stiff, and nearly 1.5 times stronger than red deer antler. However, in toughness antler ranks far superior, as it is 3.6 times more resilient than bovid bone (Currey 1979). The difference between the two tissues is evident in scanning

[2] G. Bubenik (1990) argues for its relevance to the study of bone cancer due to antler's rapid growth rate.

electron microscope (SEM) photographs of the fracture surfaces of the two types of specimens broken in bending. The antler surfaces are much rougher, which corresponds to its greater shock-absorbing potential (Currey 1979:341, Fig. 1a). The author neatly explains differences in the mechanical properties of antler and the more typical bone by recalling the biological requirements for the different types. In particular, antler impact resistance is at a premium for competing bucks who entertain frequent head-butts and pushing matches during the fall rut. Bovid bone, on the other hand, is less often loaded in sudden impact, but must be stiff to support the load of large bodies.

Woven and fibrolamellar bone are described in the literature as more highly mineralized than lamellar bone (Currey 2002:12, 18; Martin and Boardman 1993), but this is inconsistent with the fact that antler has a relatively *low* mineral content, to which Currey (1979) attributes its superior fracture resistance. Lower mineralization has been clearly shown to correlate with lower intrinsic stiffness and, to a certain degree, reduced bending strength (Currey 1988a, 2004). Red deer (wapiti) antler is 59% mineral (calcium) by weight versus 67% in bovid femoral tissue (Currey 1979:314), although antler's mineral contribution, like bone's, probably varies somewhat with age of the antler and the region sampled (Brown 1990).

How do these comparative properties hold up along various axes, as tools made from them might sometimes be loaded? As noted earlier, bones are stiffer, stronger, and more fracture resistant when loaded *along* their grain than across it (Yamada 1970). To my knowledge, the effects of loading direction on the fracture resistance of antler have not been explored but MacGregor (1985:Table 2.1) does present data on orientation effects on intrinsic stiffness and strength. Wet bovid bone and red deer antler are both about twice as strong along the grain than they are across it. The stiffness of fresh antler is more anisotropic: while bone is slightly stiffer loaded axially, antler is more than 2.5 times stiffer when loaded in this same direction.

From a technological perspective, antler and bone may be worked into tools, and those tools used and maintained either wet or dry, so that the properties of these materials in a less than fresh state are equally interesting for determining their most suitable uses. Binford (*in* White 1982:179) has claimed that "shed antler is almost useless for the manufacture of most kinds of bone tools requiring strength and resiliency." Shed antler in fact supplied most of the antler used in the late Roman period (MacGregor 1985:32), and was the preferred medium for items like composite hair combs, which were specially designed to minimize fracture potential (MacGregor and Currey 1983). Although shed antler is certainly dry in the sense that it is unvascularized, antler is probably not moist even throughout its entire tenure as an attached appendage. Chapman (1981) proposes that the moisture in antler, which is present as blood in the cancellous core, is retained during the rut, when male fighting is at its peak and antlers are most stringently required to withstand pugnacious impacts. As the frequency of fighting tapers off, the fluid is eventually lost, along with a degree of the antler's fracture resistance. Chapman provides interesting support for this hypothesis in that male muntjac, or barking deer (native to various parts of Asia), do most of their fighting with their unusually large canines rather than their diminutive antlers. Perhaps because of the resulting limited need for resilience, muntjac antlers have no spongy, fluid-filled core and are instead composed wholly of compact tissue (Chapman 1981:195).[3]

Binford is correct in assuming that shed antler looses some of its resiliency, but even so, its toughness remains superior to that of equally dry bone. The work of fracture for dry antler loaded along the grain is diminished to about that of *wet* bovid femoral bone (Currey 1979). In other words, antler's three-fold advantage in fracture resistance over bone holds whether the materials are both tested wet or dry (MacGregor and Currey 1983:Table 2). Drying also makes bone and antler stiffer and stronger, not weaker (MacGregor 1985:Table 2.1; Yamada 1970). Dry bovid bone is slightly stiffer than dry antler along the grain, while antler is slightly stronger (Appendix A).

The effects of drying are not always felt uniformly across different loading axes. Bovid bone stiffness does increase proportionately along and across the grain. However, the bending strength of bovid bone measured parallel to the grain increases, but drying has no effect on its strength across it. In other words, its strength becomes more anisotropic with drying (MacGregor and Currey 1983:Table 2). Antler stiffness and strength increase to similar degrees (about two-fold) with drying along both axes (MacGregor 1985:Table 2.1), but its dry toughness, manifested very anisotropically, is nearly *six* times greater along the grain than across it (MacGregor and Currey 1983:Table 2).

[3] Muntjac and tufted deer are unusual in other ways, including the location of the very long pedicles just above the orbits (Groves and Grubb 1990:135), atypical chromosomes counts (Goss 1983:23, Table 1), and among males, the presence of large upper canines that can move back and forth in their sockets (Goss 1983:23, 25).

The orientation effects of antler's mechanical properties -- both wet and dry-- are curious, as one might expect the direction of loading to be less influential for a material such as antler that is built from fibrolamellar bone (which includes a woven bone component) rather than pure lamellar bone. Macroscopically, a branching architecture helps to ensure antler's ability to withstand collisions from multiple directions, and tines that do not aid in this endeavor tend to be resorbed or reshaped (A. Bubenik 1990:41). The trabecular core may also provide some extra shock-absorbance. These features may obviate the need for an isotropic building material, especially one whose objective degree of fracture resistance is so great.

The extent of anisotropy in the fracture resistance of fresh antler clearly needs to be investigated, given the importance of this property in the biology of its bearers. When viewed from a technological perspective, anisotropy may be less important. With the exception of the largely spongy-tissue-filled palmate regions present in the antlers of a few species, antler's shape is strongly linear, thereby limiting the size of tool components that can be created across the grain (e.g., Corbin 1975). A second limiting factor is the degree and distribution of compact tissue, as this is the portion that has often been sought for technological purposes. The cortical portion of reindeer antler is thickest at the base of the brow tines, providing as much as 15 mm of material in fully developed antler and thinning distally to only 2-3 mm in the upper regions of the main palm (Corbin 1975:75, Appendix B).

Summary

Bones consist of a hierarchically organized set of materials containing both organic and mineral components. The structure and properties of whole bones and bone tissue strongly reflect an animal's mode of life: whether a species is primarily terrestrial, airborne, or committed to the sea, for instance, and have affected their use as raw materials in the past. Ungulate limb shafts cleaned of their soft tissues are stiff and strong hollow tubes. While smaller, bird bones maintain these same features through a weight-reducing thin-walled design. The cortical thickness of marine mammal bones varies considerably but the largest elements, those of large-bodied whales, are primarily of a spongy tissue. Limited research suggests they possess a low density and mineral content, accompanied by low stiffness and strength. Finally, antler is flexible and shock absorbent. Compared to dry ungulate bone, dry antler retains its relative degree of fracture resistance.

CHAPTER 3:
TESTING THE STIFFNESS, STRENGTH, AND FRACTURE RESISTANCE OF SKELETAL MATERIALS

Mechanical Testing: Terms and Concepts

In 1676 the physicist Robert Hooke penned an anagram which unscrambled reads: "*ut tensio sic vis*" or "the force varies as the stretch" (Popov 1976:35). Now a basic tenet of engineering and materials research, the statement means that in certain (linearly elastic) solids, the degree of extension, or "stretch," an object undergoes is proportional to the amount of applied force. In the last 330 years, a large battery of tests has been developed to formally characterize the properties of materials and structures, including bone.

Archaeologists interested in materials technology stand to learn a great deal from this type of research, but face the daunting task of distilling and translating the now vast array of testing terms and measured properties into those that relate most directly to the performance of skeletal materials as technological ones: how they can be shaped into tools, and how these tools perform under the stresses of use. This chapter reports on three of the most basic and widely applicable of the mechanical properties of skeletal materials: stiffness, strength, and fracture resistance, as measured for a range of skeletal materials.

Scalar Properties of Bone

Hooke's expression of the proportionality of force to deformation was conceived to describe the behavior of entire structures, whose size and proportions affect their overall strength and stiffness. It is easy to imagine how a long slender splinter of bone is less stiff than a short and stout fragment of the same material. However, two types of materials engineered to identical dimensions might also exhibit different mechanical properties. The explanation for this phenomenon lies in the intrinsic properties of the materials themselves. *Intrinsic*, or *material* properties, are dimensionless, meaning that they do not vary with the geometry of an object.

Bone averages about 60-70% percent biological apatite by weight, but variation in the mineral composition, or *mineral density* between different bone types has distinct effects on their mechanical properties (Currey 1979; Erickson et al. 2002), as discussed in Chapter 2 in the case of antler versus bovid bone. Such properties are most often determined experimentally using small test specimens of compact bone tissue, which is structurally more or less homogenous rather than porous at the macroscopic scale. Spongy tissue differs from its compact counterpart in that it is made up of a web of bony plates or struts which gives it a lower *structural density*, or weight per unit volume, than compact bone (Lyman 1994:237). The biomechanical study of spongy tissue presents methodological and even epistemological challenges to scientists because its mechanical properties stem not only from the mineral density of the basic bone matrix but also from the amount and distribution of air spaces within the overall fabric. A good analogy is polystyrene foam, or Styrofoam®, a synthetic polymer that incorporates numerous void spaces into its structure making it light, insulating, and shock-absorbent.

The distinction between *material* and *tissue* is critical here, because many osseous tools incorporate some spongy tissue or were engineered entirely from the porous bones of sea mammals. In these cases, a study of the mechanical properties of the underlying bone material that does not give equal consideration to those of the whole tissue would give highly misleading results. The laboratory samples tested in this study all consisted solely of compact tissue, but I will return to the problem of spongy tissue properties near the end of the chapter, as it is central to understanding the technological choices made by coastal foragers for whom marine mammal bone was a rich and plentiful resource.

Modulus of Elasticity (Materials Stiffness)

Stress and strain are measures reflecting the intrinsic properties of materials rather than the features that characterize whole structures. To obtain stress, the force that is acting on a test specimen (measured in kilograms force, or newtons) is divided by the cross-sectional area of the piece. Strain is a unitless measure that is calculated by dividing the change in one specimen dimension by its original dimension.

A plot of stress versus strain will have a constant slope when the material is deforming an in elastic, Hookean fashion (Figure 3.1). Once the stress is removed, the material is able to fully recover its original dimensions. The ratio of stress to strain in the elastic region is known as Young's Modulus of Elasticity, the elastic modulus, or simply E.

$$E = \Delta \text{ stress} / \Delta \text{ strain} \quad (1)$$

The stress/ strain slope will be steep for stiff materials, demonstrating that a relatively large amount of stress is required to create a small amount of strain, and will be shallow for flexible materials that are easily deformed by small stresses.

If a material is not brittle, then increased stress will cause it to eventually enter a new phase of permanent, or plastic, deformation. The moment of transition from elastic to plastic deformation is described as the yield point. The shift between the two deformation phases is not always distinct, as is the case for bone tested in bending, which results in a more attenuated yield region. In contrast, stone and other brittle solids show little or no plastic deformation, and a graph of stress versus strain will be nearly linear (Figure 3.2).

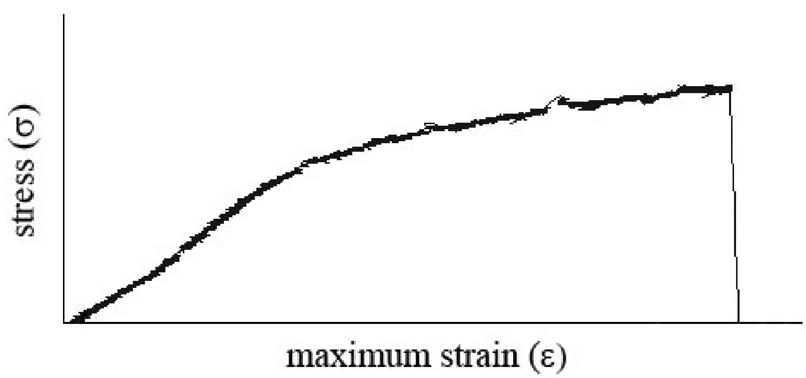

Figure 3.1: A diagram of stress versus maximum strain in a sample from the radius of a California sea lion (*Zalophus californianus*) loaded to failure. The short region of constant slope near the origin was used to calculate stiffness. Note that strain (ε) is plotted on the x-axis, and stress (σ) on the y-axis. Deformation (from which strain is obtained) is typically controlled during testing while the load required to produce the deformation acts as the measured variable (Currey 2002:35).

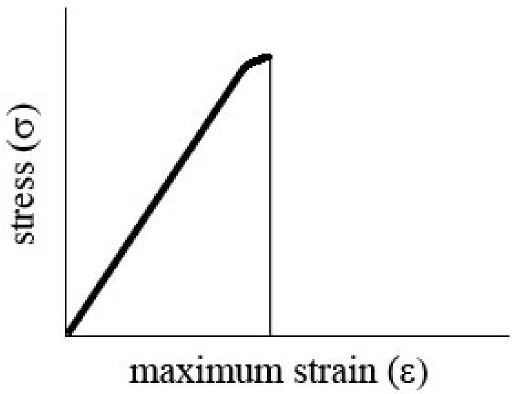

Figure 3.2: An idealized diagram of stress versus maximum strain for a brittle material. The vertical line represents specimen failure, which occurs after very little plastic deformation. Compare with the sea lion specimen diagram in Figure 3.1.

The intrinsic nature of the elastic modulus as a formal property gives it widespread utility. It can be measured from specimens loaded in a variety of ways, but the most common mode is in tension. The bending test employed here is another common approach that requires less complex shaping of the experimental specimen, which in turn reduces the likelihood of some types of measurement errors. To clarify that stiffness values were obtained in bending rather than in tension or by some other scheme, I use the term "bending modulus" throughout the chapter. The process of bending combines tensile and compressive forces and for this reason the properties of a material or sample in bending are not considered "pure" measures by engineers. But for bone, bending tests give the most realistic measures of a sample's overall failure pattern because *in vivo* limb bones break most often in bending (Wainwright et al. 1982:178), and the same is probably true of tools that are constructed of bone tissue in most applications.

Ultimate Strength (Stress)

Colloquially one can say that steel is strong and unfired clay is weak, but strength, like stiffness, is a term commonly used to describe both structures and materials. The strength values reported here are material properties, and are expressed in units of stress such as newtons/m^2 (pascals).

Various points along a stress-strain curve indicate important shifts that occur in the material as a result of internal rearrangements and stress concentrations (Figure 3.3). The stress at the yield point, or "yield strength" represents the point where plastic deformation begins. The ultimate strength represents the peak stress a material can withstand, and breaking strength is the point where a specimen fails, in some cases after a prolonged period of cracking and damage accumulation.

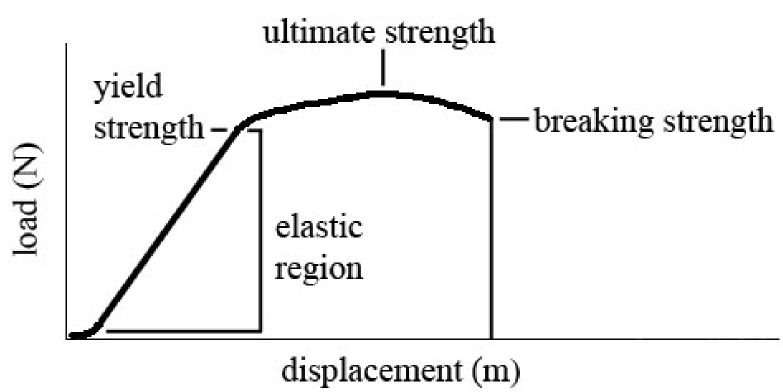

Figure 3.3: Schematic load-displacement curve showing key strength landmarks.

Turner and Burr state that the ultimate and breaking strengths of bone are often equivalent (1993:596) but as will be shown, this is only true for fairly brittle skeletal materials that are not structured to resist much cracking and damage. Failure in tougher materials is less catastrophic, and hence, occurs less consistently from specimen to specimen within a given type. For these reasons, ultimate rather than breaking strength is a more reliable indicator of a bone's practical limits, and the one reported here.

Fracture Resistance (Work to Fracture)

"The worst sin in an engineering material is not lack of strength or lack of stiffness, desirable as these properties are, but lack of toughness, that is to say, lack of resistance to the propagation of cracks (Gordon 1976:101)."

Work is the amount of energy (force applied over a distance) required to produce a certain amount of strain in a material, and can be measured up to any standard location in a load-deformation curve, such as up to the yield point. Work to fracture specifically refers to the amount of energy a material can absorb before it breaks, which is reflected in the total area under the load-deformation curve of a sample loaded to the point of failure. The greater the area of this region, the tougher (less brittle) is the material. Engineers may desire both toughness and strength in a material but the two do not go hand-in-hand. Many materials are strong but brittle, meaning that they can withstand great loads but once a crack is formed in them, they fail quickly and catastrophically. Fired ceramics and high carbon-content steel are both brittle. Tough materials are prized because although they may begin to deform plastically under low stresses, their ability to absorb large amounts of energy allows them to remain cohesive long after a brittle material would break apart. Ductile metals are able to flow under pressure and are hence fairly resistant to fracture, but some of the most successful tough materials are engineered composites, such as reinforced plastic (fiberglass), which typically combine strong but brittle materials with tough, flexible ones. Bone is a natural fibrous composite of this same type, and serves, along with other mixed mineral-protein biological structures, as an important model in the field of biomimetic materials design (e.g., Calvert et al. 2002).

Fracture resistance depends not only on the intrinsic strength of the material, but also on its geometry and the rate at which it is loaded. It is thus crucial to explicitly state the loading rate of test samples. A slow (static) rate was used in this analysis, but rapid (dynamic) loading is also possible. Consider an awl, pressed slowly and consistently against a working surface, versus a projectile tip of identical material and shape hurled into a target. The two will respond differently because the load rates are very different. The science of fracture mechanics has been developed relating the intrinsic strength and toughness of materials to their geometry, the loads on them, and how these affect their likelihood of fracture. “Work to fracture” is a very simple version of the kinds of tests that are used, but if the size and shape of the samples are held constant, as they are here, it provides a good measure of toughness.

Mechanical Testing Experiments

Introduction

Ungulates have supplied bone and antler to past artisans across diverse geographic and temporal contexts, beginning in earnest in the Upper Paleolithic of Eurasia (White 1982) or even earlier in Africa (Henshilwood et al. 2001; Yellen et al. 1995). The formal tools recovered from Upper Paleolithic sites range from Aurignacian split and bevel-based antler projectile points (H. Knecht 1997) to the literally thousands of reindeer metapodial and hare tibia needles found at the Magdalenian site of Petersfels (Albrecht and Berke 1982/1983). Coastal and inland Arctic foragers also relied heavily on caribou antler and limb bones to create diverse and highly-specialized tool kits (Corbin 1975; Hodgetts and Rahemtulla 2001; Murdoch 1892; Nelson 1899; Stordeur-Yedid 1980). Not just the purview of forager groups, a variety of osseous tools were also created by indigenous farmers of the Americas (Griffitts 2006; Olsen 1979, 1980; Steinbring 1966) and antler-working continued well into the Roman and Medieval periods of Europe on an industrial scale (Luik et al. 2005; MacGregor 1985) and as Griffitts (2006) has shown, these technologies continue in use today in industrial societies.

Ungulate limb bones and antler also have well-explored mechanical properties. Antler cortex has a low mineral content and a correspondingly low modulus of elasticity and intrinsic strength, and a high degree of toughness. The particular values vary somewhat depending on whether the antler is fully mature but nonetheless they tend to lie at the extremes for bony tissues (Currey 2002:Table 4.3, 1979). The mechanical data on ungulate limb tissues are scattered by skeletal element as well as by species but cortical tissue in these bones is always intrinsically stiffer and stronger than antler (Table 3.1).

Species and Tissue Type	**Mineral Volume Fraction (parts per thousand)**	**E (GPa)**	**Ultimate Tensile Stress (MPa)**	**Work Under the Stress-Strain Curve (MJ/m^3)**
Red deer immature antler	281	10	250	15.6
Red deer mature antler	287	7.2	158	9.3
Reindeer antler	300	8.1	95	3.2
Walrus humerus	352	14.2	105	1.4
Fallow deer radius	360	25.5	213	2.1
Bovid tibia	364	19.7	146	1.8
Brown bear femur	377	16.9	152	2.3
Roe deer femur	383	18.4	150	0.9
Horse femur	395	24.5	152	0.5
Bovid femur	410	26.1	148	0.3
Axis deer femur	428	31.6	221	2.4
Fallow deer tibia	430	26.8	131	0.4
Fin whale bulla	560	34.1	27	0.02

Table 3.1: Mineral content and mechanical properties of some mammalian cortical tissue samples tested in tension. Data from Currey 2002:Table 4.3.

Unlike coastal foragers of the past, however, researchers of bone properties have ventured little into the marine realm. Sea mammals are more enigmatic than those dwelling in humans' more familiar terrestrial habitats. In the United States and elsewhere, many species of marine mammals are protected by federal law, so obtaining fresh skeletal materials for laboratory testing is difficult, and is no doubt part of the reason they have been investigated so little. With the exception of whale bone as a generous source of cancellous tissue (Kabel et al. 1999), bones of marine mammals have little apparent applicability to current medical research. They have, however, contributed to the toolkits of forager groups even into the early 19th century. Examples include South American fur seal long bones with beveled ends used as wood-working bits by prehistoric Fuegians (Scheinsohn and Ferretti 1997) and limb elements from Steller's sea lions, worked by Native residents at the Russian station of Fort Ross in northern California (Wake 1999).

Mechanical tests of intrinsic stiffness, strength, and fracture resistance were carried out on cortical samples of sea lion limb elements, with the goal of determining the mechanical properties of a previously untested type of semi-marine adapted bone that competed for use in the toolkits of some northern forager groups. Samples of better-studied antler and ungulate cortical limb tissues served as references points. The more porous bones of cetaceans, also of great relevance to the study of maritime forager technologies, call for alternative and more challenging testing procedures not undertaken in this study. This issue is turned to in greater detail near the end of the chapter.

Sample Selection

Three broad categories of bony tissues representing greatly differing functional adaptations were chosen for study: (1) limb bones of a medium-sized marine mammal (2) limb bones from small to medium-bodied ungulates, and (3) antler.

Sea mammal bone is represented by three limb elements from an adult male California sea lion (*Zalophus californianus*). Sea lions are common along the Pacific coast of the U.S. and Canada, and were important resources for marine foragers, including Alutiiq groups, in the prehistoric past (Crowell et al. 2001; Fitzhugh 2003; Kopperl 2003;

Partlow 2000). They are adapted to life on land as well as at sea. Unlike the fully aquatic cetaceans (whales, dolphins, and porpoises), sea lions have a high proportion of compact to spongy tissue along their long bone shafts, and the structural densities of these whole bones are at the high end of the range exhibited by terrestrial species (Wall 1983). Structural densities of the humerus, radius, femur and tibia of the California sea lion all exceed those of corresponding elements from Eld's deer of Southeast Asia (*Cervus eldi*), reindeer/caribou (*Rangifer tarandus*), moose (*Alces alces*), and Alaskan brown bear (*Ursus arctos*), for instance (Wall 1983:199).

Land mammal bone in this study is represented by cervids of two body sizes: American elk, or wapiti (*Cervus canadensis)*, and white-tailed deer (*Odocoileus virginianus*) from Arizona. The final type of tissue is reindeer antler, whose mechanical properties, as noted earlier, have been fairly well explored, although not well in relation to those of sea mammals. The species and types of tissues included in the study are presented in Table 3.2:

Species Scientific Name	Species Common Name	Species Abbreviation	Tissues Tested
Zalophus californianus	California sea lion	CSL	radius (rad) ulna (uln) humerus (hum)
Cervus canadensis	elk (wapiti)	ELK	femur (fem) ulna
Odocoileus virginianus	white-tailed deer	WTD	radius
Rangifer tarandus	reindeer	RANG	antler (ant)

Table 3.2: Tissue types included in the analysis. Sample sizes per test are indicated in Tables 3.3-3.5.

Sample Preparation

Fresh white-tailed deer and elk long bones were obtained from a local game processor. A small amount of soft tissue, including the periosteum, remained on the samples. The samples were wrapped in saline-soaked gauze and frozen at approximately -20° C until needed, for a period of up to one year. The bones were thawed in the refrigerator and retained in the saline bath in anticipation of their use (following Pelker et al. 1984 and Sedlin 1965). Each skeletal element derived from a different individual but all samples of a given element type were extracted from the same bone. In the case of the white-tailed deer, only one element (radius) was included in the study, and thus the samples represent a single individual.

The antler derived from one reindeer[4] shot on Kodiak Island. The antler had lain exposed for roughly a year when collected by a member of the Alaska Department of Fish and Game[5] and had thus been subject to one yearly cycle on the island (Larry Van Daele, personal communication 1995). The sample was dry but much of the protective velvet layer was intact. The rack was sectioned and portions rehydrated in tap water (pH 7.5); antler blanks and finished test specimens were soaked in physiological saline beginning the day before testing.

The marine mammal bones were donated by any agency participating in the California Marine Mammal Stranding Network, with permission for their study granted from the National Oceanic and Atmospheric Administration. The donor animal had died despite rehabilitation attempts and was not sacrificed for this study. Its articulated limbs were received frozen with dry ice via overnight mail service. The bones were dissected out of the soft tissue and stored frozen and wrapped in physiological saline-soaked gauze until testing began, also a period of up to one year.

Prismatic, parallel-sided samples of compact tissue with rectangular cross-section were used for testing material properties. Although the sea lion bones are relatively thick-walled for aquatic mammals, they possess little shaft region to speak of, and the practical limits of extracting sufficient compact tissue for laboratory testing is one of the

[4] Although caribou and reindeer belong to the same species (*Rangifer tarandus*) and are morphologically identical, a distinction is made on Kodiak between caribou, local to the Alaska Peninsula but never to Kodiak itself, and reindeer. Reindeer were introduced on Kodiak in the 1920's in a failed commercial herding endeavor (Lantis 1952; Rausch 1969:217), and descendents of the original herds currently run wild in certain areas of the island.

likely factors responsible for the small corpus of knowledge that currently exists regarding the mechanical properties of aquatic and semi-aquatic mammals.

The samples were cut along the long axis of the long bones and the antler beam. A band saw can be used to create rough-outs but was found to generate large quantities of dust (even with frequent wetting of the specimen) and more importantly, high friction and occasional burning of the bone. Using a hacksaw for preliminary and intermediate shaping cuts allowed for the creation of regularly sized pieces while causing minimal thermal stress to the material. Occasionally, finer cuts were created with a hand-held electric Dremel tool. Samples were immersed in saline prior to and following cutting to reduce heat build-up and to retain moisture. A water-irrigated radial sander with successively finer grits of sandpaper was used to finish the specimens to a smooth glassy luster, and their final dimensions were measured to the nearest hundredth of a millimeter with vernier calipers.

The specimens were finished to ideal dimensions of 40 x 4 x 2 mm. True beam length varied between 35-40 mm per specimen depending on the available length of compact tissue in the bone, but in all cases the specimen's length-to-width ratio exceeded the minimum of 16:1 recommended for four-point bend tests (Turner and Burr (1993:601). The absolute values of width and thickness must be more tightly controlled as fracture resistance is sensitive to variation in cross-section dimensions. The mean width error for the 27 samples was 0.19 mm (s.d. = 0.050) and thickness error averaged 0.13 mm (s.d. = 0.049).

The limited availability of fresh tissues and ethical considerations often precludes the use of large sample sizes in biomechanical tests. The number of samples used here (Tables **3-5**) varies slightly by test, but accords well with that used by other researchers for similar experiments, which tends to range from 1- 13 per material type (Currey 1979:314; Currey 1988a:132; MacGregor and Currey 1983:75; Spatz et al. 1996:289).

Testing Bone Stiffness, Strength, and Fracture Resistance

The bone specimens were tested in four-point bending, which is becoming the flexural test of choice over the more traditional three-point set-up. In a four-point bend test a regular, prismatic beam rests across two supports and is bent through the lowering of a shaft (cross-head) fitted at the end with two closely-spaced top loading points (Figure **4**), much like a person standing on a skateboard. As with three-point bending, the top half of the specimen is thus loaded in compression and the bottom half in tension. A great advantage of a four-point set-up, however, is that a uniform bending moment is created in the beam between the inner load points, which not only allows the specimen to fracture at its weakest point (Lopez and Markel 2000:213), but also eliminates shear stresses between the two points. If a strain gauge is used to collect strain data directly (rather than calculating strain from cross-head displacement) such a device can be affixed to the sample anywhere in the region between these top two load points with consistent results. A three-point set-up utilizes a single top load point, resulting in a high probability of failure where tensile stress is highest – at the spot opposite where the load point contacts the beam – rather than where the beam is weakest. Moreover, complex shear forces can contribute to failure in three-point loading if specimen dimensions are not kept within a relatively bounded range (Jackson 1992:40; Turner and Burr 1993:601).

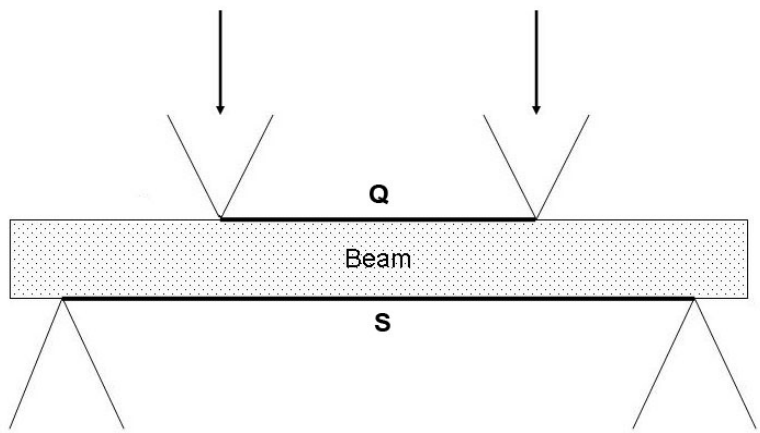

Figure 3.4: Schematic diagram of a beam loaded in four-point bending. The sample is suspended across the lower supports and the ends bent upwards as the two upper load points are lowered. The top of the beam is thus loaded in compression during testing, and the bottom in tension. Q = inner load span, S = outer load span.

A specimen holder designed for the experiments consisted of two aluminum slabs (each roughly 20 x 8 x 0.75 cm) that sandwiched a sample between laterally adjustable load points. The top slab bolted to the descending cross-head. The piece was custom-manufactured by Arcal Precision Components Inc. (Tucson, AZ) and included a hard anodized coating to prevent corrosion under wet testing conditions. During “compress and release” tests to determine stiffness, strain was measured directly using a 120 ohm strain gauge affixed to each sample with M-Bond 200 (cyanoacrylate) adhesive (Vishay Micromeasurements Group, Inc., Raleigh, NC) in the area between load points on the specimen’s top surface, which undergoes compression during the test. The gauges were in turn soldered to lead wires connected to a data acquisition system that outputs strain values.

The test samples were tested at room temperature (22° C) using an 810 Materials Testing System (MTS) linked to a data acquisition system and a desktop computer running LabView™ (Signalogic, Dallas, TX) software. Raw data output in tab-delimited files were converted to Microsoft Excel (Microsoft Corporation, Redmond, WA) spreadsheets for calculations and analysis. All tests were conducted in the Orthopaedic Research Lab at the University of Arizona Medical Center in Tucson, AZ under the direction of Dr. John Szivek.

The specimens were kept moist throughout preparation and up to the point of testing, at which point they were lightly blotted to avoid saline-induced changes in electrical conductivity at the gauge/MTS boundary. They were generally gauged and tested on the same day to ensure that no corrosion of the gauge or lead wires occurred. This obviated the need to waterproof the gauge-wire assembly, which would create an extra layer of thickness and potentially increase the stiffness of the sample. There are two advantages to testing the samples wet. First, it allows the data to be compared with results from typical biomedical studies which seek to emulate *in vivo* conditions of bone. Second, osseous hunting and fishing equipment, including the tools from Kodiak, were probably produced when the raw materials were relatively fresh. Fishing and sea mammal hunting gear would also have been saturated with water during use.

Two types of tests were performed on each specimen. During the first, the samples were placed in the specimen holder and flexed lightly in the elastic range only, which allowed stiffness to be calculated but produced no plastic (permanent) deformation. A slow cross-head speed of 0.52 mm/min was used for a period of 60 seconds, and a total of 3200 data points were collected at the rate of 50 points/second.

A second test was designed to bend each sample until failure. Here a more rapid cross-head speed of 2 mm/min was used for a period of about 130 seconds, yielding a total of 4,000 data points collected at a rate of 30 data points/second. The resulting curve was used to calculate strength and work to fracture, and to provide additional modulus (stiffness) data. Because bone has some viscoelasticity, the apparent stiffness of a specimen can vary depending on the rate at which it was loaded during testing (Currey 2002). Here, the "flex" and "bend to failure" tests utilized slightly varying cross-head speeds but the resulting modulus of elasticity values obtained from each type of test are comparable, as intra-specimen variation in modulus values was small and non-directional. The mean modulus data provide a better approximation of a material's true stiffness than could be obtained from a single trial.

Strain gauge tolerances were sufficient for measuring strain during "flex" tests but "bend to failure" tests produced strains beyond the recordable limits of the gauges. For consistency's sake, all tests used strain values calculated from cross-head displacement rather than readings obtained directly from the gauges, but the gauge data provided a useful means for assessing the accuracy of the cross-head values. While the bending modulus values obtained using strain gauges were considerably higher than those using calculated strain, the two data sets are strongly correlated (R^2= 0.91) (Figure 3.5).

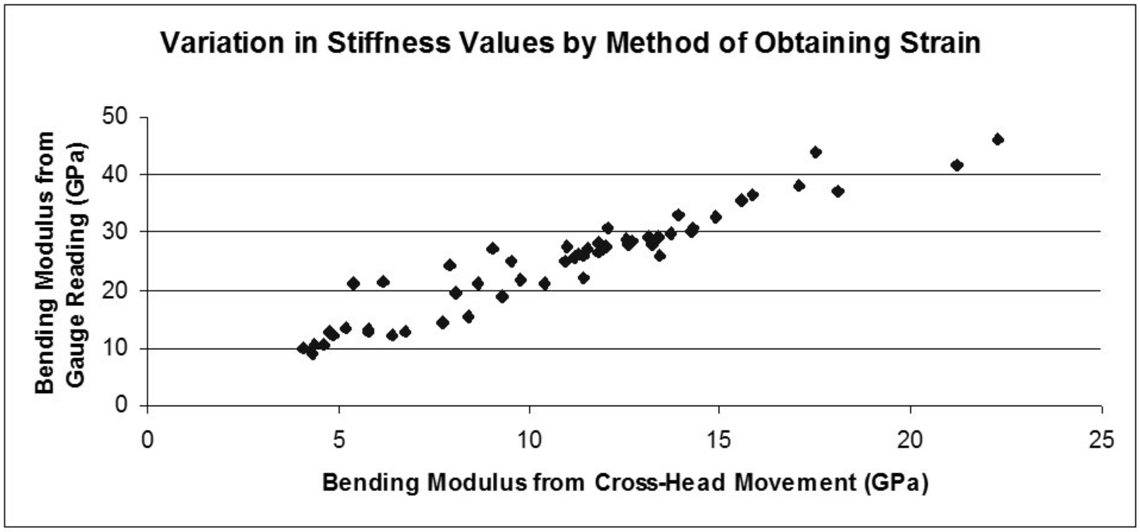

Figure 3.5: Values obtained here for the bending modulus based on strain calculated from cross-head displacement and direct strain gauge output.

The disparity in absolute values stems from shear stresses that occurred during bending, which are lower in specimens loaded in a four-point than in a three-point loading scheme but are nonetheless unavoidable. As a result, strain is overestimated when it is calculated from cross-head movement, so that the bending modulus (stress/strain) is underestimated (Turner and Burr 1993:601). This fact should be kept in mind when comparing the results obtained here to those of other researchers, and applies as a general caution because of the great diversity of testing protocols used in biomechanical studies (Turner and Burr 1993). For the purposes of this study, however, the difference between the two sets of values is unimportant because the data that are obtained are evaluated along an ordinal scale only.

Calculating Stiffness, Strength, and Fracture Resistance

The Elastic Modulus (E) for a material is simply change in stress over change in strain as measured in the linear elastic part of the stress/strain curve. Stress is calculated from the load placed on the specimen, and stress measures the amount of deformation the sample undergoes during loading. When a sample is tested in bending, its cross-sectional dimensions and rate of loading must also be taken into account. The results, expressed in units of gigapascals (GPa), reflect the intrinsic property of the material regardless of test specimen size or dimensions. Load versus cross-head movement distance was plotted for each sample. The slope of the linearly elastic region was used to calculate the bending modulus in four-point bending according to the following formula (from Jackson 1992:42):

$$E = (F/x)\ S^3 / \ 12I \times (3n-4/n^3) \qquad (2)$$

where S = outer load span (see Figure 3.4),

(F/x) = slope of tangent to initial linear portion of graph,

$I = bh^3/12$

where b = specimen breadth and

h = specimen height, and

n = 2S/(S-Q)

where Q = inner load span

The ultimate strength of a material represents the greatest stress it can endure before it begins to fail. It is reported here in units of megapascals (MPa). In four-point bend tests, ultimate strength is calculated using the following formula (adapted from breaking strength in Jackson 1992:46):

$$\text{Ultimate Bending Strength} = 3P_{max}\,(S\text{-}Q)/\,2bd^2 \quad (3)$$

where P_{max} = maximum load sustained by the sample,

S = outer load span,

Q = inner load span,

b = specimen breadth, and

d = specimen depth

Work to fracture was calculated by dividing the area under the load-deformation curve by twice the cross-sectional area of the specimen to account for its dimensions. Doubling the sample area accounts for the two fracture surfaces created when the piece fails.

$$\text{Work to Fracture} = W/\,2bd \quad (4)$$

where W = area under the load-deformation curve

b = specimen breadth, and

d = specimen depth

Results

Twenty seven samples were tested, with sample sizes ranging between 4 and 10 depending on the tissue type. Due to machine or human errors, no data were recorded for 2 of the sea lion work-to-fracture tests. All other tests were successful, and the results are given below (Tables 3.3-3.5).

Species and Tissue Type	**No. Tested**	**Bending Modulus (GPa) ± S.D.**	**Range**
RANG antler	7	5.68 ± 1.27	4.37-8.09
WTD limb bone	6	9.75 ± 2.32	5.78-12.14
CSL limb bone	10	11.97 ± 1.99	8.93-15.37
ELK limb bone	4	16.14 ± 2.86	13.56-19.89

Table 3.3: Bending modulus data by tissue type: RANG (reindeer antler), WTD (white-tailed deer radius), CSL (sea lion radius, ulna, and humerus combined), and ELK (elk femur and ulna combined).

Species and Tissue Type	**No. Tested**	**Ultimate Stress (MPa) ± S.D.**	**Range**
RANG antler	7	126.47 ± 17.18	106.68-151.01
WTD limb bone	6	168.61 ± 27.36	117.79-193.34
CSL limb bone	10	175.70 ± 30.85	125.85-223.84
ELK limb bone	4	244.57 ± 22.02	213.5-264.77

Table 3.4: Bending strength data by tissue type: RANG (reindeer antler), WTD (white-tailed deer radius), CSL (sea lion radius, ulna, and humerus combined), and ELK (elk femur and ulna combined).

Species and Tissue Type	**No. Tested**	**Work to Fracture (J/m^2) ± S.D.**	**Range**
RANG antler	7	*24,140 ± 11,654*	*12,059-44,345*
WTD limb bone	6	*24,326 ± 9,289*	*13,433-31,940*
CSL limb bone	8	15,298 ± 7,111	7,163-27,515
ELK limb bone	4	8,511 ± 3,604	4,883-13,452

Table 3.5: Work to fracture data by tissue type: RANG (reindeer antler), WTD (white-tailed deer radius), CSL (sea lion radius, ulna, and humerus combined), and ELK (elk femur and ulna combined). Work numbers in italics for RANG and WTD are approximations.

Stiffness

Rangifer antler stiffness values cluster tightly with a mean that is nearly a third that of elk long bone, the stiffest tissues sampled. The results accord well those from earlier studies demonstrating that antler is considerably more flexible than the compact tissue from bovid femora (Currey 1979; MacGregor and Currey 1983). The mechanical properties of sea lion limb bone have not, to my knowledge, been previously researched. The sea lion bending moduli data obtained here lie between those for the long bones of the two cervid species, demonstrating that the intrinsic stiffness of *Zalophus* cortical bone material is not categorically different from the values obtained for land mammals. On the other hand, the disparity in stiffness values between limb bones belonging to the two cervid species is notable. However, because the white-tailed deer specimens derived from a single skeletal element, and the elk samples from two elements of two individuals, it is not possible to assess if the large gap separating their stiffness values is the result of species-specific or individual differences.

Strength

The strong positive correlation ($R^2 = 0.73$) demonstrated here between bending strength and stiffness (Figure **6**) has been shown elsewhere for all but the most highly mineralized of skeletal materials (Currey 2002:97). In terms of strength, the antler values are less clustered than they are in the distribution of stiffness values but antler nonetheless ranks at the low end of the scale. Elk limb bone samples are twice as strong, with white-tailed deer and sea lion limb samples again found at intermediate values that largely overlap. There is little inter-element variation among both the elk and sea lion specimens. Mean stiffness versus strength values are shown plotted by element ($R^2 = 0.88$) (Figure 3.7) and grouped according to tissue type ($R^2 = 0.96$) (Figure 3.8).

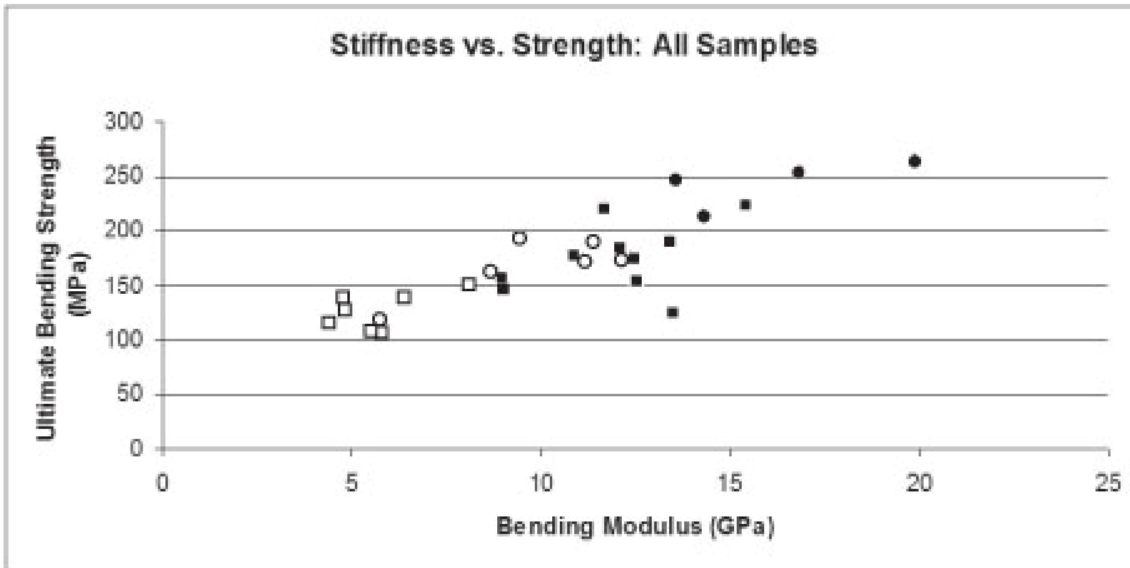

Figure 3.6: The relationship between intrinsic bending strength and bending modulus for all samples. *Open squares = antler; open circles = white-tailed deer limb bone; filled square = sea lion limb bone; filled circles = elk limb bone.* For comparison, the elastic modulus of collagen is only about 2 GPa (Catanese et al. *in* Erickson et al. 2002) while that of pure bone mineral (hydroxyapatite) is in the range of 110 GPa (Currey 1984:44; Weiner and Wagner 1998:276).

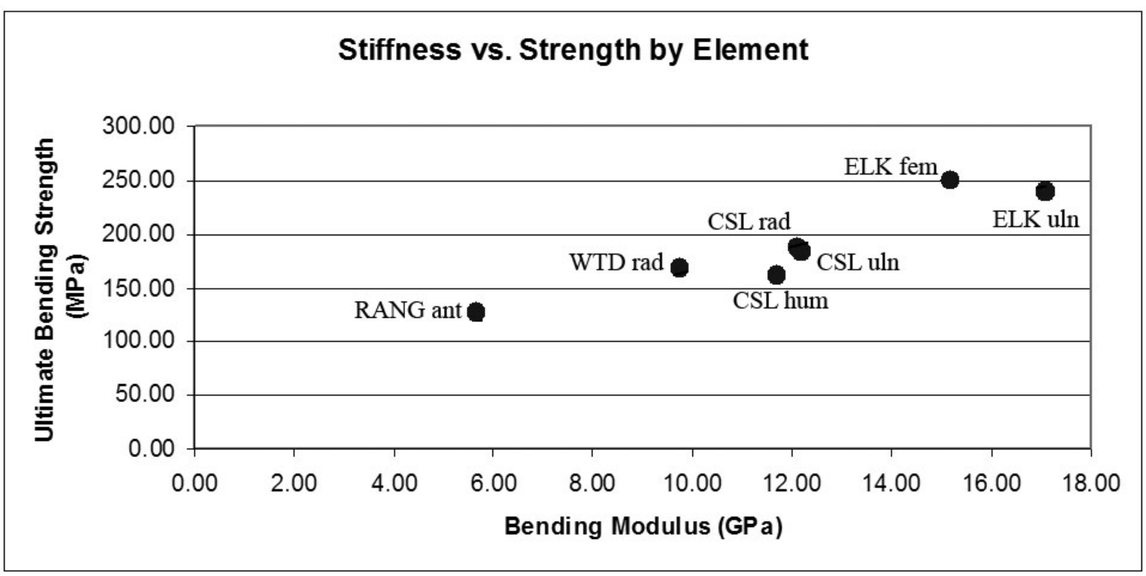

Figure 3.7: Mean values for strength plotted against mean stiffness by element.

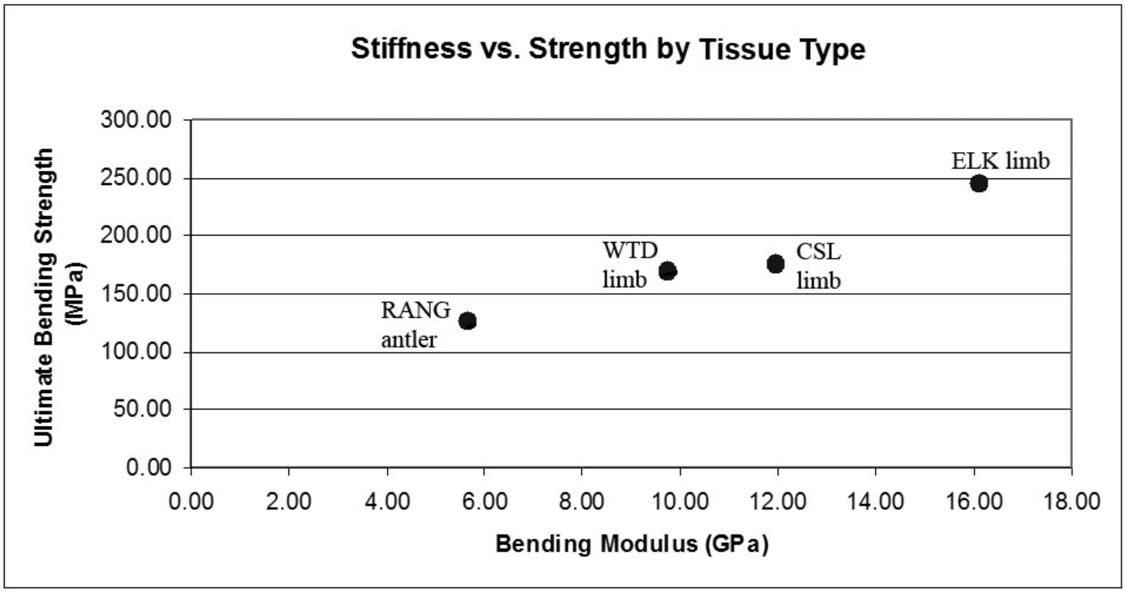

Figure 3.8: Mean values for strength plotted against mean stiffness by tissue type.

Work to Fracture (Toughness)

The work-to-fracture results demonstrate that fracture resistance in bone must be gained at the expense of strength and stiffness. Elk limb bone, both strong and stiff, proved to be quite brittle, in general showing little deformation following the yield region. Sea lion bone was nearly twice as tough, sustaining loads for nearly twice as long, but both materials paled in comparison to the antler and white-tailed deer limb samples. Both reindeer antler and white-tailed deer long bone showed the ability to undergo a large degree of plastic deformation as attested to by their notable behaviors during loading: four out of six white-tailed deer bones samples and all seven antler samples *did not fracture* during loading, merely bending in the specimen holder. Similar results have been previously demonstrated for antler (Albrecht 1977; Currey 1979), but not for deer limb bone. Currey (2002:130, Table 4.3) loaded compact limb samples from four cervid species to fracture in tension (the component of bending in which bone is weaker) and found that their work to fracture values were considerably lower than those of reindeer antler tested in the same study. In light of the brittle fracture exhibited by Currey's specimens and by some of those tested here, it is possible that the white-tailed deer bone tested was immature, as woven bone, with its randomly collagen fibril arrangement, would likely exhibit lower strength and stiffness than fibrolamellar or osteonal bone.

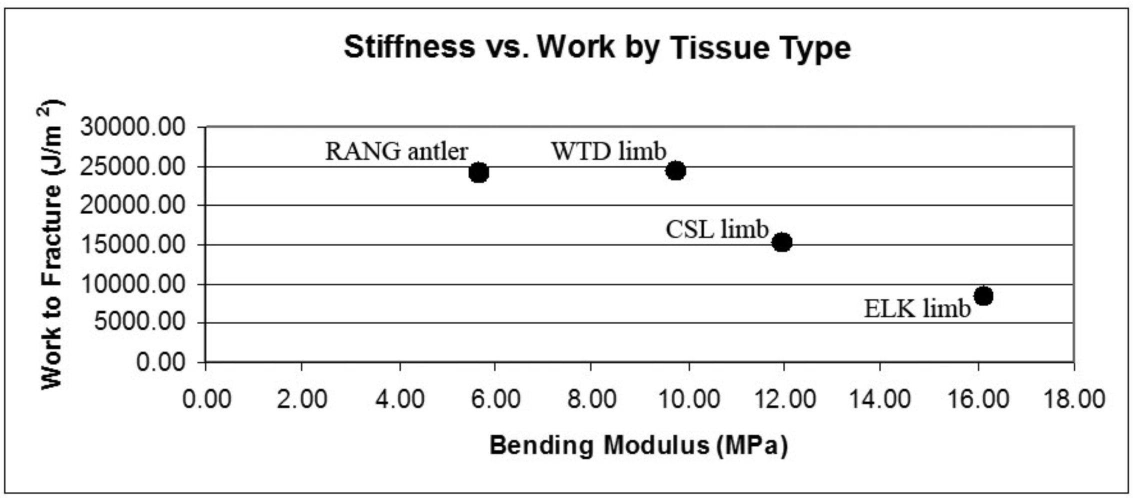

Figure 3.9: Plotting stiffness against work to fracture shows an artificial plateau representing underestimated work values for white-tailed deer long bone and reindeer antler samples.

In Figure 3.9 bending modulus data for the four types of tissues are plotted against mean work-to-fracture values. These "apparent" values for antler and white-tailed deer were calculated from the total area under the load-deformation curve regardless of whether fracture occurred. They are similar for the two types of specimens, and demonstrate the samples to be nearly three times more resistant to fracture than the elk samples, a considerable difference and one which prehistoric technicians would likely have recognized. The results are even more striking when considering the fact that with only two exceptions, the areas under the curves for white-tailed deer and antler samples do not represent work all the way to fracture.

A reasonable estimate of the full work-to-fracture values for antler can be made from the graphs for two samples (RANG 032 and 033) for which cross-head displacement was allowed to continue well beyond the range sufficient to produce fracture in the limb bone specimens (approximately 0.008 m, versus 0.004 m) with the exception of two white-tailed deer samples. Load-deformation curves for samples RANG 032 and 033 are bow-shaped, showing a decline in stress that approaches zero at a displacement of approximately 0.008 m, and graphically capturing close to the entire energy required to produce failure. Work values for these specimens were correspondingly the highest of the antler group, and with a mean of 40257 J/m^2, demonstrate that significant energy absorption would be expected to continue in this type of tissue beyond the known degree of deformation at which the limb bone specimens fractured.

The two white-tailed deer samples for which total work to fracture could be calculated (WTD 01 and 02) were simply more brittle than the other white-tailed deer samples. Yielding values that were among the lowest of the group (mean work = 17,367 J/m^2), they establish a lower limit on the white-tailed deer specimens. No such lower boundary has been established for antler but the true value can be considered close to that of RANG 032 and 033, considerably higher than is reflected in the total group average in Table 3.5.

A very rough approximation of antler work to fracture can also be made by extrapolating from the relationship between intrinsic stiffness and work to fracture by tissue type for WTD, CSL, and ELK, which is strong and linear ($R^2 = 0.94$). Plotting the mean stiffness of RANG antler (5.68 GPa) along the same regression line gives a work value of 32,463 J/m^2 (shown in gray in Figure 3.10). This is somewhat lower than the value indicated by RANG samples 032 and 033, but is nonetheless higher than the underestimated mean which is based on all seven antler samples. This approach does not take into account the fact that the WTD work values are also underestimates, thus shifting the mean WTD higher on the y-axis would elevate the work values for RANG even further.

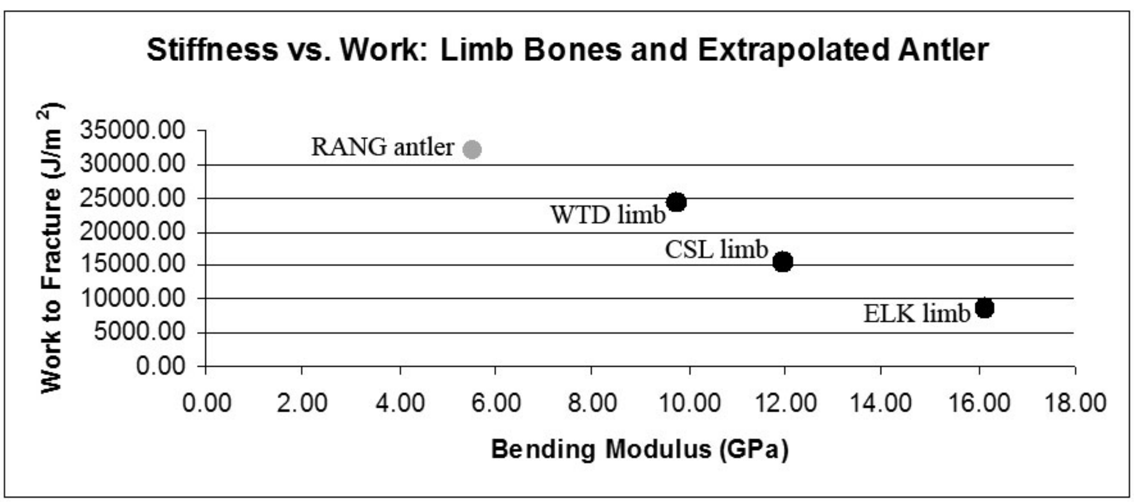

Figure 3.10: Estimated antler toughness.

Conclusions

Antler is grown rapidly and seasonally and with different load-bearing requirements than corporeal bone. It has been previously shown to lie at the lower boundary of strength and stiffness in bony tissues, and at the upper reaches in toughness in relation to a bovid bone standard (Currey 1979; MacGregor and Currey 1983). The results here demonstrate that the same contrasting relationship characterizes the properties of antler and those of the limb bones of the American elk (*Cervus canadensis*). Mineral volume is a major predictor of strength and stiffness, and is as much as 30% lower in antler than in the limb bones of bovid, brown bear, and other common terrestrial mammalian species (Currey 1979, 2002: Table 4.3). The results are particularly revealing for archaeologists interested in the many prehistoric societies in which deer antler, as a technological material, was selected over the limb bones of the very same animal, examples of which range from the Upper Paleolithic in Europe (Julien 1982; H. Knecht 1993) to more recent high-latitude foragers such as Alutiiq groups of Alaska (Chapter 6).

Samples from both elk and white-tailed deer were chosen as an additional guidepost for this study with the belief that the mechanical values of the specimens would align more closely to each other than to those of antler. The low modulus of elasticity and other mechanical properties of the white-tailed deer specimens were therefore unexpected. Currey's (2002: Table 4.3) data demonstrate that separate skeletal elements from the same species can possess divergent mechanical properties, such as in the radius and tibia of the fallow deer. (Currey does not specify if the elements derived from the same individual.) In the case of the present study, only a single white-tailed deer element was tested, whereas the elk samples were created from two elements from two individuals. The notably low modulus and strength values and great fracture resistance that the white-tailed deer samples exhibited may reflect a number of factors, such as the singularity of element type, or the sex or nutritional status of the individual (which can affect mineral density -- Ioannidou 2003; Pavao and Stahl 1999), or locomotory differences between white-tailed deer and elk. The fact that some white-tailed deer samples fractured during testing while others did not also suggests that mechanical properties can vary considerably between different regions of a single skeletal element. It is thus unclear in what way white-tailed deer data may be considered representative. If the results are accepted at face value, white-tailed deer limb bone would make a more mechanically acceptable substitute for antler, morphological distinctions aside, than elk bone.

This study has also explored the previously unknown properties of the compact tissue of *Zalophus californianus*, the California sea lion which, along with its cousin, the Steller's sea lion (*Eumetopias jubatus)* was a technological resource for prehistoric groups along the western coast of North America (e.g., Fitzhugh 2003:25; Wake 1997, 1999).

As a semi-aquatically adapted species whose limbs have a noted high *structural* density (Wall 1983), sea lion *material* limb bone properties lying outside the range of those of land mammals might have been expected. This was proved not to be the case, and in all respects samples of compact tissue from the sea lion limb bones tested here, humerus, radius, and ulna, fell squarely within the range of the terrestrially-adapted tissues. Although the form, function, and whole-bone densities of the limbs of most aquatically and terrestrially adapted mammalian species are divergent, the data obtained here suggest that the mechanical properties of the underlying compact bone do not divide along such neat lines.

A Comparison with the Cancellous Tissues of Sea Mammals

It is worth noting that select limb bones of the elephant seal (*Mirounga angustirostrus*) were also obtained for the study but were excluded on the basis that they possess too little (< 2 mm thick) compact diaphysial tissue from which to excise suitable test samples. The structural densities of elephant seal limb elements are low compared to those of both other pinnipeds and terrestrial mammals (Wall 1983), but the amedullary diaphyses of these bones are filled with closely-spaced spongy tissue (Versaggi 1981), giving them a dense appearance in longitudinal cross-section. A similar adaptation may be seen in the low structural density bones of cetaceans (whales, dolphins, and porpoises) (Wall 1983), about which little is known from a biomechanical perspective (but see Currey 1988a; Kabel et al. 1999), but are of importance here because of their use in prehistoric forager toolkits. Cortical tissue is largely absent in cetacean bones, which instead exhibit a complex mosaic of porous regions (Felts and Spurrell 1965) whose pattern shifts throughout ontogeny (de Buffrénil and Schoevaert 1998).

The mechanical properties of cancellous tissue are less well understood than those of compact tissue, in part due to practical barriers to testing spongy materials by traditional mechanical means. Ultrasonic, nanoindentation, and computer modeling techniques have been employed to derive some general properties of cancellous bone but results vary widely by approach (see Currey 2002:Table 5.1). Nonetheless, the Young's modulus of cancellous tissue has been shown to vary dramatically according to differences in both mineral density and porosity (Turner et al. 1990).

Research on cancellous tissue properties is undertaken at two scales: at the material level, or the bone which makes up individual trabeculae, and at the level of the entire spongy architecture, or tissue (Currey 2002:146). In the case of cancellous bone it is at the *tissue* rather than material level that the properties become most relevant to tool performance characteristics, especially as macroscopic porosity grades considerably within and between skeletal elements. Microscopic porosity in bone is created by features including Haversian systems, canaliculi, and the lacunae in which the cells reside (Wainwright et al. 1982:172), but it is at the macroscopic scale at which compact and spongy bone are (somewhat arbitrarily) divided, that porosity most strongly influences bone's mechanical properties.

Orientation of the trabeculae can impose a "grain" much as in compact tissue (Gibson and Ashby 1997:Figure 11.2, 431-433; Murray 1985:Fig. 23), and consequent anisotropy in a tissue's mechanical properties (Currey 2002:155). Hence, porosity and trabecular organization, born in this case of the functional adaptations required for aquatic life, are keys to understanding the mechanical properties of cetacean bone, a culturally important resource in the Kodiak region (Chapter 6) and one that merits increased scientific research as an engineering material.

Turning Towards a Cultural Context

Stiffness, strength, and fracture-resistance are objective properties, but the values these material properties assume from a cost-benefit perspective are more subjective and contextual. The ultimate goal of this research is not to generate recondite, numerical indices of bone properties but to be able to place them in real human contexts of use. The relationship between worker and material is dynamic and interactive, and through experimentation and observation of materials as they performed in a variety of contexts, ancient workers ascertained what materials would best succeed for certain tasks. No knowledge of molecular arrangements, stress accumulations, and other modern-science explanatory schemes is required by toolmakers to arrive at an understanding of the general limits of how a material is able to perform, making it more or less suitable for a particular use.

The innate properties of raw materials are a necessary starting place for understanding technological behavior because they place unavoidable limits on how the materials can be used. The intrinsic mechanical property data obtained here for several types of cortical bone are presented below along an ordinal scale (Figure 3.11). The relative tissue-scale stiffness of whale bone is also provided, based on data from two previous studies. Estimates of other mechanical properties of whale bone are based on the stiffness data and are indicated in gray.

MATERIALS	MECHANICAL (INTRINSIC) PROPERTIES: Stiffness	Bending Strength	Fracture Resistance (static loading)
reindeer antler	○	○	●
white-tailed deer (limb bones)	◉	◉	●
American elk (limb bones)	●	●	○
California sea lion (limb bones)	◉	◉	◉
whale bone (unspecified)	○	○ (gray)	● (gray)

● = HIGH

◉ = MEDIUM

○ = LOW

Figure 3.11: Some objective properties of prehistoric raw materials shown on an ordinal scale. Whale bone stiffness data derive from tests performed on sperm whale vertebrae by Kabel et al. (1999) and an Atlantic whale rib by Currey (1988a). Associated bending strength and toughness estimates of whale bone (indicated in gray) are based on these stiffness data.

Technical choices are not driven by material properties in isolation, however, but by the needs and constraints imposed on individuals who interact with those materials: the intended use of tools and tool components, how raw materials can be worked, and their availability or accessibility in particular ecologically and culturally bound contexts. Some of these constraints have wide-reaching relevance, such as the fact that elephant seal bones contain so little compact tissue that mechanical considerations may be of little consequence as far as most subsistence technology is concerned.

Other constraints may not accord with any starkly utilitarian predictions. The data presented here have broad baseline applicability, but ultimately make sense only when used to ground studies that draw on a wide range of variables to explain or compare the technological practices of specific cultural groups. Chapter 4 details some preliminary explorations into the performance characteristics of osseous materials in contexts of tool manufacture. In Chapter 6, the mechanical data obtained here are combined with evidence for how different raw materials were incorporated into actual tool design and use strategies by Alutiiq communities before and closely following Russian contact.

CHAPTER 4:
MANUFACTURING EXPERIMENTS

Introduction

The ways in which a tool can be manufactured and subsequently maintained, repaired, or reworked into something new are necessarily limited by the properties of the materials from which it is constructed. Some properties relate to the gross size and shape of the raw materials; others stem from their composition and finer levels of structure. The intrinsic mechanical properties of a variety of osseous tissues were explored in Chapter 3, providing essential baseline data during a key interval of time when these tissues are hydrated. Osseous implements, however, can enjoy great longevity -- sometimes on the scale of human generations -- and they differ from lithic tools in that their biological origins grant them susceptibility to physical and chemical changes that can occur over spans of days, months or years. In an important break from traditional biomechanical testing procedures, MacGregor (1985) measured various properties of dry skeletal materials, with the rationale that many Roman-era osseous implements would have been used, if not worked, in a dry state. What does dry really mean, however? Water loss, lipid destruction, and collagen breakdown are, after all, ongoing processes, and there is no binary distinction between wet and dry bone, or between fresh and old.

The processes that act on skeletal materials post-mortem but pre-burial deserve their own study, as they relate to the potential use of the materials as technological media. Determining intrinsic mechanical properties of raw materials is thus an essential but only preliminary step toward understanding the performance characteristics of the materials as they are delegated specific technological roles. It is important that a bridge be built between studies that seek to delineate the intrinsic properties of the materials in isolation from human behavior, and those that explore human technological activities within their larger ecological contexts.

Bone, antler, and ivory-working have been deemed time-consuming and laborious tasks, both by archaeologists (Guthrie 1983; H. Knecht 1997), and by modern-day, professional artisans who work with these materials, even those economizing their time and labor expenditures with the help of electric machinery (e.g., Lind personal communication). Yet the amount of time or labor required for "bone working" depends on any number of factors. Although many useful studies have ascertained the manufacturing stages involved in creating various types of bone, antler, or ivory blanks or finished tools (Campana 1989; Christenson 1999; Clark and Thompson 1953; Gelvin-Reymiller et al. 2006; Griffitts 2006; Julien 1982; H. Knecht 1993; LeMoine and Darwent 1998; McComb 1989; Newcomer 1974; Olsen 1979, 1980; Stordeur-Yedid 1980; White 1989, 1993), data on actual working times remain scarce, especially regarding variations between materials (but see Newcomer 1977). The next step is to outline and investigate the factors that lead to variability in labor commitments for the manufacture of skeletal technologies. Some variables to consider include the type of raw material and its state at the time it is worked, the chosen manufacturing methods, the tools that are employed, the desired end product, personal working skills, and culturally-prescribed working styles.

This chapter is divided into four parts, each treating bone and antler as materials whose properties are dynamic, shifting over the course of their life histories. First, I describe a series of exploratory timed bone- and antler-working studies. The experiments were planned to gauge the time investments required for producing tool blanks using several manufacturing techniques. Unplanned, post-mortem forces became factors in how the experiments played out, and the results of the study are discussed in the conclusions section that follows. Despite some shortcomings of the experimental procedures undertaken here, the data point toward some important areas for future research. Relevant information provided by bone-workers more experienced than myself and from ethnohistoric accounts is also discussed. In the third section, I briefly review some studies, largely from outside of archaeology, of the effects of three post-mortem processes to which bone and antler are susceptible: drying and rewetting, freezing and thawing, and exposure to salt water. Here the research interests of archaeologists and clinicians intersect, as these studies bear on how the physical and chemical changes that result from natural or human activities affect bone and antler's mechanical properties, and how the materials can be worked at various stages or degrees of alteration. In the final discussion a hypothesis is proposed for raw material selection based on the scheduling of blank production. However, further research on the working properties of fresh, dry, and re-wetted materials must first be conducted to evaluate this proposition.

Timed Manufacturing Experiments

Introduction

A series of exploratory bone- and antler-working studies were carried out over the course of 15 months. The initial aim was to gauge the time required for three techniques employed widely in the past for work osseous materials: (1) the groove and splinter technique for creating tool blanks, (2) the saw and snap method of removing unwanted end portions of a bone or antler, or to section them transversely, and (3) abrading, used to create and maintain the final contours of tool components. These techniques all involve a series of repetitive motions that leave diagnostic traces on the final products or waste products of manufacture, that have allowed the processes to be reconstructed in detail (Campana 1989; d'Errico et al. 1984).

As the experiments proceeded, it became clear that a number of unanticipated variables affected how efficiently the three techniques could be carried out. For instance, some specimens were allowed to dry for a period greater than would have likely been tolerated by tool-makers in the past. Although the experiments were performed systematically (e.g., timing of each activity, careful measuring of the surface areas of cuts), the extent of drying was not well controlled. Other working procedures such as tool maintenance and repair activities would have been conducted on materials that were less than fresh, however. To my knowledge, a longitudinal study on the effects of progressive drying stages on bone and antler workability has yet to be conducted: this would be an important avenue for future research. Some of the trends I have tentatively identified have also been touched on by other bone-tool workers, and their insights are discussed in the conclusions. When appropriate, these issues are pointed out along with suggestions for further research. Finally, some hypotheses placing tool production in the larger economic context of labor scheduling around osseous raw material procurement and tool production are outlined.

Material Selection and Preparation

The materials used here are largely the same as those used in the mechanical experiments discussed in Chapter 3, and include limb elements of white-tailed deer (*Odocoileus virginianus*), American elk, or wapiti (*Cervus canadensis*), and portions of a single antler rack of reindeer (*Rangifer tarandus*) hunted on Kodiak island at least one year prior to its use in this study. A game processor in Tucson, Arizona provided one-stop access to various fresh limb elements of the two cervid species. The bones were immersed in heated tap water that was heated and maintained at a low boiling temperature for about one hour in order to reduce the risk of microbial infection that may occur from working with wild animal tissues. The treatment also opened access to the bone itself by loosening some adhering soft tissue and portions of the marrow. Although no visible changes to the bones were evident after the treatment, some thermal alteration of the collagen component likely occurred. Because of the use of what is essentially an accelerated aging process, the limb elements cannot be considered truly “green”: the mineral component of the bones was intact and no cracking was visible, but some organic loss had certainly occurred.

There were slight differences in the length of time bones of different species were stored prior to use. White-tailed deer was worked immediately following processing, at "time zero." The elk elements were set aside in a freezer until they were needed, a period of about one year. This is standard procedure in storing bone for medical purposes and should have little influence on mechanical properties.

Production times for individual experiments were recorded. In combination with assessments of the length and depth of each cut (measured with calipers to the nearest tenth of a centimeter) these data yielded cutting rates expressed as cm^2/hr. Tap water (pH 7.5) was used at all times to irrigate the working surfaces of the bones and stone tools. This had the effect of keeping the bone surface soft and hydrated, and easier to eased work. It also reduced air-borne dust, and removed the buildup of bone slurry that develops as dust and liquid combine. The experimental tissues were irrigated regardless of whether the bone was relatively fresh, dried, or had been soaked prior to working.

<u>The Groove and Splinter Technique</u>

This classic technique for blank production involves cutting two closely-spaced parallel or intersecting channels parallel to a long bone or antler tine axis. A narrow rectangle can be created by connecting channels via two short perpendicular cuts, or the grooves can be made to angle together, producing as splinter that is wedge-shaped in cross-section (Clark 1972; Clark and Thompson 1953). If the two grooves are more widely spaced they permit the removal of a tablet of bone. Skeletal elements with fairly broad, flat areas such as ungulate metapodia or basal regions of antler are needed to create wide blanks.

Even with a majority of soft tissue removed, fresh bone is slippery, and it is made more so when flushed with water. Whether the bone is wet or dry, guide-lines must first be incised along its surface so that the stone tool will not slip wildly. Slow, controlled strokes of the flake or burin are required to etch an outline of the final blank shape, but once the incised lines are well-established the cutting tool can be drawn back and forth in a rhythmic motion that requires little conscious monitoring on the part of the worker.

Grooves tend to deepen toward the middle where the number of strokes is highest and remain shallowest at the would-be ends of the splinters where the direction of motion is reversed. Some tool-makers of the past may have compensated for this problem by producing grooves that were longer than the intended size of the blank, which may explain why remnants of grooves can sometimes be seen on discarded blanks. It is otherwise important that the cut remain relatively consistent in depth so that one can pry out a complete splinter whose length is not sacrificed by too-shallow ends.

The Saw and Snap Technique

Saw and snap is similar to the groove and splinter technique but is oriented circumferentially in order to remove bone epiphyses, antler tines, or to section long pieces of either material into smaller segments. Crucially then, the cutting is done across rather than with the grain of the bone, which has the potential to increase the time required to remove an equivalent amount of material. Cutting guide-lines must still be established, but more care is required to rotate the piece periodically in order to produce a groove that is of more-or-less even depth all the way around. Once a groove is completed the two sections of the material can then be separated by striking with a hammerstone or against a stone anvil. The point at which percussion becomes effective depends on a number of variables, including the strength of the worker and the materials at hand, how much damage is allowable to either end of the bone, and how much "touching up" is allowable: the shallower the groves, the more jagged and unpredictable fracture can be.

For tubular bones I found it most useful to cut through the bone entirely in at least one area, and to make certain that the entire ringed cut appeared translucent in light. Lucidity signals that the remaining layer of material is thin enough to be easily broken using percussion.

Abrading

Abrasion with sandstone or other grainy or porous materials was a widespread technique for shaping simple pieces like awls or unbarbed arrows. Abrasion can also be used to create or maintain fine points or other features. An alternative is shaving (Campana 1989). Both techniques were used by Alutiiq workers to sharpen points in the study region of Kodiak, Alaska.

Groove and Splinter I: White-Tailed Deer Limb Bone

Three white-tailed deer humeri were used to create sharpened splinters of the sort that could be shaped into a number of tool forms, including awls or needles, toggles, small arrows, and fish gorges. Modern game processors can easily disarticulate skeletons by transversely sawing directly through whole elements rather than by tediously separating them at the joints. As a result, most of the (white-tailed) deer and elk bones used here were obtained as half-elements, which limited the length of material to create long splinters. In order to maximize the use of the remaining bone, the traditional groove and splinter technique outlined above was modified by cutting two intersecting grooves that began at the butcher's transverse cut. Creating narrow triangular splinters whose bases were "open" cuts made it relatively easy to pry splinters from the bone and obviated the need to make transverse cuts to unseat the splinter. This is not a problem as splinter removal constitutes a separate manufacturing stage, and the various techniques that can be applied to lift the splinter out and their times should be recorded separately. Only the times required to cut the splinter grooves are reported here. The times required to produce the two individual grooves on the white-tailed deer material were not recorded separately, as my work frequently alternated between the two.

The first set of converging cuts was made on the distal humerus of a white-tailed deer that was boiled for hygienic purposes but was otherwise fresh. Two grooves, each approximately 5.8 cm long, together required 50 minutes to create (Table 4.1). After thirty days of air drying in an air-conditioned environment, a second distal humerus was cut in the same fashion. The second splinter, slightly longer at 8.5 cm, took 55 minutes to produce. The procedure was repeated on a third distal humerus which had been allowed to air dry for nearly two months and was soaked in tap water only 10 minutes prior to working. The 7.4 cm-long splinter was completed in a laborious 2 hours and 15 minutes. A variety of flint flakes and burins were experimented with to discover the most efficient tool for the task.

Despite variation in the state of preservation of the three specimens, all specimens and the tools used to work them were frequently flushed with water which kept the working surfaces lubricated and free of detritus. This brief process along with periodic retouch of stone tools contributed to the recorded production time. Part of the production time also involved carefully incising straight guide-lines, which was most easily accomplished with a thick-edged flake or burin, and took approximately 10 minutes per pair of grooves.

In general, burins or flakes with retouched edges were found to be useful for creating guide grooves and initial splinter cuts. Thinner flakes were more difficult to hold in the hand and more likely to fracture under pressure, but provided a sharper edge needed for the final stages of cutting. Thicker flakes produced wider grooves, wasting both time and raw material. Other researchers have eschewed the use of thin, unmodified flakes on the grounds of their delicate and friable cutting surface (e.g., Griffitts 2006), but on the thin-walled (3-4 mm) bones of the deer used here thin flakes were preferable.

Experimentation in the choice of cutting implement, variation in the length of the splinters, and very minor differences in the thickness of the humeral diaphysis through which cuts were made may have contributed to the different of rates at which the blanks were cut out. Despite the greater area of bone to work through, the second splinter was created at a faster rate than the first, and the *absolute* time investments for the first two attempts were nearly identical.

The third specimen was noticeably more difficult to work than the other two. The bone was dry and hard and took over twice as long to work, resulting in a drastically reduced production rate. The most critical factor in production times (with raw material held constant) was clearly the state of the raw material, which varied from relatively fresh and pliant to dry, exceedingly strong and stiff, and very difficult to work regardless of the type of stone cutting tool chosen for the job.

Drying Time (days)	Area of Cut (cm^2)	Cutting Time (hrs.)	Cut Rate (cm^2/hr)
0	3.48	0.83	4.18
30	5.95	0.92	6.49
54	4.44	2.25	1.97

Table 4.1: Groove and splinter cutting times and rates for white-tailed deer humeri air-dried for increasing periods of time.

<u>Groove and Splinter II: Elk Limb Bone</u>

Two grooves were cut on a mid-shaft femoral segment from a hunted elk (wapiti) which was previously frozen. Day "0" (Table 4.2) indicates first day after thawing. The compact margin of the elk bone was over twice as thick as that of the white-tailed deer (8 mm, versus 3-4 mm) and a *single* 6.7 cm long groove required just under two hours to produce on the first day when no air-drying had occurred. After 8 days of air-drying a second, parallel groove took two hours to produce. Both cuts were worked with thin flakes with unmodified edges, and were cut to a depth at which the grooves appeared translucent in light. Because the blank was truncated on both ends by transverse butcher's cuts, the blank was easily removed by tapping a rock along the grooves.

Drying Time (days)	Area of Cut (cm^2)	Cutting Time (hrs.)	Est. Cutting Time: **2 Grooves** (hrs.)	Cut Rate (cm^2/hr)
0 (thawed)	5.36	1.83	3.66	2.92
8	5.36	2.00	4.00	2.68

Table 4.2: Groove and splinter cutting times and rates for elk freshly thawed, and thawed and air-dried for about a week. Cutting times each day for two grooves (as reported for white-tailed deer in Table 4.1) were estimated by doubling the times for each individual groove.

Eight days of air drying had little or no effect on the workability of the elk bone.

Although the bone was fresh and the length of the grooves was comparable, it took nearly four times as long to create two parallel grooves as on white-tailed deer bone, which can be attributed to the greater cortical thickness of elk bone and corresponding greater depth of the blank. Flake thickness was also found to influence cutting times. Thick flakes are sturdy but as the depth of their cut increases, so does the width of the cut. Less material and time was lost with the use of thinner flakes, which were preferred for the final stages of cutting.

Saw and Snap I: White-Tailed Deer Limb Bone

Four trials using the saw and snap technique were performed on a single white-tailed deer radius (Table 4.3). In two the epiphyses were cut away to produce a usable tube of bone. The proximal epiphysis was removed in 60 minutes, at first using an inefficient, thick flint flake with a retouched edge, followed by a thin flint flake with an unmodified edge as the groove nearly penetrated the thickness of the bone margin. A thin flake with a retouched, serrated edge was used with greater ease to remove the element’s opposite end in 55 minutes (0.92 hrs.). The procedures were completed one day apart on a radius that had been air-dried for approximately five months but was still greasy to the touch. During both cuts water was used to flush the bone but during the first the bone was otherwise dry. The bone was soaked in tap water for 6 hours before the second and third cuts.

Drying Time (days)	Area of Cut (cm^2)	Cutting Time (hrs.)	Cut Rate (cm^2/hr)
76	2.07	1	2.07
77	2.74	0.92	2.99
92	1.32	1.2	1.1
117	1.63	1.68	0.96

Table 4.3: Saw and snap times and rates for a white-tailed deer radius air-dried for increasing periods of time. The bone was soaked in tap water for 6 hours prior to working on days 77 and 92.

During the second two trials, the bone diaphysis was sectioned as though to create a succession of beads or other modularly-produced items, or to remove epiphyses. Sectioning can also be used to remove broken portions of artifacts for repair or recycling. It is unlikely that tools would have been manufactured from very dry bone, but depending on the longevity of a tool and the rate at which post-mortem changes set in, tools may be reworked or repaired when the material is less than fresh.

The bone was re-soaked in water for several days prior to day 92, on which it was sectioned using a thick, denticulate-edged flake tool. At this point in the drying process little headway could be made and the total production time continued to increase, even as the amount of material worked decreased. In contrast, a hacksaw made quick work of sectioning, which was done in 50 seconds as opposed to 1.32 hours.

Finally, the experiment was repeated a final time on day 117 when the piece was dry (unsoaked), using a quartzite flake cutting tool. Quartzite crumbled in response to downward or back-and-forth pressure and unduly widened the width of the cut. The cut rate improved in the second cut by using the more efficient serrated tool. As a result, the working times for days 76 and 77 were essentially the same despite the greater area of tissue cut through on day 99. Soaking the bone for a period of from several hours to several days was found to improve the workability of only the outermost millimeter or so of the bone table, leaving the interior unaltered.

In general, as dryness increased, so too did the time needed to section the bone. This pattern arose despite the smaller amount of material to cut through and the continued use of the serrated tool that had proved to be efficient in earlier trials. Production rates for saw and snap were slower than those for the groove and snap technique despite the smaller area of bone to be sawn through. This can be attributed to the drier condition of the bone, but also to the greater challenge of cutting across the grain that along it.

Saw and Snap II: Reindeer Antler

Five trials of transversely sectioning portions of reindeer antler were conducted. In three of these a portion of the beam was sectioned, while in the other two I removed one or more tines in order to isolate the technologically more useful beam (the part of the antler with the thickest cortex) (Corbin 1975:75, Appendix B). Many examples of severed tines can be found in the Karluk collection from Kodiak, providing evidence for this kind of procedure.

The motions and materials used on antler were similar to those for the long bones of deer; both denticulated flakes and burins were used to inscribe a groove around the circumference of the beam. Unlike bone, however, the core of an antler is filled with spongy tissue rather than an open medullary cavity. As a result, the amount of material that must be cut through can be minimal compared to the size of the resulting blank. A relatively shallow groove cut all the way around the piece is generally all that is required to prepare the piece for snapping (Figure 4.1). A well-placed blow from a heavy hammerstone with an acutely angled tip makes quick work of the final step.

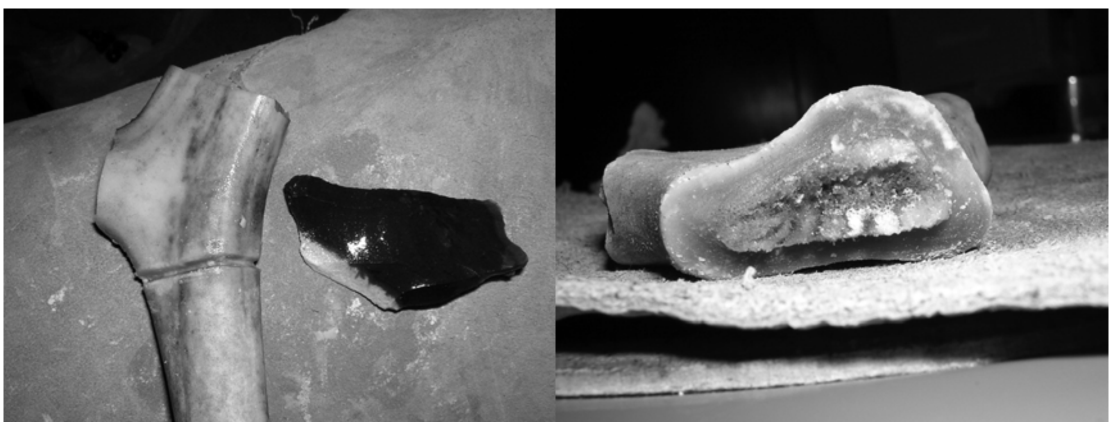

Figure 4.1: Circumferential grooving prepares an antler blank to be snapped.

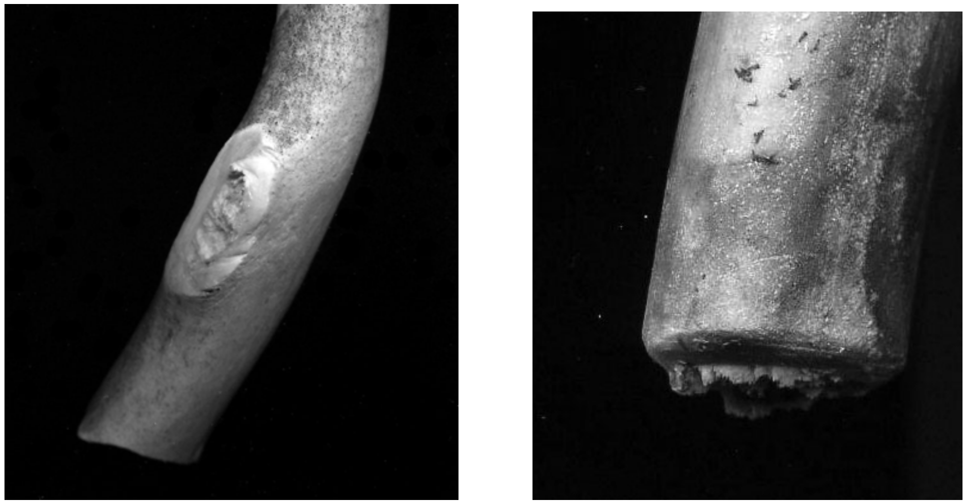

Figure 4.2: Smooth margins (left) versus rough edges (right) of worked antler. There is a trade-off between sawing and grinding investments.

Sectioning the antler with only minimal cutting does result in a trade-off between time spent sawing the piece in preparation for removal, and the labor required to smooth the jagged edges that are inevitably formed along the break margin: this is only an issue if this edge is to become a part of the tool (Figure 4.2). Antler is also morphologically more complex than corporeal bones. When removing the tines it is difficult to maintain a firm grip on the rack, and to manipulate the cutting flake around the jutting topography where a tine branches from the beam. Thus, it was found that working times for sectioning antler in the five trials varied quite dramatically. These times were unrelated to the duration of soaking (Table 4.4).

Drying Time (days)	Area of Cut (cm^2)	Cutting Time (hrs.)	Cut Rate (cm^2/hr)
2	2.91	1	2.91
7	1.18	0.83	1.41
9	0.69	0.42	1.64
9	0.75	0.22	3.41
38	1.59	1	1.59

Table 4.4: Saw and snap times for reindeer antler soaked in tap water. Cutting times do not include time spent separating the sections using a hammer technique.

Antler was worked after being immersed in tap water for two days (Day 2) and subsequent days up to a period of 38 days of immersion. The water was changed repeatedly to avoid the florescence of microorganisms. The compact part of antlers from small cervids such as white-tailed deer is quite thin, and was cut nearly through before the sections were snapped apart. On the other hand, snapping through an antler's cancellous core takes longer. Thus, in the case of the saw and snap technique, it is the absolute amount of time required to separate pieces that is of the greatest importance, rather than the cut rate. Although cutting rates differ widely, a trend is evident in the absolute cutting time: pieces worked on days 2, 7, and 38 were sawed deeply to reach the compact/spongy boundary at the nucleus of the beam section. Despite some variation in the amount of material to be sawn through, approximately one hour was required to complete each of these tasks, equivalent to that required for working the simmered white-tailed deer bone. Soaking effectiveness set in rapidly, and so cutting times did not diminish as soaking times increased.

Conclusions

Effects of Freezing and Thawing

Previously frozen elk bone was worked here but without a fresh counterpart to contrast working times. However, it took Wescott and Holladay (1999) three times longer to longitudinally section a deer metapodial that had been previously frozen than it took them to section one that was fresh (Table 4.5). Drying associated with the freezing may be to blame, as it would increased the bone's material strength (hardness) and stiffness, making it more difficult to work.

Manufacturing Materials and Tools

In these experiments a thin flint flake was the preferred manufacturing implement. Other workers prefer thicker, denticulated flakes or burins for the work, or alternative materials such as a durable quartzite. A thinner flake may be more effective at cutting through dry bone or antler, but the difference in working efficiency may also have to do with the thickness of bone cortex. Thicker flakes or burins may make quicker work of cutting roughly through the thick-walled bones of bison, for instance, while the more slender cuts created by thin flakes work effectively on more gracile skeletal elements while simultaneously conserving raw material (Griffitts 2006). Not surprisingly, it took only 1 minute to section a dry white-tailed deer limb bone using a hacksaw, as opposed to the hour or more required using stone tools.

"Workability" is thus dependent not only on the formal properties of the raw materials themselves, but also on the implements used to shape them. A worker using stone tools will find that the workability of osseous materials varies greatly according to whether the materials are fresh or old, and soaked or dry. These divides largely disappear when metal tools enter the picture. The right metal tool can provide a very effective cutting edge, and this fact has been used to argue for their objective superiority over tools of bone (e.g., Guthrie 1983). Many factors figure into the overall utility of metal tools, however, including their availability, maintainability, and the set of skills needed to work with them effectively. At the same time, raw material choices are made based on a number of competing factors of which "workability" is but one. Chapter 7 discusses Alutiiq raw material and tool design choices, especially in light of the mechanical properties of the raw materials. As will be seen, the initial introduction of Russian metal implements in the early 1800s, far from wiping out the use of skeletal materials, may actually have aided Alutiiq workers in the production of some types of osseous tools.

<u>Area or Volume of Raw Material</u>

Interestingly, working times for all but the driest of the white-tailed deer bone and for soaked reindeer antler converged on the one-hour mark, which accords with Newcomer's 60-minute blank production time using American elk antler (Newcomer 1977). Two factors likely account for this phenomenon. The first is simply the learning curve for a novice worker. However, the second, and probably more powerful explanation, is that the primary determinant of cutting rate is the depth of the splinter, not its length. If the worker can establish a repetitive sawing motion in which the entire length of the cut can be traversed in a single stroke, shorter or longer splinters can be created in about the same amount of time.

Morphological Complexity of the Raw Material

Antler working times and rates varied considerably with ease of access to the cutting surface, and independently of soaking time. Tines, which tend to contain less compact tissue than beam areas (Corbin 1975:75, Appendix B), were most easily removed by bashing followed, if necessary, by grinding or scraping the resulting rough edges. Sawing into difficult nooks and crannies of the material was more laborious and challenging.

Moldability

Numerous sources cite the use of steaming to temporarily increase the flexibility of antler so that it can be bent (or straightened) into a desired shape. For instance:

> For plucking out the beard, the Hidatsa (in the early part of the twentieth century) used metal tweezers of almost uniform design. These find their prototype in the elkhorn [elk antler] tweezers after which they are modeled. A long thin flat piece of elkhorn rendered soft and pliable in boiling water was bent over two sticks and bound in place with sinews. When the elkhorn had dried and set into the desired shape, the binding sinews were removed and the tweezers were ready for use (Weitzner 1979:221).

Seasonal restrictions could apply, depending on the particular steaming process. The frozen ground apparently barred the Hidatsa from making steamed elk antler bows in the winter; the process required digging a long trench in which to bury the antler, which was warmed and steamed by fires built on the ground surface above (Weitzner 1979:230).

Effects of Drying and Rewetting

Sedlin (1965) found that following 5 days of air-drying, human cortical bone samples became significantly stiffer in laboratory tests. In the present study, however, air-drying white-tailed deer bone for a period of up to 30 days (in indoor conditions) had little effect on its actual workability. Only after 30 days did the bone become at least twice as difficult to cut as the same bone worked in a fresher condition. However, data from other researchers suggest these two observations may not be at odds. Westcott and Holladay (1999:66-67) report taking less than 10 minutes to longitudinally section the metapodial of a fresh road-kill deer using jasper burins, while the same task took over 45 minutes when the bone had been air-dried for an unspecified amount of time. Newcomer (1977) created two grooves for a splinter blank from a fresh ox metacarpal in 80 minutes, a rapid rate given the thickness of the cortex (Table 4.5).

ACTIVITY	RAW MATERIAL	TOOLS	TIME	WORKERS
2 grooves	deer metapodial, fresh	jasper burins	< 10 min	Wescott and Holladay (1999)
2 grooves	ox metacarpal, fresh	burin	80 min	Newcomer (1977)
2 grooves	antler, shed, soaked 7 days	burin	60 min	Newcomer (1977)
2 grooves	deer metapodial, dry	jasper burins	> 45 min	Wescott and Holladay (1999)
2 grooves	deer metapodial, previously frozen	jasper burins	30 min	Wescott and Holladay (1999)

Table 4.5: Data from two sets of researchers clocking approximate time investments for groove and splinter technique (splinter removal excluded).

In light of these findings, the most reasonable conclusion is that the working times obtained here on white-tailed deer are likely very slow and not representative of those of most tool-workers who had any hope of obtaining their materials fresh. The problem can be traced back to the initial boiling treatment, which robbed the bone of some of its pliancy. Truly green bone could likely have been worked with considerably less effort, although additional experiments would be needed to determine if working times would be on par with those reported by Westcott and Holladay. The 30-day air-drying period that followed boiling may represent a plateau of sorts where "workability" remains fairly constant, only to drop off further with additional time and drying. Boiling aside, because the maintenance of any tool must occur some period after its production, the drying process is of obvious relevance to the treatment of actual implements. An experiment designed to systematically test the ease of working of a single material as it runs its natural course of drying would provide valuable data on the best workability window for minimizing labor costs during blank-production and subsequent stages.

Some archaeologists and avocational researchers who have replicated osseous tools report that re-wetting improves the "working properties" of bony materials by softening (Campana 1989; Guthrie 1983). MacGregor (1985:63-65) reviews several methods proposed by various researchers for softening corporeal bone, all of which entail treating the tissues with some form of acid. One such acid was derived from the leaves and roots of the sorrel plant, which is rich in ascorbic acid (Geraci and Smith 1979). Urine is not discussed, but would provide acid in the form of urea. Acids soften bone by dissolving its mineral component. The changes are thus irreversible, albeit potentially disguised by the increased stiffness and strength accrued simply as the materials dry.

Boiled antler was softened enough to be shaved with a knife, but simply soaking the antler had the same effect (MacGregor 1985:64). In the study conducted here, the workability of dry bone was little improved by its soaking in tap water. Only the surface of the bone was softened through re-wetting, whereas old but re-wetted antler could be cut as easily as fresh/boiled bone. H. Knecht (1997:200) reports that antler can be softened and made more moldable by soaking it in water, whereas soaking and even boiling bone does little to increase its pliancy (H. Knecht 1988; Newcomer and Watson 1984).

In a 1964 study of metapodial fleshers made by the Little Black River Ojibwa of Manitoba, Canada, Steinbring (1966) reports precautions apparently taken in order to ensure the bone tool did not dry and crack. Introducing a tool to temperature extremes by placing it too close to a fire or leaving it in freezing temperatures outside were to be avoided (Steinbring 1966:580). A bone tool's longevity could be extended by leaving some marrow within the long bone cavity or inserting fat into it. The outside of the piece could also be kept lubricated by spreading grease around the working surface and protecting the area with cloth coverings (Steinbring 1966:579). All of these precautions point to the attempt to prevent damage to the tool that can occur with the loss of water, protein, or fats. Similarly, Peter Lind, at Alutiiq Native artist who works in bone, antler, wood and baleen, warned against leaving natural materials like these in direct sunlight because it can cause them to warp or crack (Lind 2004), no doubt due to the effects of ultraviolet radiation.

However, the natural process of drying may not be a total impediment to working with osseous materials. Watts (1999:64) suggests that it is easiest to produce blanks from fresh bone, but that final shaping (through abrading or scraping) is best done when the bone has partially dried. It may be easier to polish bone when it has dried even further (Wescott and Holladay 1999:66). In the experiments conducted here, abrasion was found to be a rapid means of sharpening and shaping a blank. I did not attempt to track the absolute amount of waste material that was removed during each attempt, but my impression is that abrasion proved at least as effective, if not more so, when the blank was dry as when wet. (In all cases water was used to lubricate the working surface.) Campana (1989:32) reports the same findings. A quantitative comparison between the two techniques could be made, either by tracking working times against the progressive mass of the piece that is lost (in which case is would be necessary to account for the differential mass of wet versus dry bone) or by recording the times required to work dry and wet test specimens of identical geometries to the same pre-established sizes.

Mechanical Effects of Post-Mortem Processes

Skeletal materials become thermodynamically unstable, both macroscopically and microscopically, when removed from *in vivo* contexts. In the external environment they become susceptible to drying (Goss 1983; Guthrie 1983; MacGregor 1985), collagen hydrolysis (DiNiro and Weiner 1998; Turner-Walker and Parry 1995), microbial attack (Bell et al. 1996; Garland 1989; Hackett 1981), and other natural processes active in human time frames. These processes have corresponding effects on the mechanical properties of the materials. Important material alterations may also stem from human activities, including the repeated immersion of tools into fresh or salt water (Currey 1988; Sedlin 1965; Sedlin and Hirsch 1966; Smith and Walmsley 1959) -- as might occur with fishing and marine mammal hunting gear -- and temperature oscillations created by moving tools between sheltered and unprotected environments in cold climates (Pavlish et al. 2002; Pelker et al. 1984; Turner and Burr 1993). These changes in turn may have important consequences for the performance characteristics of raw materials or for whole artifact components constructed from them.

In the strictest sense the changes occurring *ex vivo* cannot be called taphonomic because they occur while materials and tools are actively in use, but they are similar to the results of forces that work post-depositionally (Lyman 1994). Some quantitative data on the effects of these post-mortem processes can be gleaned from mechanical testing studies which appear in the medical literature. Early studies sometimes failed to simulate the conditions of bone's *in vivo* environment during testing: they tested specimens dry rather than wet, took measurements at room rather than body temperature, or used samples that were embalmed rather than preserved frozen in physiological saline, which is the currently accepted practice (Sedlin 1965). Fortuitously for archaeologists, some of these departures from the ideal replicated conditions in which bone might be used in cultural environments, and as such can provide insight to researchers interested in this second chapter in the life history of skeletal materials.

<u>Drying and Rewetting</u>

Drying has clear and well-explored effects on corporeal bone's intrinsic mechanical properties, some of which were also discussed in Chapter 2. Bone's tensile and compressive strengths, the modulus of elasticity (material stiffness), and hardness all increase when it is left to dry, but drying compromises bone's toughness and shear strength (Dempster and Liddicoat 1952; Evans 1973; MacGregor 1985; Sedlin 1965; Yamada 1970). Rewetting is another essential parameter to consider. Dempster and Liddicoat (*in* Evans 1973:52) showed that the material stiffness of dry bone can be reduced by about 20% by soaking the bone in water for a few hours. The human cortical bone for this study was obtained primarily from a university osteological collection, so the extent of drying is perhaps on par with that of raw materials that have been scavenged or stockpiled.

In a frequently-cited study Sedlin (1965) found that dry human femoral cortical bone recovers most of its original mechanical properties if it is completely re-wetted prior to testing. Currey (1988b) noted a small (5%) but statistically significant reduction in the bending strength of bovid femoral bone that had been dried for 25 days and rewetted for 3 hours, compared to fresh bone. Currey found no significant change in Young's modulus measured in bending or in the work of fracture however.

Drying and re-wetting cycles can have strong effects on bone post-depositionally (Behrensmeyer 1978:154) but could also influence the use-lives of bone and antler tools, especially those used for tasks in freshwater or marine contexts. However, it is not clear that bone and antler can indeed be "rejuvenated" to their original state by rewetting once they have dried completely. Nor do existing studies show the degree of drying that is needed to cause irrevocable consequences for the workability of bone and antler. No studies to my knowledge have addressed the effects of *multiple* cycles of drying and rewetting. The need for these kinds of data does not exist in medical settings, but they would clearly benefit the study of bone in technological settings of the past.

Freezing and Thawing

Freezing experiments conducted to determine the best way to preserve bone tissue for grafting are relevant to osseous materials collected, processed, or used as tool components in cold climates. The mechanical properties of bone frozen at -20° C (-4° F) for several weeks and then brought to human body temperature are not significantly different from those of fresh bone (Sedlin 1965). However, rapid freezing can causing cracking due to the expansion of internal moisture (Pelker et al. 1984:408).

Crack propagation associated with rapid deep freezing may explain the results of a study showing that fracture resistance diminishes with lowered temperatures (Pavlish et al. 2002). Fresh bovine femora were subjected to a variety of temperatures ranging from -196° to + 20° C (-321° to +68° F) and fractured at these temperatures by a worker wielding a two kg hammer. With the exception of samples brought just to the point of freezing (0° C), the specimens were cooled using dry ice or liquid nitrogen, agents that act very quickly. Taken at face value, the results suggest that osseous tools used in cold climates are more susceptible to fracture than those employed in more temperate environments. All else equal, a worker choosing from an array of bony tissues should select those with superior fracture resistance to create cold-weather instruments. Antler would be the clear choice over most types of land mammal limb bone, assuming freezing affects the two materials equivalently. However, the method and rate of freezing may be important variables that affect how well the material can accommodate the expansion of water and thus its susceptibility to lowered impact resistance. To address this problem it would be necessary to design an experiment that faithfully represents actual climatic conditions in which skeletal technologies might be used. Data on how other fibrous composites with integral water components, especially wood, are affected by natural freezing might also offer some insights.

The experiments discussed here run the gamut in experimental design but have been produced mostly in laboratory rather than field settings. Although a few researchers have advocated testing material properties through actualistic studies (e.g., Pavlish et al. 2002), the results of such exercises run the risk of narrow applicability because the tests use highly context-specific and qualitative testing procedures. Conversely, laboratory studies can produce measures of strength or toughness in tidy and standardized units, but are nevertheless difficult for archaeologists to translate into behaviorally meaningful values. Actualistic and laboratory-controlled experiments can offer complementary insights into material dynamics and a judicious use of both approaches, I would argue, is the best starting place for understanding baseline limitations in how humans can utilize various materials.

Discussion

Creating tools of bone and antler is a multi-stage production process that minimally involves extracting a blank, rough shaping, and refining its contours using whittling or abrasion. Among the materials tested here, the factor that most strongly influenced blank production time was the *state* of the raw material as it followed a natural drying course, becoming stiffer and more resistant to cutting with time. The results obtained here were deeply affected by this drying process, underscoring the importance of labor scheduling in the tool production process (Torrence 1983), and of conservation measures that can extend the use-life of completed bone and antler tools.

There seems to be a general consensus among experimenters that abrading, usually reserved for the final shaping of a piece, is most effective when a material is dry (e.g., Watts 1999:64; Wescott and Holladay 1999:66). Blanks could thus be set aside and finished at a leisurely pace. In contrast, drying impedes the rate at which earlier stages of osseous tool manufacture using sawing and cutting techniques can be carried out, suggesting that that these early stages of manufacture should be performed within a more restricted labor schedule. The tempo at which progressive drying can affect actual workability is not currently clear, however, and must be empirically tested. Nonetheless, the immediate time investment required for extracting carcass' hard tissues, if not for blank production, would compete in a relatively narrow temporal window with key activities related to extracting and processing other economic products such as meat, marrow, hides, fat, or tendon. Ojibwa elders, for instance, held that bone earmarked for tool-used had to be extracted quickly from the carcass while the adhering soft tissues were still soft, as it was difficult to cut through toughened tendon at the joints (Steinbring 1966:579).

From this perspective, an optimal raw material would be one that could be worked rapidly or does not pose special scheduling constraints on the worker. As data from Table 4.5 show (compiled from the work of other researchers), fresh antler does not appear to be easier to work than fresh bone possessing a similar amount of cortex, even though antler is less highly mineralized than typical corporeal bone (Currey 1979). As the two types of material age, however, a disparity apparently develops in terms of their technological utility. While a water-soaking treatment does little to "rejuvenate" dry corporeal bone, it is, according to MacGregor (1985:64) and H. Knecht (1997:200), quite effective on antler. The experiments reported here confirm their observations. Not coincidentally, key mechanical tests demonstrating antler's surprisingly low degree of intrinsic rigidity and strength in contrast to corporeal bone were performed using soaked rather than fresh material (Currey 1979, 1989).

If antler can indeed be revived by soaking to recapture close to its original ease of working in a way that bone cannot – a supposition that certainly requires further testing – then serious implications would follow for the optimal timing in the use of these resources. Specifically, if usable antler could be obtained fresh or shed, it could be stockpiled in anticipation of future needs and used according to a flexible schedule, significantly relaxing the time stress involved in producing tool blanks from more recalcitrant materials.

Finally, time and labor costs may vary widely according to raw material type, and with the chosen methods and tools of manufacture. The simple size and shape of materials also bear on how easily materials can be worked, and the types of objects that can be created from them (Figure 4.3). Whale bone has yet to be discussed here because its intrinsic and working properties are poorly understood. It is clear that its sheer size, though, makes this type of bone amenable for use as architectural elements, as bowls (made from vertebral centra), and as large wedges for woodworking. In modern times, monumental sculptures from the eastern Canadian Arctic evoke days past when whales were prevalent in the cultural landscapes of maritime foragers. As discussed in the following chapters, whales and whalers held special places in Alutiiq society, and Alutiiq workers chose whale bone for the production of certain types of portable gear in addition to more massive paraphernalia.

MATERIALS	CONSTRUCTION & REPAIR					
	Ease of Working FRESH, with STONE TOOLS	Ease of Working OLD, with STONE TOOLS	Ease of Working FRESH, with METAL TOOLS	Ease of Working OLD, with METAL TOOLS	Plasticity (Moldability)	Package Size
reindeer antler	◉	◉?	●	◉	●	◉
white-tailed deer (limb bones)	◉	○	●	◉	◉	◉
American elk (limb bones)	◉	○	●	◉	◉	◉
California sea lion (limb bones)	◉	○	●	◉	◉	○
whale bone (unspecified)	◉	○	●	◉	?	●

● = HIGH/ LARGE

◉ = MEDIUM

○ = LOW/ SMALL

Figure 4.3: Factors influencing ease of construction and repair of several types of skeletal materials. Whale bone was not tested; estimates are in gray.

CHAPTER 5: INTRODUCTION TO PROTOHISTORIC ALUTIIQ SUBSISTENCE, ARCHAEOLOGICAL SITES, AND FIVE TOOL TYPES

The Study Region

Kodiak, fondly referred to as Alaska's "Emerald Isle," and its spray of neighboring islands stretch southward from the Kenai Peninsula within the gentle arc of the Gulf of Alaska. A maritime climate insulates the island chain against dramatic seasonal temperature oscillations, but frequent storms challenge navigation by sea even today. Nonetheless, the sea provided an essential means of travel and subsistence for Alutiiq peoples who have occupied the Kodiak Archipelago for at least 7,000 years (Clark 1979; Fitzhugh 2003:40).

Aside from the famous Kodiak brown bear, the few land mammals native to the Archipelago include red foxes, voles, weasels, and brown bats (Rausch 1969). No ungulates of any kind were present until their introduction in historic times (Clark 1975:204). Today, most of Kodiak's rugged mountainous interior makes up the Kodiak National Wildlife Refuge and, as in the past, is largely uninhabited by humans. Prehistoric Alutiiq groups settled along shorelines and riverways to take advantage of the rich diversity of fish, shellfish, marine mammals, and birds that they offered.

Several seamen and members of the Russian clergy recorded accounts of Alutiiq subsistence activities and equipment as they were observed in the early 1800s. The Hieromonk Gideon lived on Kodiak from 1804-1807 (Gideon 1989), arriving there onboard a ship with the Navy officer Iurii Lisiansky, who also penned an account of his time spent on Kodiak between 1804 and 1805 (Lisiansky 1968). An earlier resident, the clergyman Ioasaf Bolotov, lived on Kodiak between the years of 1794-1799 (Bolotov in Black 1977). In 1799 Bolotov returned briefly to Russia where he was appointed the first Russian Orthodox bishop in America. He never assumed his post, however, dying at sea on the voyage back to Kodiak (Black 1977:80). Finally, Gavriil Davydov was a young naval officer who wintered on Kodiak in 1802-1803: his journal provides a wealth of ethnographic details (Davydov 1977).

According to these ethnohistoric accounts, Alutiiq subsistence rounds targeted seasonally abundant salmon, halibut, cod, and a variety of other species of fish which were taken with hooks and multi-pronged leisters (Lisiansky 1968:206). Barbed harpoon and dart assemblies used in conjunction with throwing boards were essential for taking harbor seals, sea otters, Steller sea lions, and dolphins from small skin kayaks (*baidarkas*) (Lisiansky 1968:206) whose coverings were themselves made from the skins of sea lions or seals (Bolotov in Black 1977:84-5). Seals were also hunted at their haul-outs using spears or nets (Gideon 1989:56-57). Seal, sea lion, or bear gut was sewn into waterproof jackets, or *kamleikas* (Gideon 1989:62) which would have been indispensable in the region's frequently inclement weather. Littoral resources such as clams, mussels, and sea urchins provided valuable nourishment, especially in lean winter months (Gideon 1989:67) while sea birds, taken with arrows (Davydov 1977:228), nets (Lisiansky 1968:205), or snares (Gideon 1989:65) were especially prized for their skins which were made into parkas (Bolotov in Black 1977:85). According to Gideon (1989:65) the construction of one such garment required the skins of thirty five puffins.

Figure 5.1: Near Island Harbor, City of Kodiak.

Kodiak Alutiiqs also practiced whaling (Black 1987). Whale meat and blubber were mixed with berries and consumed, often with fish, and the sinew was woven into bird nets (Bolotov in Black 1977:85). Whale bones were also used as architectural elements (Black 1987) and for constructing portable tools (Chapter 6). Whaling in the Kodiak region was a specialized, secretive, and dangerous profession. Kodiak whalers worked alone, hunting from *baidarkas* using harpoons tipped with aconite, a poison made from monkshood root (Black 1987:9; Lisiansky 1968:202). The process was marked by uncertainty, as whalers maintained no physical attachment to their prey, and they inscribed their harpoon end-blades with personalized emblems in order to claim the kill, should a fortunate tide wash the carcass near to shore (Gideon 1989:68). A whaling position was passed from a father to his worthiest sons and was surrounded by rituals and social prescriptions that underscore both the power and danger associated with the role.

While whalers were highly esteemed (Lisiansky 1968:174, 209), they simultaneously inhabited society's fringes during the whaling season.

> Of these whalers a story prevails, that when the fishing [whaling] season is over, they conceal their instruments in the mountains, till wanted again; and that they steal, whenever they can, the bodies of such fishermen as die, and were known to have distinguished themselves in their calling, which they preserve in caves. These bodies are said by some to be stolen, from the idea that the possession of them conduces to render the fishing season prosperous; and by others, that a juice or fat is extracted from them, into which if an arrow be dipped, the whale, when wounded by it, dies the sooner (Lisiansky 1968:174).

As Clark (1975:203) has noted, Kodiak represents a sort of "four corners" of the North, a geographic and cultural crossroads between Athabaskans, Yupiks, Northwest Coast tribes, and Aleuts. The Alutiiq language is a dialect of Yupik Eskimo (Woodbury 1984) but the semi-sedentary Alutiiq whom Russian fur traders encountered in the 18th century shared many outward similarities with tribes of the Northwest Coast, including traditions of spruce root weaving, ranked social organization, and raven myths (Steffian and Saltonstall 2006).

Several centuries before Russian arrival, Alutiiq household organization began to change, as the once-prevalent single-room house style gave way to multi-roomed houses which likely housed extended families. Moreover, while some houses grew much larger, others remained small, suggesting an increase in social differentiation (Fitzhugh 2003). Salmon fishing efforts were also intensified along with a concomitant increase in salmon storage. These changes, along with trends in artifact styles (discussed below) were once used to define the boundary between the Early and Developed Koniag Phases, at circa A.D. 1400 (Jordan and Knecht 1988; Knecht 1995). Recent interpretations place the transition to multi-roomed houses even earlier, around A.D. 1100 (Steffian and Saltonstall 2006).

The *in situ* social and economic shifts that occurred within the Koniag Tradition were not nearly so dramatic, however, as the transformations brought about by the incursion of Russian fur traders into the Archipelago in the late 1700s. Earlier Russian fur-seeking ventures in the Aleutians were undertaken by small privately-funded companies crewed partly by Kamchatkan Natives skilled in hunting and trapping (Black 2004:66; Gibson 1969:30). Aleut Natives were taken hostage and provided another essential labor source, as their mastery of sea otter hunting and seafaring in kayaks were explicitly relied upon by their captors (Black 2004:70; Gibson 1969:30). The sea otter pelts, or "soft gold" obtained on these ventures were not particularly warm or practical in cold weather, but could be sold at great profit to China, where they were dyed and used as decorative trim on aristocratic attire (Gibson 1969:27). As market competition increased and sea otter populations declined, ship crews were forced to set up camp for longer durations – months or even years -- and to venture further east in search of new fur sources. By the late 1795s, the many competing companies were reduced to three, one of which was the Golikov-Shelikhov Company.

Grigorii Shelikhov was a dark visionary of sorts, who dreamed of expanding the borders of the Russian empire by establishing the first permanent settlement in America, on the shores of Kodiak Island. His means were unscrupulous, and although mistreatment of Natives was considered a serious crime by the Russian government (Black 2004:106), distance and isolation from the mother country allowed grave abuses to be committed without penalty. In 1784 Shelikhov and his crew arrived at a quiet harbor on the southeastern shore of Kodiak, where they waged a devastating battle against a group of Alutiiq individuals gathering at Awa'uq, or Refuge Rock, a steep near-shore island. Shelikhov's success opened the door to permanent settlement at that spot, christened (somewhat ironically) Three Saints Harbor (Crowell 1994:47-55). Numerous smaller outposts called *artels* were set up to provision the major settlement. They consisted of a Russian local manager (*baidarshchik*), a few mid-level employees, and a small conscripted Native labor force (Black 1977:13) of young men forced into intensive sea otter hunting (Black 2004:128). The young boys and older men who remained in the villages were organized into birding parties, and women toiled to meet strict quotas for berry collection and to sew special bird-skin parkas to exchange for more valuable sea otter pelts (Gideon 1989:64-66).

Communications to Catherine the Great, from whom Shelikhov and his partner sought additional funding for their operation, show the extent of their obsequiousness and deceit:

> He showed them means for getting nourishment unknown to them until then, and for lack of which they had often been victims of famine, and furnished them with necessary tools. By such means, and with his kindly treatment, he inclined them to him in love, aroused their trust and convinced them that the arrival of the Russians in their land had brought them innumerable advantages, security, and prosperity (Shelikhov 1981:121).
> *Petition, Shelikhov and Golikov, to the Empress Catherine II, St. Petersburg, February 13, 1788.*

Some of the osseous artifacts selected for analysis (Chapter 6) were created in the period just after the arrival of Shelikhov and his crew on the eastern shores of Kodiak

Island. The site from which the artifacts were recovered was likely an *artel* where a *baidarshchik* and conscripted Alutiiq hunters lived and worked. The remainder of the artifacts date to the cultural period that directly preceded the Russian Period, known as the Koniag Tradition. A brief description of the sites (Figure 5.2) is given here, followed by an introduction to the artifacts themselves, including their likely uses.

Figure 5.2: Location of Kodiak and Afognak Island sites: Karluk One (1); the Afognak Artel (2); and Settlement Point (3).

The Study Sites

Karluk One (KAR-001)

Karluk One is one of a complex cluster of sites once located along the Karluk drainage system on the southwest edge of Kodiak Island. Before its destruction by wave action, the site sat on the south shore of the Karluk Lagoon near the narrow spit which separates lagoon waters from the choppy coasts of of Shelikof Strait (R. Knecht 1995). The closest point on the mainland of the Alaska Peninsula lies some thirty miles to the northwest of Karluk. The Karluk drainage is an extraordinarily productive habitat for salmon and other anadromous fish, a feature which has provided a draw for human settlement in both prehistoric and more recent times. Richard Knecht's 1995 dissertation (which includes a useful history of recent archaeological research on the Kodiak Archipelago) documents the 1983-1985, and 1987 field seasons at Karluk One.

Sites along the rivers system were returned to time and time again. The result is a complex overlapping of occupation layers. Below a disturbed surface layer that contained a mix of prehistoric, Russian, and American period artifacts lay a sequence of eight Koniag *barabaras* (house-floors) punctuated by midden and roof fill deposits. Another two, more partial house-floor layers, floors 9 and 10 lay beneath these (R. Knecht 1995). Together these yielded an array of artifacts exquisitely preserved by waterlogged sediments. Many of the objects recovered had never been found before in the region by archaeologists and included artifacts of wood and grass, feathers, hair and basketry, as well as a wealth of osseous artifacts and faunal remains (R. Knecht 1995). The base of the site is dated to roughly A.D. 1250 (calibrated radiocarbon), or the beginning of the Early Koniag Phase. The partially excavated House-floor 8, with its mix of Early and Developed Koniag artifact types and transitional date (A. D. 1431) played a crucial role in Knecht and Jordan's definition of the two phases (Knecht and Jordan 1988).

House-floor 8 contained many artifacts typical of the Early Koniag Phase, including fish harpoon heads with scarfed bases -- part of a 3-piece tip system first seen in the earlier Kachemak Tradition (R. Knecht 1995:719) – along with stemmed ulu blades and ground slate lances with a medial ridge that gives the pieces a distinctive diamond-shaped cross section. In contrast, assemblages from House-floors 1-7 are typical of the subsequent Developed Koniag Phase, in which fish harpoon heads are two piece arrangements with socketed, rather than scarfed bases (described in greater detail to follow) (R. Knecht 1995:154).

Settlement Point (AM 33; AFG-015)

Settlement Point is a Koniag village site on the southern end of Afognak Island, near the entrance to Afognak Bay. The site sits on an old beach berm set back from the modern shoreline, and consists of the remains of at least seven multi-floored house structures, as well as a large elongate midden area which runs nearly the length of the approximately 67 meter long site (Partlow 2000:71). Testing and excavations at Settlement Point were carried out from 1994-1997 and were sponsored by the Afognak Native Corporation's Dig Afognak volunteer program. Richard Knecht, Patrick Saltonstall, and Megan Partlow led the work; Saltonstall conducted preliminary analyses of the artifacts, and Partlow's

2000 dissertation includes an analysis of the faunal remains, which include salmon, shellfish, harbor seal, cetaceans, and cormorants (Partlow 2000:145, 152, 190, 193-194, 208).

One house (House 1) was excavated completely and large portions of six additional houses (Houses 2-7) were tested; an eighth house floor was located and left undisturbed. The midden, which surrounded and infilled House 1, was tested in two separate trenches totaling 24 square meters (Partlow 2000; Saltonstall 1997). Unworked faunal remains and bone and antler tools were preserved by a layer of post-abandonment fill of shell built up in the house by later occupants at the site (Saltonstall 1997:26-27). The excavators found fish bones scattered on the floor, within clay-lined pits, and in slate storage boxes located in the structure's main room (Partlow 2000:79). House 1 also dates to earlier than the other deposits; the two calibrated radiocarbon dates: A. D. 1305-1400 (hearth) and A. D.1310-1430 (floor) (Partlow 2000:74) place it chronologically within the Early Koniag Phase (A. D. 1200-1400) (Saltonstall 1997). Other house deposits also yielded artifacts diagnostic of the Early Koniag Phase, including incised pebbles, diamond cross-sectioned slate points, and stemmed ulus (Saltonstall 1997:29).

The region's characteristically acidic soils have not allowed for good bone preservation at the Settlement Point site except in the House 1/midden area, where otherwise low pH has been buffered by the accumulation of carbonaceous shell (Saltonstall 1997:26). Hence, the majority of osseous tools recovered at Settlement Point, and especially those in good state of preservation, were recovered from trash rather than residential deposits. Partlow's (2000) analysis of unworked faunal remains from the site similarly demonstrated that faunal preservation was very poor in the house-floor layers with the exception of those in House 1, which were buried beneath midden deposits. In some cases, chemical stabilizers such as Acrysol were used to conserve fragile items (Saltonstall 1997:36). The coating gives a darkened sheen to the artifact surfaces and may slightly obscure any possible manufacture traces. However, the effect is slight compared to the poor state of preservation which the stabilizers are intended to keep in check.

The Afognak Artel (AM 34; AFG-016)

Two *artels*, or small work stations, are known to have been established on Afognak Island (Gideon in Black 1977:90). There is some ambiguity in the historical accounts as to the exact location of the outposts, but in 1994 a small team of archaeologists discovered a series of structures and middens fitting the description. The site is located just east of the Afognak River on Afognak Island close to the site of Settlement Point. The remains of at least five Russian-period structures were preserved. These are believed to have been separate Russian and Alutiiq living quarters with their associated middens, Alutiiq work areas, and a company storehouse. Four of these structures and their contents, including the Alutiiq work quarters, are described in Woodhouse-Beyer's 2001 dissertation. Based on artifacts and historical records the author believes the site was occupied from roughly A.D. 1786 – 1839 (Woodhouse-Beyer 2001:61).

Artifact Descriptions

"The men are taught early to construct bidarkas, and to manage them at sea; to make arrows, and to shoot with them: and the women are exercised from their infancy in needle-works, in making nets, lines, and other things adapted to their sex".
Lisiansky 1968 [1814]:202

All of the artifacts analyzed for this project are housed at the Alutiiq Museum and Archaeological Repository in the city of Kodiak, Alaska. The collections from the sites of Karluk One, Settlement Point, and the Afognak Artel contain an array of osseous tool types, some represented by scores of specimens, some by only a few. Those chosen for analysis were the most numerous in the collections, and include unbarbed arrow points, barbed harpoon points used for sea mammal hunting, toggling fish harpoon "valves" used in shallow water fishing, awls, and woodworking wedges. Other types of osseous tool components will occasionally enter the discussion in chapters to follow as they relate to the recycling of one tool form into another, or to the overall patterns of osseous raw material selection observed at the three sites.

Arrow Points

The most common type of arrows recovered from the three sites featured unbarbed blades and "stemmed" bases (Figure 5.3). The blades of unbarbed, or what I have termed "simple", arrows are round or semi-circular in cross-section. Like the wings of an airplane, this design might have aerodynamic benefits. Many have blunt tips, although whether by design or from use is unclear; arrows with both sharp and blunt tips were analyzed. Five unbarbed arrows which had tapered, beveled, or indistinct bases were included only in the analysis of raw material use.

Figure 5.3: Sharp and blunt-tipped arrows from Settlement Point.

Surprisingly little data on unbarbed points can be found in ethnohistoric accounts. Barbed arrow tips were used in warfare (Gideon 1989:42) and possibly for taking bears (Birket-Smith *in* R. Knecht 1995:293).

> They went into battle with painted faces, holding a bone [tipped] spear in the right, a bow in the left hand…The arrow shafts are three handspans or more long, with the foreshaft or [sic] caribou bone, one handspan long having three 1-handspan long barbs and armed with a stone or copper blade…(Gideon 1989:42).

Some barbed arrows were not so much points themselves as foreshafts, with slotted tips to accommodate a separate end-blade of slate or, later on, of metal. Very similar arrows have been found in the region of Kachemak Bay to the north (DeLaguna 1975). The unbarbed Kodiak points were no doubt used for smaller game. They differ in design, however, from those bird arrows pictured by Nelson (1899: Plate LXI Figure *c*; 159-160) which are made of bone or ivory but have short, blunt tips with crenulated edges. Saltonstall believes unbarbed arrows could have been used for taking ducks or puffins (Saltonstall, personal communication 2005). Cormorants, anatids (ducks and geese), and alcids (murres and puffins) comprise the majority of identifiable avian specimens recovered at Settlement Point (Partlow 2000:208).

> When several baidarkas sight a flock of these birds [ducks] they paddle up to them, suddenly fire several arrows and shout for all they are worth. At this some of the ducks take fright, but before they can fly out of the water they have to dive. Thus they surely fall into the hands of the Americans, who give them no chance to draw breath, firing a constant barrage of arrows at them. In the end the ducks become so tired that they pass out, and are killed with paddles, or they escape ashore where they are caught by hand (Davydov 1977:228).

Other possible targets of arrows include cormorants, which were hunted in the spring (Gideon 1989:67), or even ground squirrels. The skins of both animals were used to construct parkas and it would have been important to preserve the integrity of the skins by stunning the prey rather than piercing them with arrows. Some wooden shafts from Karluk One are self-tipped blunts for birding (R. Knecht 1995:288), and it is likely that simple arrow points, some with quite blunt tips, were an alternative system for achieving the same end.

Barbed Harpoon Points

All barbed harpoon points have pointed and barbed tips, with up to two additional barbs placed unilaterally along the shaft. (A single harpoon from Karluk One is bilaterally barbed. Knecht (1995:226) argues that because it lacks both a line hole and a shouldered base, the piece was likely an import.) Barb placement in serially-barbed harpoons falls into two distinct categories, which I have termed “stacked” and “separated”. Harpoons with “stacked” barbs (n=8) have a continuous barbed sequence down the shaft, while those with barbs with a “separated” style (n=18) have a measurable length of shaft between them. Some barbs are straight and others curved, but the morphology is always consistent within a single piece.

Figure 5.4: A typical barbed harpoon from Karluk One.

Diagnostic features are a base with a single shoulder that is always located on the same edge of the piece as the barbs (Figure 5.4), and a line hole placed predictably in the crook of the shoulder. The outline of the hole can vary from perfectly circular to ovoid, but the placement of the hole itself, at the farthest point from the unbarbed edged and where the base is widest, is extremely consistent.

Most harpoon fragments, as well as harpoon preforms worked beyond the initial blank production stage, can be easily identified by several unique morphological features. The line holes preserved on many basal fragments are exclusive to barbed harpoons and their smaller cousin, sea otter darts. Barbs, often slightly curved, leave the “spine” of the harpoon at an acute but pronounced range of angles that are easily distinguishable from those seen on other types of barbed tool components. The barbs along the edge of “people killer” arrows are streamlined against the body of the arrow (Figure 5.5), while leister prongs feature barbs that are small and/or emanate at a shallow angle (Figure 5.6).

Figure 5.5: Barbed arrows.

Figure 5.6: Fish leister prongs from Settlement Point.

Finally, the assertively jutting barb style that characterizes Koniag Tradition harpoons requires that the pieces be created from relatively wide blanks, and perhaps for this reason the harpoons have a flat-to-oval cross-section. In addition to aerodynamic considerations, restrictions of time and overall size of most raw materials might have encouraged the production of wide but shallow tool blanks by past toolmakers. Many tip fragments from barbed harpoons can thus be identified by their cross-sections, which differ from the more rounded one of arrows, foreshafts, leister equipment and many awls. Nonetheless, tip fragments (from all artifact types) are those pieces most likely to be erroneously assigned to an artifact class or unable to classify further and excluded from analysis.

A harpoon point is the most distal component of a complex series of interlocking parts which makes up the entire harpoon assembly, traditionally used by men to hunt sea mammals from boats. The point's shouldered base slipped into the wide groove at the tip of a socket, which could be made of very dense bone, such as an *oosik*, the baculum of a large pinniped such as a sea lion. The opposite end of the socket made a tongue-and-groove articulation with the wooden main shaft, which was equipped with a dart butt at its base to aid its launching with a throwing board. After a strike the point detached from the socket but remained connected to the shaft via a sinew line tied through the hole in the harpoon's base. The harpoon was not used to kill the animal but to incapacitate it and, with the help of floats, track its movements until the final blow could be struck by a hunter from his boat.

Lisiansky describes a harpoon used specifically for seal hunting (1968: Plate III Figure *o*.). It lacks a dart butt and fletching, and was probably thrown by hand or used to tip a lance rather than launched with a throwing board. Other harpoons featured in the illustration are shorter and designed for use with the throwing board, and the points are detachable but have a different style of base.

<u>Fish Harpoon Valves</u>

Toggling fishing "valves" are so named because, like bivalve mollusks, they consist of two components that were cupped together and bound at their bases to form a bi-convex weapon tip. The resulting composite point was then set loosely over a foreshaft. A thrust of the spear would bring both tip and foreshaft all the way through the body of the fish, allowing the tip to slip off the foreshaft and toggle sideways to prevent the animal's escape. As Knecht (1995:198) notes, the small hole created by the long and narrow foreshaft and harpoon assembly would help ensure a strong toggle that would not tear through the soft body of the fish.

Similar weapons were used along the Northwest Coast but the Alutiiq technology differs in important ways. First, harpoon valve points are self-tipped, while the Northwest Coast sea mammal and whaling harpoons feature slots for end-blades (Stewart 1996:109). Second, with the exception of spurred valves, joined valves are asymmetrical, with implications for the types of stresses encountered by the separate valve components of each composite tip.

The simplest design for fish valves involves a large valve and a smaller one that is countersunk within it. When the two are lashed together, the larger valve forms the "working point", and only this component directly contacts the fish and the rocky substrate below. At the proximal end, the two halves together create a basal socket that encloses a narrow foreshaft (Figure 5.7).

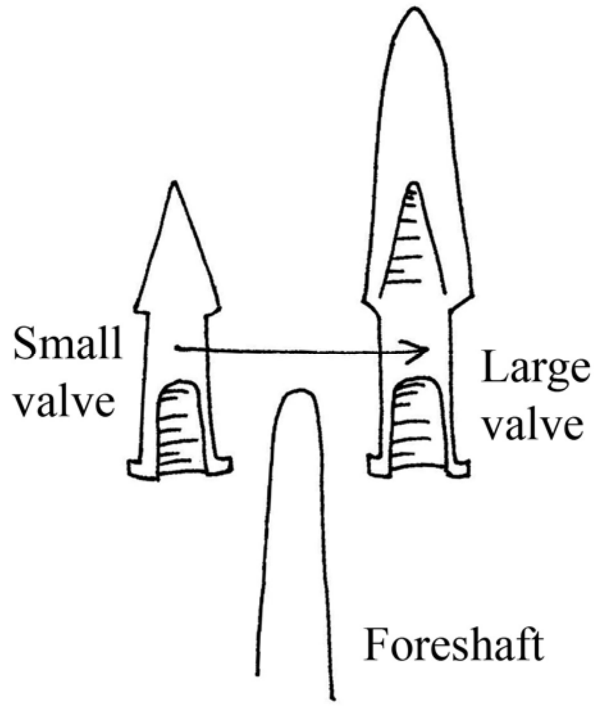

Figure 5.7: Two valves join to form a socketed fish spear point.

Figure 5.8: Two fish valves with socketed bases.

Most socketed components have straight, lipped bases such as those pictured above (Figure 5.8), but a few have a curved basal spur. Spurred pieces fit together symmetrically, so that both halves would absorb impacts. Several spurs were found as isolated fragments. Stand-alone tips comprise a final type of fish “valve”. These are bilaterally barbed and socketed on one side but are otherwise symmetrically convex from front to back (Figure 5.9).

Figure 5.9: Two spurred valves (left) and stand-alone socketed valve (right).

The presence of socket cavities on basal or medial fragments clearly identifies the fragments as portions of harpoon valves. Stand-alone socketed points lack countersinks and are rounded on both sides, while the area where multiple valves join is flat.

Roughly 35% of the valves feature a different type of attachment mechanism that is “scarfed” rather than socketed (Figure 5.10). Scarfed valves were used in triplicate. Like socketed valves, two valves fit together to form a point. In the case of scarfed valves, however, the longer of the two components held a third, smaller valve within it, the joint lending mobility to the assembly and reducing the risk of fracture upon impact (R. Knecht 1995:205-211). I was unable to locate any tertiary valves among the collections, a possible researcher oversight, or perhaps a testament to the longevity of the innermost, protected component of the scarfed style of harpoon tip.

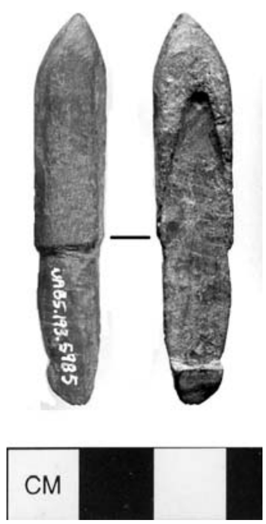

Figure 5.10: Two views of a scarfed valve from Karluk One. The lashing region can be seen on the left; the countersink (right) accommodated a smaller valve. The tip has been resharpened close to the level of the countersink.

Design differences between all fishing valves relate primarily to how the valves articulate, but with the exception of spurred and stand-alone tips, all would be expected to function similarly. When possible, however, in the analyses that follow (Chapter 6) valve components were grouped by base type in the event that morphological differences would result in divergent fracture patterns.

<u>Awls</u>

Awls comprise a loose category, defined here as pieces with at least one sharpened end created either through breakage or deliberate working. Many are long and slender, while others possess a flat and wide gripping region and "nosed' end. In actuality, awls are a heterogeneous and informal group of objects. As classed here, they likely overlap several other artifact types due to analyst error, and possibly they assumed different functions throughout their use-lives. Awls and awl-like instruments run the risk of being conflated with any number of simply and similarly-shaped accoutrements, from slender foreshafts, (whose tips are narrowed but not pointed) to toggles. Nonetheless, some awls possess classical features that distinguish them from other artifact types. Several made on land mammal bone retain an articular end, for instance. A good number are also made of slender bird bones. Related technologies offer some clues to how awls and awl-like instruments could have been used, including sewing *kamleikas*, and kayak covers, and in creating the type of expertly woven objects recovered at Karluk One.

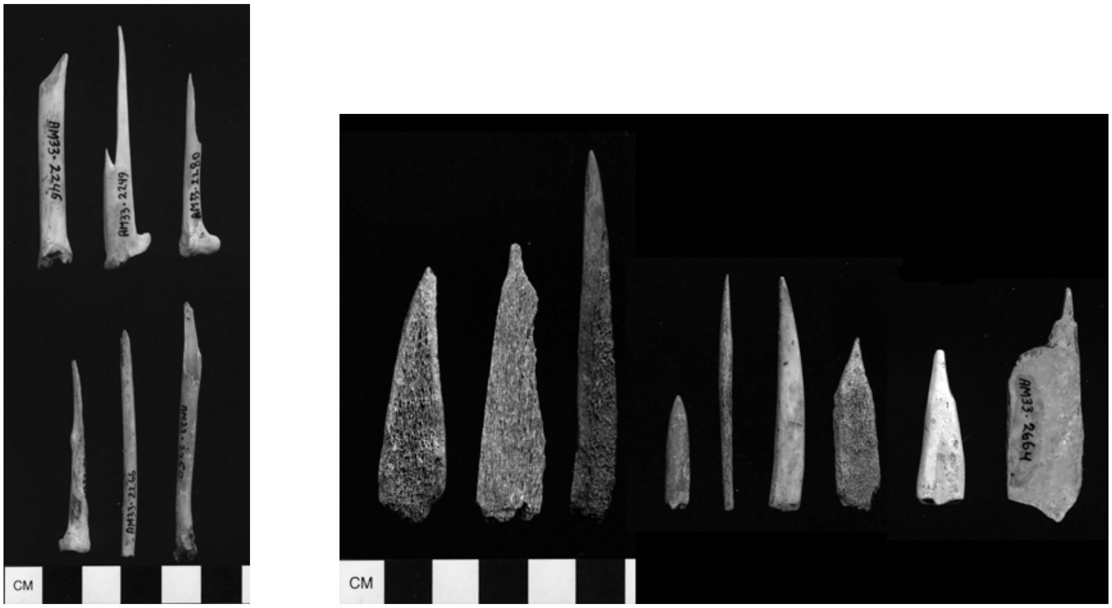

Figure 5.11: Bird bone awls with splintered ends from Settlement Point (left). Settlement Point awls and awl fragments made from a variety of materials (right).

Woodworking Wedges

Wedges were used in conjunction with a hammerstone for splitting wood. Like modern-day metal wedges, most are of uniform width but taper from a wide striking platform to a narrow splitting edge. There is great variation in their length, and they were no doubt used for a range of tasks from heavy splitting of driftwood logs (Knecht 1995:439) to more delicate finishing work.

Most of these pieces were large, coarse grained, and almost certainly constructed of sections of whale ribs, the lateral edges of which have been left unaltered. According to local oral histories, fat was used to lubricate wedges in the past, and Knecht (1995:439) proposes that interesting concavities found in some faces of whale bone wedges may have been used to contain lubricating fat or blubber.

Figure 5.12: Selection of Karluk One wedges. Note “fat hole” concavity in second wedge from the left.

In sum, unbarbed arrows, fish and sea mammal harpoons, awl-like instruments, and woodworking wedges were implements used by Alutiiq foragers to capture or process an array of maritime resources. The brief overview provided here of the economic contexts in which each of the five artifact types would have been used leads, in the following chapter, to a consideration of the particular mechanical stresses each would have encountered during their use. This information, paired with data on the mechanical properties of the osseous materials Alutiiq workers chose to construct these tools, lends unique insights into Alutiiq tool design strategies.

CHAPTER 6:
ALUTIIQ OSSEOUS RAW MATERIAL SELECTION AND TOOL DESIGN

Introduction

Modern engineers are pressed with the job of creating structures that can withstand the rigors of use while generally having to economize material expenditures. Their work may draw from a wide aesthetic palette but any successful design must also meet certain functional requirements (Petroski 1985; Skibo and Schiffer 2001). To this end, engineering design bridges two operational scales. The first deals with features of whole structures, such as their size and shape, and how much weight they can bear along various axes. Underlying gross structure are the chosen materials of manufacture, each of which possesses unique physical and aesthetic properties that make them more or less suited for use for particular types of uses. The mechanical effectiveness of structures created by human labor, just as for whole bone elements, results from the interplay of material and structural properties.

Prehistoric engineers may have lacked the kind of precise testing equipment routinely used in the industry today, but nonetheless shared the same concerns with the design of whole structures, including tools, and with choosing raw materials that could hold up to the tasks that were demanded of them. Like museum visitors today, early explorers and ethnologists who visited the North were fascinated by the engineering ingenuity demonstrated in the complex, multi-component tools high latitude foragers used to work and travel in extreme climates. These voyagers of the 18th through early 20th centuries were often careful to illustrate or carry back with them examples of tools, and to document their uses (e.g., Birket-Smith 1929, 1945; Jenness 1922; Mathiassen 1928; Murdoch 1892; Nelson 1899). Compared to the tools' original makers and users, however, modern analysts know very little about the materials of manufacture and why they were selected for various purposes – despite their contribution to the functioning of the complete instrument.

This chapter applies the laboratory data on osseous material mechanics presented in Chapter 3 by examining patterns of raw selection and other design choices evidenced in osseous technologies created by prehistoric and early historic Alutiiq foragers of the Kodiak archipelago. From one perspective the study is quite narrow, as it does not concern the slate, driftwood, and even the occasional scrap of metal that was put to use in prehistoric and later times within the region. Instead it looks only at the osseous artifacts, bringing greater depth to the often over-simplified raw material category of "bone" by considering how specific classes of skeletal tissues were selected for use in particular contexts. By wedding patterns of raw material use with data on their mechanical properties, items of material culture can be viewed not as static objects, but as solutions to technological quandaries encountered as Alutiiq people made a series of technical choices that balanced potentially conflicting interests like maximum durability and costs of obtaining raw materials. Thus, the analysis adds a new dimension to previous studies of protohistoric and early historic Alutiiq tool repertoires (Clark 1974; Knecht 1995; Jordan and Knecht 1988; Knecht and Jordan 1985; Woodhouse-Beyer 2001) and to other osseous tool assemblages worldwide, especially those which contain similar tool forms such as barbed harpoons, awls, and arrows.

Methods

Chapter 5 described the functions of the five types of tool components chosen for analysis here, which include unbarbed arrows, barbed harpoon points, toggling fish harpoons, awls, and woodworking wedges. Morphometric and other data (see below) were collected on a wider range of osseous artifact types, but the five types included in the current study were numerically dominant, totaling just over 300 objects. Depending on the particular type of analysis, the pool of included artifact types could consist of whole tools as well as broken tools, and tool blanks, when identifiable. A majority of the artifacts analyzed here were found at the Karluk One site, where excellent preservation and a long occupation sequence led to the recovery of not only large numbers of osseous objects, but also of rarely-seen materials such as wood, horn, and baleen (Knecht 1995). All of the artifacts were examined according to the following criteria:

1. Artifact type
2. Artifact portion (whole, proximal, barb, etc.)
3. Raw material type
4. Detailed morphometrics of artifacts and regions including shafts, bases, barbs, hooks, tangs, line holes, etc.
5. Location and angle of breaks
6. Location and characterization of manufacture marks, where visible under low-power magnification
7. Inferred manufacturing techniques and tools, where possible

Raw Material Determination

To my knowledge, no how-to manual exists to aid in the rapid and reliable identification of a wide range of skeletal materials that have been altered through human workmanship. Some materials are easy to distinguish, others, such as marine mammal bone, can be more difficult. Raw material distinctions were built up here using comparative collections of unworked raw materials samples curated at the Alutiiq Museum and Archaeological Repository in the city of Kodiak, Alaska and by consultation with archaeologists, museum staff, and Alaska Department of Natural Resources employees who routinely work with skeletal materials particular to the Kodiak region.

Two references: T. K. Penniman's (1952) *Pictures of Ivory and Other Animal Teeth, Bone and Antler*, and Olga Krzyszkowska's (1990) *Ivory and Related Materials: An Illustrated Guide* also provided some guidance. Both works contain high-resolution black and white plates. Penniman's illustrations primarily detail whole or sectioned specimens, while identification criteria rely for the most part on microscopic analysis, including the use of thin sections. In addition to the obvious problem of destructive sampling, microscopic analyses are impractical for a researcher faced with large sample sizes that must be examined in a limited time span. Krzyszkowska's work is more appropriate for identifying museum specimens, which are often highly altered from their natural shapes. Ivory figures heavily in her analysis, which gives lighter treatment to land mammal bone and antler. Sea mammal bone is not addressed.

Identification Criteria

McComb (1989:14) observed that fresh reindeer antler often appears grayer than fresh bone. I found that this distinction sometimes held for archaeological specimens as well, but the possibility of post-depositional staining limits the use of color as a diagnostic criterion. Post-depositional alterations to the surface of osseous tissues can also obscure such important features as manufacture and use wear traces. However, these alterations affect antler and marine mammal bone in different ways that actually aid the distinction between the two. Antler's cortical surface appears more "fuzzy" than both marine mammal bone and the cortex of land mammal bone, and the phenomenon is accentuated by degradation. Degradation of compact antler tissue begins in surficial patches, creating alternating planes of lowered (altered) and raised, (intact) surfaces on an otherwise smooth surface. It also reveals an increasingly granular texture as the tissue transitions with depth to a more cancellous structure. Often the affected artifact appears delaminated, stripped of its outermost layer but with remarkably little change to its overall morphology, including fine details such as the sharp margins of a line hole or barb tip (Figure 6.1).

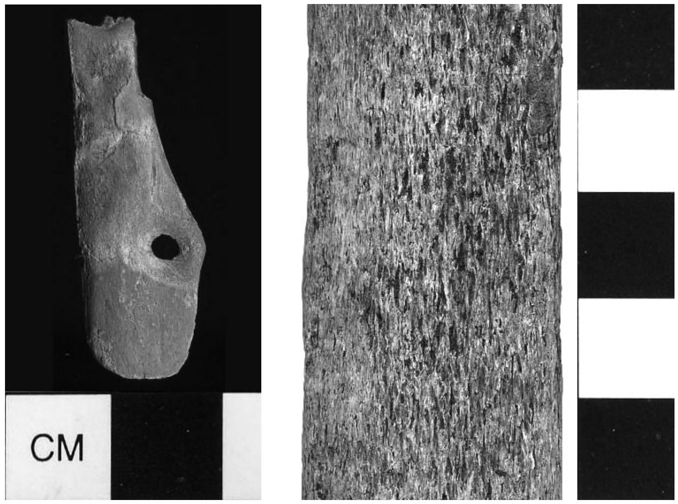

Figure 6.1: Degraded antler harpoon fragment showing clear line hole margin (left) and worked whale bone fragment showing regions of graded porosity (right).

Weathering tends to round the contours of whale bone, where it is most porous. Whale bone's wide gradient of porosity (Figure 6.1) can overlap that of antler's spongy core and even its denser cortex, which hampers one's ability to make material distinctions. McComb (1989:14) notes that the pores of cancellous antler tissue are smaller than that of (land mammal) bone. The same generally holds for antler contrasted with whale bone, but in small samples these tissues can be particularly challenging to distinguish.

An important aid in the identification of whale bone is the character of its nutrient foramina, which are visible in the denser regions of the tissue (Krzyszkowska 1990). These tubes generally run parallel to the long axis of the element, and in cross-section appear as small dark pores. Post-depositional darkening helps to contrast the foramina with the lighter bone backdrop (Krzyszkowska 1990:57). For example, a 70 cm long worked segment of the long bone of a very large animal, possibly of a giraffe, is shown with concomitantly large nutrient foramina seen running along the outer surface, some of which are as much as a centimeter in length (Krzyszkowska 1990: Plate 22c). Although it is unclear if the length of the foramina are most closely correlated with body size or the size of the skeletal element, even small artifacts of highly worked bone and antler can be potentially identified based on foramina length, which is sufficient for distinguishing caribou antler from whale bone.

Diagnostic skeletal landmarks present on artifacts such as ulna awls, and the sheer size of large pieces can also aid in their identification. The largest artifacts studied here include rib-bone wedges which are assuredly of whale bone, and often retain some of the original gross morphology of the element. Finally, antler artifacts often retain a bit of cancellous tissue. Antler differs from whale bone in that in antler, the transition from compact to cancellous tissue is abrupt, not gradual. In some cases (specified below by artifact type) raw material type could not be assigned with certainty. The likely choices were recorded for these pieces which were excluded from analyses comparing raw material use.

Analysis of Osseous Tool Components

Arrow Points

An arrow point would be subjected to considerable stress as it made contact with the prey or fell to the substrate below. Strength would be key desired property of a successful and reusable arrow, as would stiffness to some degree, although high velocity would help to compensate for a less stiff material, particularly if stunning the animal, rather then penetrating valuable pelts, was the primary goal. *Land mammal bone exhibits the highest degree of strength and stiffness and is the predicted material of choice for arrow manufacture.*

As with any tool component that is released from the direct control of its user, arrows were unlikely to undergo pure compression on contact – unless a hunter's aim was perfect and the target was stationary. Instead bending forces, a combination of compression and tension, would ensue especially if the arrow struck a hard target. The same is true of limb bones that fracture in the body, generally as a result of bending rather than pure compression or tension (Currey 1984:74; Wainwright et al. 1982:178), and is the reason the mechanical testing presented in Chapter 3 utilized a bending set-up.

Raw Material Selection at Each Site

The Karluk One and Settlement Point sites together yielded a total of 44 unbarbed arrows and arrow fragments. Contrary to expectation, all were constructed from either antler or marine mammal bone. (One additional arrow for which the material distinction between these two could not be made is excluded from the analysis.) Although marine mammal bone and antler were primary materials chosen for use at both sites, the proportions of these varied. At Settlement Point, 10 of the 16 unbarbed arrows were made of marine mammal bone (62.5%), compared to 10 out of 28 (35.7%) at Karluk One; this more intensive use of antler at Karluk One over other raw material types extends to other types of tools, as will be seen later. But considering the two prehistoric sites jointly, the preference for antler in arrow construction, at 54.5%, is slight.

Breakage and Reworking

At both sites whole arrows outnumbered those that were broken: 75% were intact at Karluk One, and 58 % at Settlement Point. Not all arrows that were broken during use would be expected to make it back to residential areas for repairs, especially those propelled over open water. Unbarbed arrows have a fairly simple morphology, and their low breakage rates may speak to a high repair potential, especially in the tip region where damage is most likely to accrue during use. Tip maintenance would diminish the length of arrow blades over the course of their use-lives. Only very invasive reworking, however, would alter the dimensions of the proximal blade (the region where it is widest and meets the base).

Blade length and proximal blade width measurements support the possibility that arrow blades were significantly reworked. Data from the two prehistoric sites were pooled, and included complete arrows and broken portions that retained intact proximal blades or stemmed bases. Blade lengths (Figure 6.2) show a fairly normal distribution but a good deal of dispersion about the mean (n = 33, mean = 55.2 mm, C.V. = 0.424).

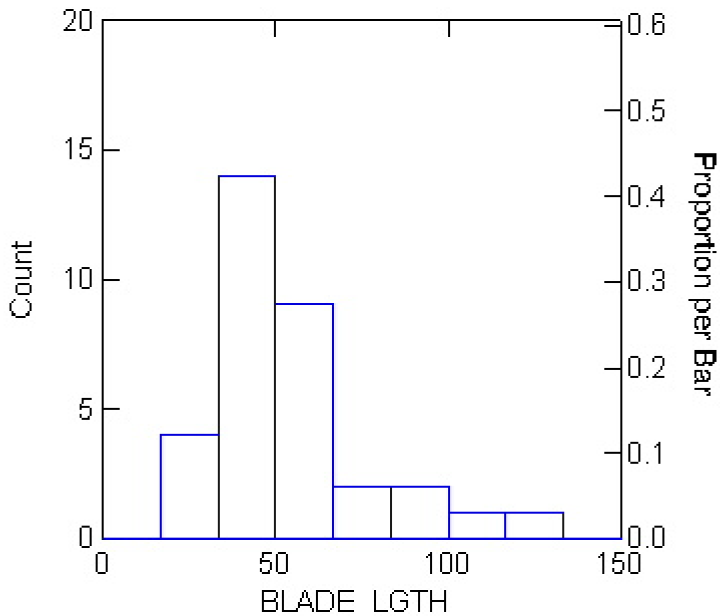

Figure 6.2: Lengths of antler and marine mammal bone arrows in millimeters.

The width of the proximal blade (Figure 6.3) is much less variable (n = 34, mean = 8.05, C.V. = 0.229). Blade lengths varied widely for arrows of both marine mammal bone and antler (Table 6.1).

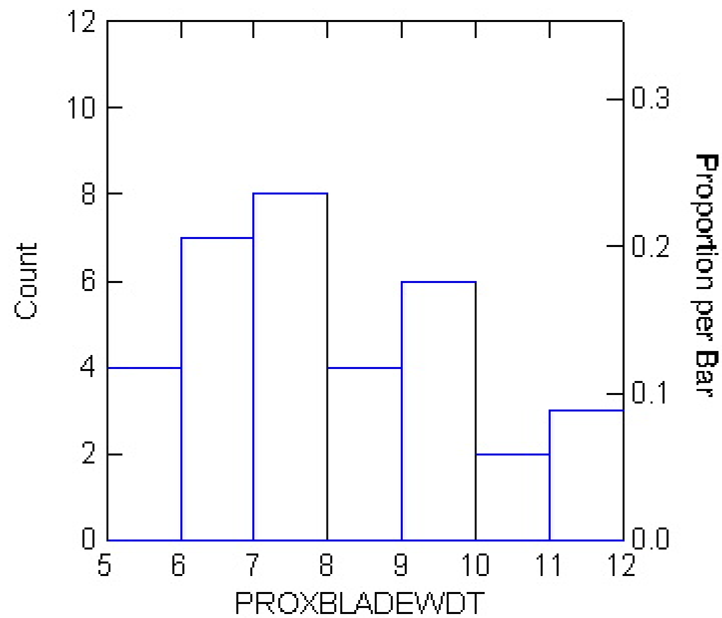

Figure 6.3: Proximal blade widths of antler and marine mammal bone arrows in millimeters.

Material	n	Mean Blade Length (cm)	Range (cm)	C.V.
antler	17	4.98	8.65	0.487
marine mammal bone	16	6.1	8.72	0.357

Table 6.1: Lengths of intact antler and marine mammal bone arrow blades.

Aerodynamic and weight considerations would ultimately delimit the range of allowable arrow blade lengths regardless of raw material type, but this tolerance is apparently very wide. One arrow of marine mammal bone is identical to others in overall design but is exceedingly long (12.8 cm) while several antler arrows are quite diminutive. Included at the small end of the scale are at least three and possibly four arrows that have been recycled, all from fish harpoon valves (Figure 6.4).

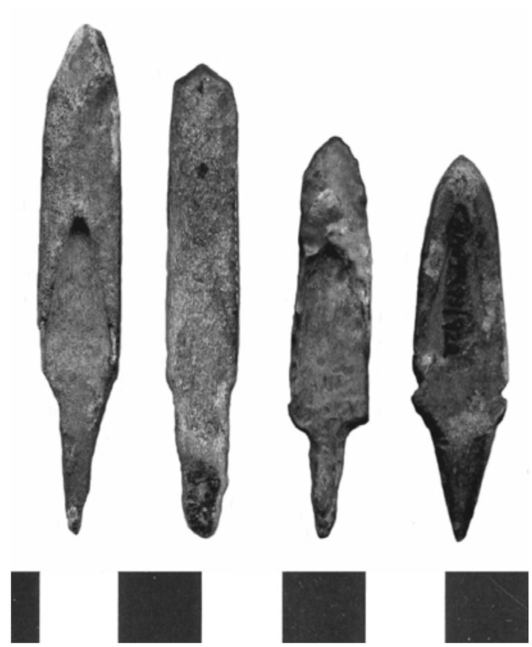

Figure 6.4: At least three fish harpoon components (all of antler) were reworked into arrows. The original v-shaped countersinks created to accommodate a second, nested valve can still be seen, and the scarfed bases have been sharpened into conical ones appropriate for hafting.

Such design flexibility means that repair and resharpening strategies could have indeed been used to extend the use-life of arrows considerably. A wide range of allowable blade lengths would also be evident if arrows of different lengths were used for distinctly different sets of tasks, such as for taking birds of different species. However, the data do not show a multi-modal distribution and, even if they did, separate functions would not preclude the recycling of long-bladed arrows into shorter ones. The fact that proximal blade width is a more consistent measure than blade length further supports the idea that original arrow production dimensions were fairly standardized, but that damage could be ameliorated through blade repairs. Raw material choice and the great range of arrow lengths together underscore the great deal of design flexibility in unbarbed arrows.

In Bleed's (1986) terms, these arrows would have been components of highly maintainable tools: easily replaceable, easily maintained, without a redundancy of parts such as barbs, and used in relatively low-risk prey encounters.

Barbed Harpoon Points

Harpoons work through a sequence of "strike and hold." Harpoons heads would initially undergo strong compressive or bending stresses as they hit their mark, and they must possess enough stiffness to successfully penetrate the tough epidermis of marine mammals. Once a harpoon head is lodged in the animal, the foreshaft with which it once articulated continues to trail behind, connected to the harpoon point by a line tied through the base of the point. Unlike unbarbed projectile heads, barbed harpoons are designed to maintain this connection to the prey despite its struggles (Julien 1982). In this second phase of the capture sequence toughness, or resilience, would aid in maintaining a harpoon's purchase, lessening the likelihood of the animal escaping as a result of the fracture of the harpoon. As demonstrated in Chapter 3, however, great stiffness and toughness are at odds in skeletal tissues, and from the standpoint of raw material selection, Alutiiq engineers may have been forced to choose between optimizing a harpoon's "striking" or "holding" abilities (see Julien 1982 for a discussion of the proposed functioning of different morphological regions of Magdalenian-era harpoons from Europe). Given their size, barbed harpoons could be created either from the strong and stiff bones of medium- to large-bodied land mammals, or from resilient antler. *Alutiiqs' selection of land mammal bone for barbed harpoons would indicate* *maximization of striking and penetrating effectiveness, while antler selection would point to design to optimize a harpoon's staying power once the harpoon was successfully lodged in the prey.*

The traction provided by the barbs ensures that the harpoon will be stressed in tension, especially in the region of the line hole. The placement of the hole very close to the lateral margin of the harpoon seems precarious. There is good evidence, however, that for unilaterally barbed harpoons, offset line holes represent a design choice meant to direct unavoidably high tensile stress into the region of the piece most equipped to support it.

If the harpoon is pulled sideways, toward the direction of the barbs, it will be further drawn into the body of the animal. If, on the other hand, it is pulled toward the direction of the unbarbed edge the force is working against the barbs. With sufficient force transmitted through a sturdy connecting line, the harpoon runs the risk of being wrenched from its hold or breaking. At this point the two regions of the harpoon most vulnerable to fracture are (1) the barbs, as they are pulled in tension, and (2) the region of the line hole where the stress originates. The design of both regions makes them particularly susceptible to fracture. Engineers have learned that stresses are concentrated by notches or holes in the surface of materials, making them more amenable to fracture (Lipson and Juvinall 1963). For this reason, the surface of commercial-grade glass is smoothed to high standards, and mechanical tests performed on impact-loaded specimens often use notched samples, as this concentrates strain energy in a controlled region (Currey et al. 2004:517-518). Barbs are nothing more than a series of reverse notches, and nonreinforced line holes are mechanical liabilities that penetrate the entire thickness of a harpoon head.

Several design strategies can guard against the failure of equipment that incorporates risky elements such as these. A building material can be chosen that is intrinsically good at resisting fracture, either by nature of its ability to safely route cracks or to resist their formation in the first place. As will be shown, raw material choice is an important element in the design of detachable barbed harpoon heads. An alternative or supplemental strategy is to design a structure (tool component or entire assembly) that channels strain energy safely, a feature which is also seen in this type of harpoon.

In a unilaterally barbed harpoon, there are two mechanical advantages to placing the line hole as far as possible from the unbarbed edge. First, as the harpoon is pulled laterally, away from the line hole, some of the tensile loading will locally grade to a compressive component around the hole, albeit across the grain of the harpoon. This is advantageous because bone and antler are better equipped to handle compressive forces than tensile ones (MacGregor 1985; Yamada 1970). Second, unlike the intrinsic strength of a material, structural strength increases with cross-sectional area. By distributing the stress across the region of the base with the greatest width, the likelihood of failure in this region is minimized (Figure 6.5).

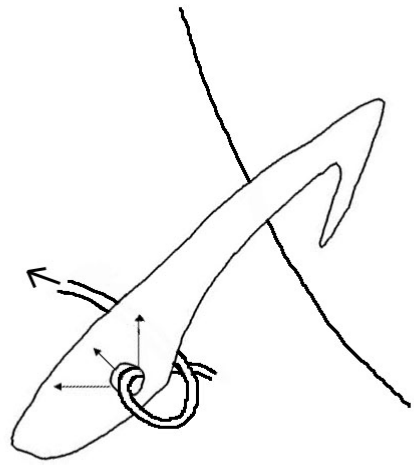

Figure 6.5: A pulled connecting line knotted at the line hole will direct stresses away from the nearest margin of the harpoon.

Publications by Stewart (1996:104-105) and Julien (1982) suggest that the same design linking line hole and barb placement is also found in osseous harpoons from the Northwest Coast region of the U.S. and from the Upper Paleolithic Magdalenian culture in France. A majority of these harpoons which Julien (1982) illustrates featured a pointed and unpierced base, but those with shouldered bases and line holes tended to also feature an offset placement of the hole. What is more, bilaterally barbed harpoons, a form which is virtually absent in Kodiak, show an alternative style of base and line hole placement that would serve a similar mechanical function. Harpoons which are barbed along both edges are shown with symmetrical bases with line holes placed directly in the center of the base, again in its widest area (Julien 1982) – a design compromise that would minimize stresses potentially exerted toward *either* lateral margin. These observations are based solely on the illustration that Julien provides, but if a systematic study of the Magdalenian collection, so far removed from the Kodiak material in both space and time, could in fact identify a strong congruity of barb and hole features, the results would lend strong support to the functional design hypothesis proposed here.

Raw Material Selection at Each Site

The three sites yielded a total of 79 whole harpoon points, fragments, and harpoon blanks. Raw material could be identified for 73 of these specimens. Raw material frequency distributions (pictured by site in Figure 6.6) demonstrate that at the sites of Karluk One and Settlement Point, materials that are tough were nearly always chosen over strong and stiff land mammal bone for barbed harpoon manufacture. Thus, striking and penetrating effectiveness of the points appears to have been a lower priority to Alutiiq engineers in these communities than the harpoon's ability to remain intact and connected to the prey following a successful strike.

At Karluk One, a majority (78%) of the total of 41 harpoon points were of antler. Two were of marine mammal bone, and four were constructed of terrestrial mammal bone which, based on the size of the pieces and the paucity of large-bodied land mammals in the region prehistorically, may have come from a Kodiak bear. Three additional points were of either antler or land mammal bone, but I could not determine which.

The 24 harpoon points from Settlement Point sort into similar raw material proportions. Two thirds of them were made of antler (n=16), five of marine mammal bone (mmb), and one of terrestrial mammal bone (tmb). The raw material of two additional harpoons could not be identified. Although the number of osseous artifacts recovered from the *artel* site is limited, many are harpoon points in some stage of manufacture. Of a sample of 14 whole, broken, and partially completed harpoon points , most of them constructed not of antler (n=4) but of marine mammal bone (n=8) (Table 6.2). Previous studies have shown that like antler, whale bone has a low Young's modulus, or stiffness (Kabel et al. 1999). The fact that Alutiiqs selected whale bone over land mammal limb bone for barbed harpoons at the Afognak Artel site suggests that the mechanical properties of whale bone and antler, the material of choice at the other study sites, may be more similar than has been previously recognized.

SITE	**antler**	**mmb**	**tmb**	**unID**	**SUM**
Karluk	*32*	*2*	*4*	*3*	*41*
Settlement Pt.	*16*	*5*	*1*	*2*	*24*
TOTAL PREHISTORIC	48	7	5	5	65
HISTORIC (AM 34)	4	8	1	1	14
TOTAL %	**65.8**	**19**	**7.6**	**7.6**	**100**

Table 6.2: Barbed harpoon counts by site and raw material.

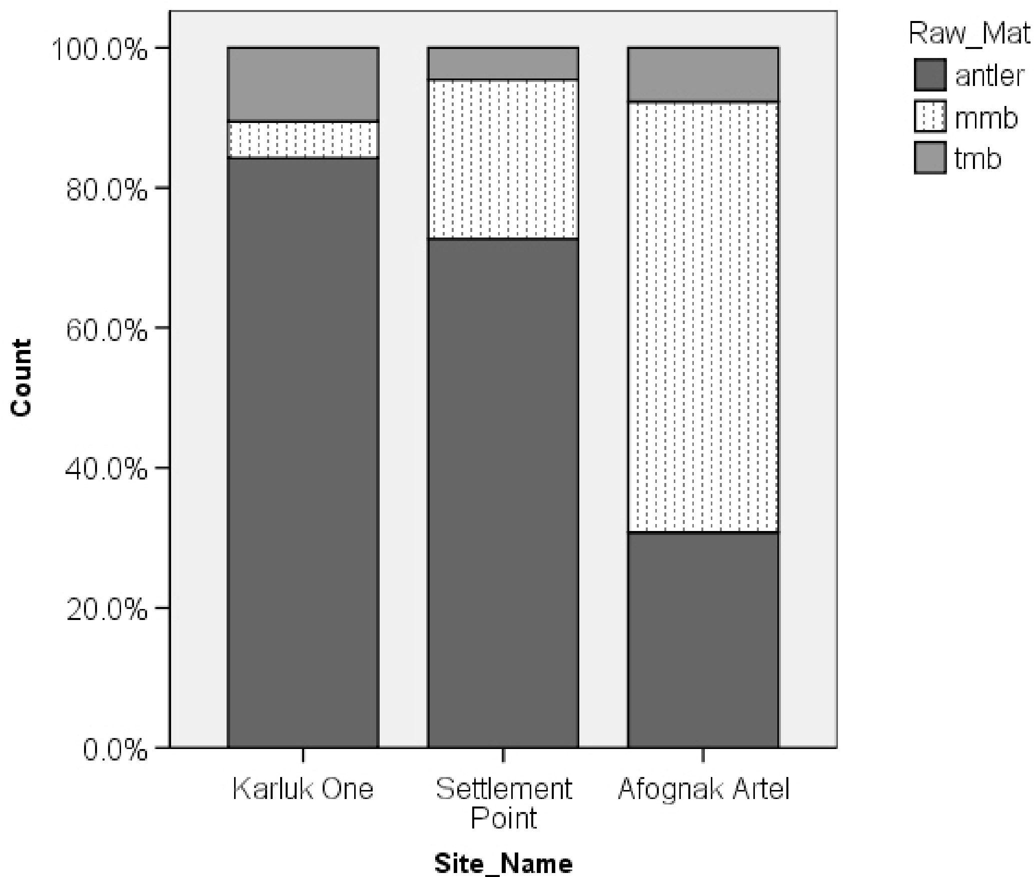

Figure 6.6: Barbed harpoon raw material frequencies by site.

General Breakage Patterns

Breakage data pooled from all three sites and including all raw material types demonstrate that harpoons were most likely to fracture transversely across the blade (Figure 6.7). The frequency of fracture diminished as the break angle becomes less orthogonal to this axis. At an angle of 0 degrees, representing a shear fracture running parallel to the harpoon's length, the fracture rate rose again slightly. No breaks occurred in the intermediate range of 10-20 degrees regardless of material type.

Other breaks occurred at the barbs, which would have been stressed as the harpoon met its target and tension was placed on the line connecting it to the foreshaft, and at the base in areas other than in the vicinity of the line hole. As is true of blade breaks, many of these fractures are oriented transversely. Finally, a small but identifiable cluster of breaks did occur in the region of the line hole. I argue that such fractures testify to the stresses caused by the pull of the connecting line, while at the same time their scarcity underscores the effective design of the base and line hole placement to minimize the impact of those stresses.

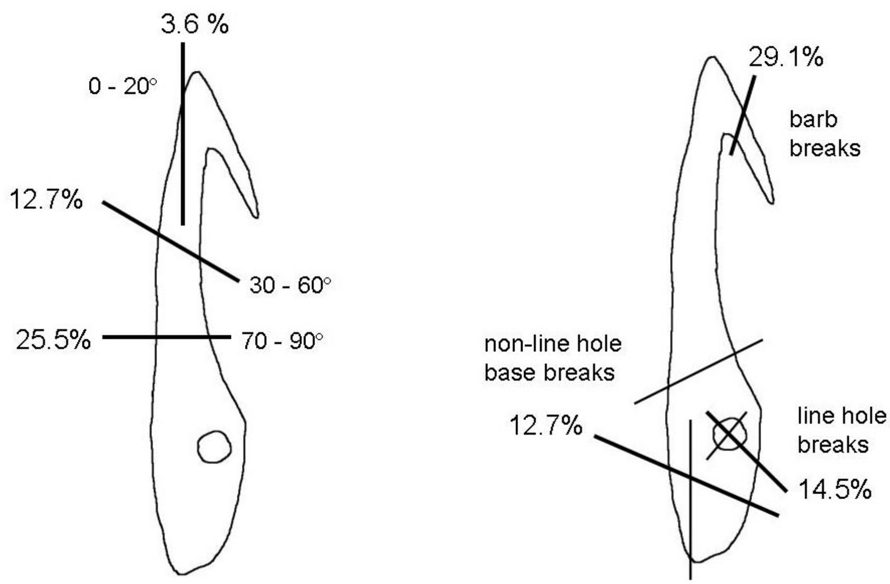

Figure 6.7: Most frequent sites and angles of breaks observed on barbed harpoon points.

A clearer picture of the stresses harpoons were expected to endure during use, and related Alutiiq raw material strategies to deal with these stresses, would emerge if breakage patterns could be linked directly to the type of forces that created them. For instance, were transverse snaps caused by static cantilever bending as a harpoon was firmly embedded in the prey at one end and bent at the other, or by rapid compressive or bending forces enacted upon impact? Visual fracture signatures would be expected to vary with the direction, magnitude and rate of loading as well as with the geometry, structure, and composition of the weapon component. The most brittle bone specimens subjected to bending tests described in Chapter 3, those of elk limb bone, exhibited a "butterfly"-shaped fracture pattern that results from the interaction of compressive and tensile stresses (Figure 6.8).

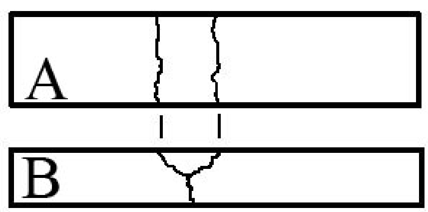

Figure 6.8: Plan (A) and side (B) views of an object fractured in bending. Stress is directed orthogonally to the object's long axis near the region of the breaks.

However, this experimental setup, in which a load force slowly descends from above, is not representative of most natural loading conditions. An experiment in which harpoons faithfully replicated from various osseous materials are subjected to a range of systematically applied stresses (torsion, bending along different axes) would help to bridge observed fracture patterns with the specific actions that created them. It is also possible that relevant, unpublished data may already exist, generated by researchers who have experimented with how raw material type or method of propulsion of prehistoric weaponry would influences rates of impact-mediated fracture in realistic settings (e.g., Guthrie 1983; H. Knecht 1997).

Breakage Patterns by Raw Material Type

Did harpoons of antler, the material of choice at both prehistoric sites, break less frequently than harpoons constructed of other materials? Due to the vagaries of excavation and preservation, it is not possible to gauge a material's success under a given use based on a comparison of raw numbers of whole versus broken tools. One can, however, compare breakage rates of artifacts of different materials scaled to the frequencies at which they were found. Thus, regardless of whether harpoons of a given material fractured rarely or often, the null hypothesis predicts that fracture rates would be proportional to rates of recovery, with no variation according to raw material type. The hypothesis also assumes that Alutiiq discard patterns did not vary systematically for harpoons made on different materials.

Figure 6.9 shows break frequencies for harpoons from all three sites by raw material type. Breaks are divided according to two general types: (1) blade and base fractures (of any angle) and (2) line hole breaks. One-way analysis of variance (ANOVA) tests demonstrate that the null hypothesis cannot be rejected for shaft and body breaks across all three raw materials ($F = 0.610$, $p = 0.546$), as well as for line hole breaks across the three raw material types ($F = 0.239$, $p = 0.788$). In other words, harpoons of the three raw material types exhibited similar fracture frequencies. This is not to say that the use-lives of all harpoons were equivalent, however. The fact that harpoons of antler dominate the two prehistoric harpoon assemblages argues that the manufacturers of these weapons deemed this material the most appropriate. Antler harpoons may well have withstood the rigors of use far longer than those of more brittle land mammal bone, as discard patterns do not indicate actual circulation times of artifacts.

Recycling and Repair

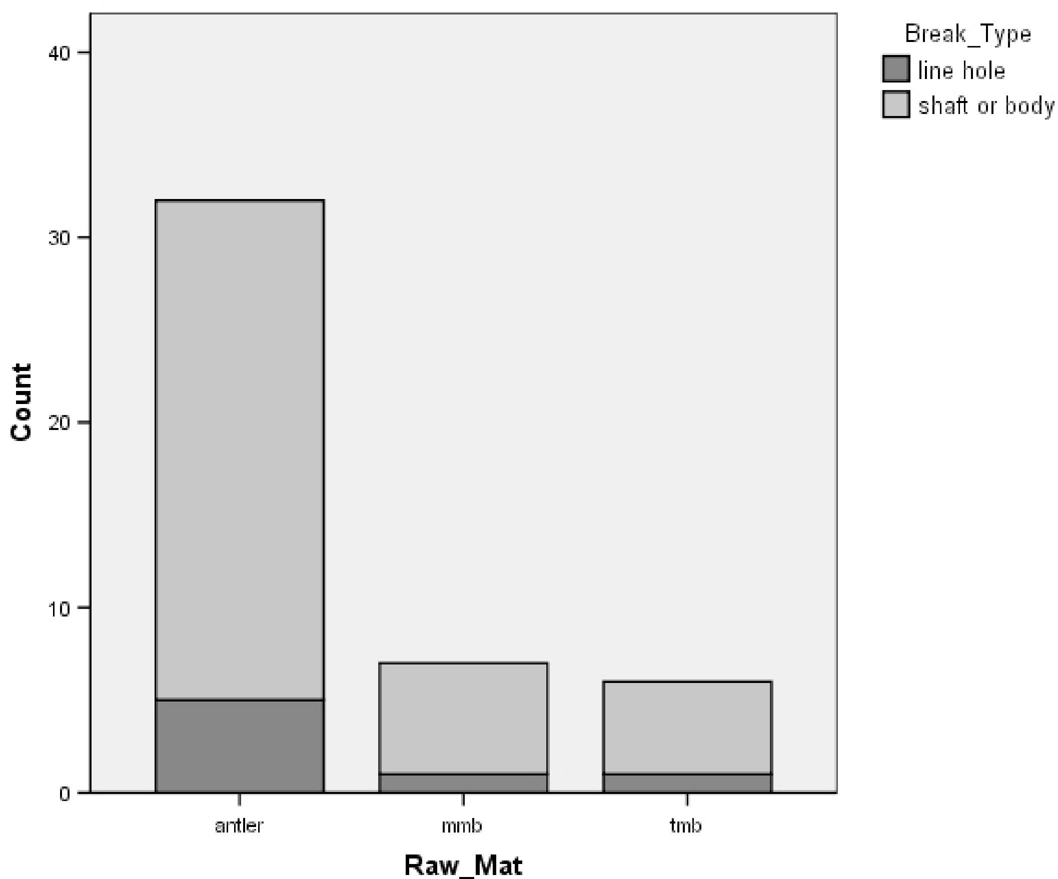

Figure 6.9: Barbed harpoon line hole, and shaft and body brakes by raw material type. Note that some harpoons exhibited more than one break.

Barbed harpoons from Kodiak have a complex morphology comprised of several distinctive regions: tip, one or more barbs, and a wide, shouldered base with a carefully positioned line hole. Highly specialized contours in some ways limited the repair or recycling potential of barbed harpoons. Chipped barbs could be resharpened, but new ones could not be added. Similarly, the wide base provides a strong substrate for the line hole, but also ensures that a new base of the same size can not be shaped from a broken distal segment. (Only a single barbed harpoon from Karluk One evidences the creation of a second line hole. The original hole was plugged, not broken, and was located uncharacteristically low on the base, suggesting the piece had been manufactured incorrectly or reworked from another type of instrument.

Other types of breaks would have allowed for recycling, if not repair. One would expect to find few distal harpoon segments broken above the line hole in the assemblages, as these would have been lost in the water. Proximal harpoons, on the other hand, would have been recoverable as long as the line hole remained, leaving the piece still attached to a connecting line and traceable by floaters. In fact, of the 37 total broken harpoons, (which excludes those whose only damage was broken barbs) nearly a quarter (24.3%) were distal portions that retained no portion of the line hole. These were perhaps brought back to camp as “riders” in captured prey or were broken on-site.

Several harpoons, all retaining the characteristic base, were reworked into other types of instruments. Although not included in this analysis, they offer interesting examples of recycling into such diverse forms as the handle of a carving tool (found at the Afognak *artel*), awls, and possibly arrows.

Finally, multi-barbed harpoons may have offered the potential for reworking and repair, thanks to the built-in redundancy of repeating barb units (Bleed 1986). A majority of the harpoons found at Karluk One are single-barbed, fewer are double-barbed, and only three are triple-barbed. The Early Koniag phase deposits yielded a majority of the multi-barbed harpoons and harpoon fragments, while the single-barbed variants were found mostly in the upper, Developed Koniag layers (Knecht 1995:226-227). Knecht interprets the temporal shift from more complex to simpler harpoon styles as corroborating evidence for an associated decreased reliance on marine mammals in favor of intensive fishing, which faunal data from other sites in the region support (Partlow 2000).

The same trend could also evidence increased recycling of multi-barbed points into single-barbed tips during the Developed Koniag, concomitant with less time and energy directed toward creating new harpoons from scratch. Thus, while the recycling potential of other regions of the harpoon body is probably limited, the redundancy of barbs might have allowed some types of damage to be corrected, a labor saving design. Specifically, these complexly-shaped components could have been modularly designed, allowing a distally damaged, multi-barbed harpoon to be reworked into a variant with fewer barbs.

Modular design dictates that certain dimensions of the harpoon, such as the dimensions of harpoon’s proximal end where the piece articulated with an interlocking tool component, be standardized. If, on the other hand, multi-barbed harpoons are also uniformly bigger harpoons (thereby limiting their potential for recycling into simpler harpoons forms) then the basal dimensions of multi-barbed harpoons should exceed those of the single-barbed variants. Two dimensions which were measurable on many broken as well as intact harpoons were chosen to test the hypothesis of possible reworking. The first was the distance from the base to the bottom of the first (most proximal) barb. The second dimension was basal width, measured at the height of the line hole (Figure 6.10).

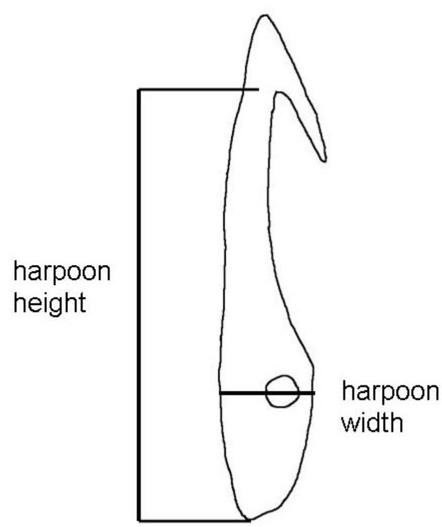

Figure 6.10: Harpoon height and width measures.

The absolute range and distribution of base-to-first barb length values are strikingly similar between the two harpoon types (Figure 6.11, Table 6.3). At just shy of 50 mm, the mean lengths are nearly identical. Base width ranges are also strongly overlapping, and the mean width of multi-barbed harpoons is only 1 millimeter greater than that of the single-barbed variety (Figure 6.12, Table 6.4), a difference which is unlikely to have had behavioral import.

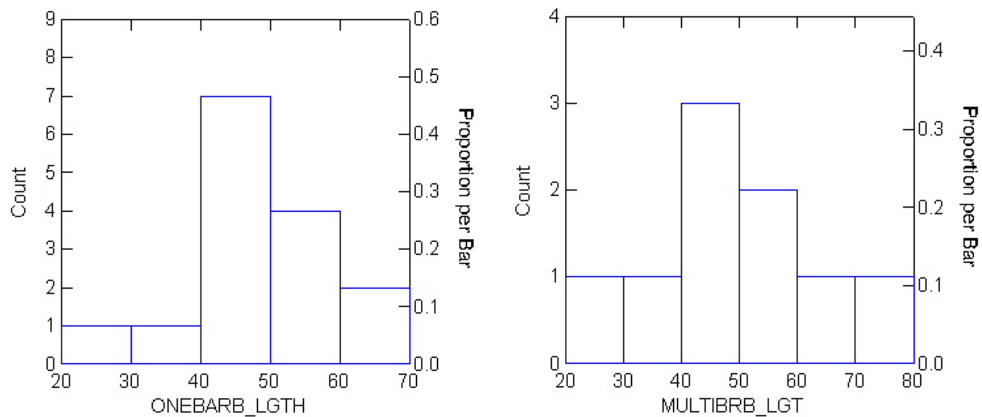

Figure 6.11: Base-to-first-barb lengths (mm) of single- and multi-barbed harpoons.

	Single-Barbed Harpoons	Multi-Barbed Harpoons
n	15	9
range	40.17	43
mean	48.43	49.77
C.V.	0.209	0.281

Table 6.3: Base-to-first-barb lengths (mm) of single- and multi-barbed harpoons.

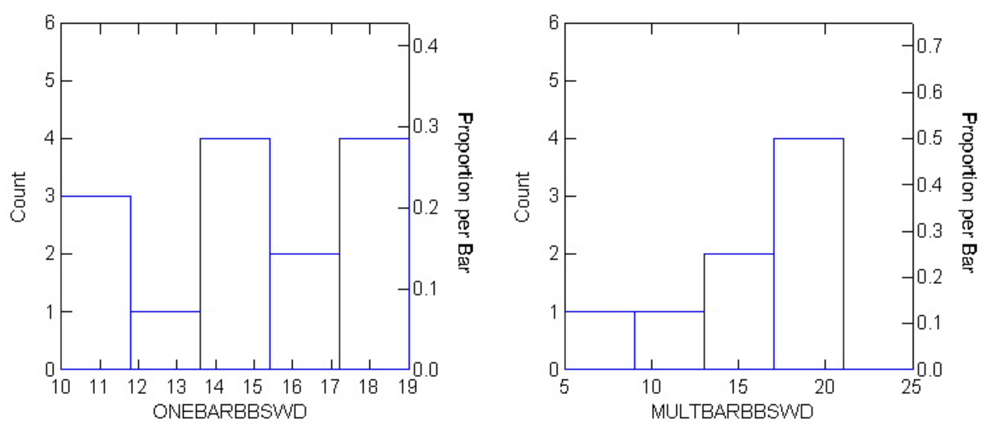

Figure 6.12: Base widths (mm) measured at the height of the line hole of single- and multi-barbed harpoons.

	Single-Barbed Harpoons	Multi-Barbed Harpoons
n	14	8
range	8.01	11.54
mean	14.64	15.56
C.V.	0.187	0.269

Table 6.4: Base widths (mm) measured at the height of the line hole of single- and multi-barbed harpoons.

It was proposed that if multi-barbed harpoons were designed to be bigger overall, then base-to-barb length and the basal width should be greater for multi-barbed harpoons than for the single barbed variant. Instead, the strong overlap in both length and width values between the two types demonstrates that multi-barbed harpoons were not built to scaled-up proportions. Rather, single-barb harpoons can be viewed simply as shortened multi-barb harpoons. In this light, it is entirely possible that morphologically complex harpoons were reworked into simpler forms during the Developed Koniag Phase. However, base-to-barb lengths and basal widths vary widely, both within and between the two harpoon types. A broad tolerance in allowable basal dimensions does *not* necessarily demonstrate modular harpoon design, at least at the level of the entire assemblage. However, it may be inappropriate to view standardization and modularity at the level of the assemblage.

Tools of a given form, hand-crafted by different makers, will inevitably exhibit some dimensional variability, even if they are designed to accord to a common cultural or community-wide set of standards. Slight morphological idiosyncrasies would be of no functional concern, unless component parts are borrowed or exchanged between users, or if select components are created by distant specialists unable to "custom fit" their products. When dimensions of tool components vary widely, as is the case for the sea mammal harpoon bases, they may express a form of standardization that does not encompass a group of practitioners but rather, represents a set of practices of a single individual.

Because weapons tips and other interchangeable parts are traded in and out of an assembly, it is important that they articulate properly with the connecting element or elements of the tool. An individual tool maker would likely benefit in this case from allowing one component of an assembly, such as the most central or durable element, to dictate the finished dimensions of the components with which it interlocks. The shape of a heavy bone socket, for instance, might set the standard for the basal dimensions of all barbed harpoons that are used in conjunction with the socket over its lifetime. The result would be dimensional synchrony in the articulating regions of a set of interchangeable components that complete a single tool.

Burials or caches that contain spatially bounded and behaviorally meaningful clusters of like artifact types would provide the best evidence for evaluating if this hypothesis holds true, since potential standardization exhibited at such a small social scale might otherwise be masked to archaeologists by larger, assemblage-wide morphological variation in artifact sizes.

Fish Harpoon Valves

Salmon and other anadromous fish were crucial resources taken in large and increasing numbers into the Developed Koniag beginning around A.D. 1400 (Partlow 2000). It was necessary that they be collected quickly in summer and early fall to ensure an adequate winter's supply, and weirs were probably used to aggregate the fish for easier capture (Knecht 1995:199). Because fish harpoons were used not just once but repeatedly throughout a critical period it was crucial that the technology be both reliable and maintainable (*sensu* Bleed 1986).

As the fish harpoon and articulating foreshaft were stabbed through the soft bodies of the fish they risked frequent contact with the shallow rocky creek beds below. Impact resistance would have been a critical design feature. This is seen in the design of the entire weapon head assembly which, rather than created as a single piece, consisted of at least two valves which nested together to provide "give" upon impact.

> Items subject to heavy use and breakage, like dart shafts, kayak keelsons, and other items of Koniag material culture, were frequently made of ingeniously joined composite parts. Composite designs, although somewhat more labor intensive, made equipment repair easier, and are more often observed on hunting and fishing gear, where speedy repair makes good economic sense (R. Knecht 1995:199).

The multicomponent design also ensured that only one valve of the assembly would feel the direct force of a strike, as one or more smaller daughter valves nested within a larger parent valve. The exception is the rarer valve type featuring basal spurs, in which the two articulating pieces were identical.

The optimal raw material to complement the structural impact resistance built into fishing harpoon design would be one that is effective at absorbing repeated high-intensity stresses. But because penetration through the soft-bodied prey would have posed no challenge, stiffness and strength would have been a low priority. Moderate flexibility may have in fact been desired to help counter impacts. *Considered from a mechanical perspective, antler, a tough material with "give," would have been the clear material of choice from which to construct fishing harpoon valves.*

Breakage Patterns

Nearly all (97%) of the 112 valves analyzed were recovered from the Karluk One site. Only one-third were broken but many showed basal damage, especially socketed-style valves. Transverse breaks occurred along the shaft, across the socket, and in the intermediate region, while longitudinal breaks or damage tended to original at the base (Figure 6.13).

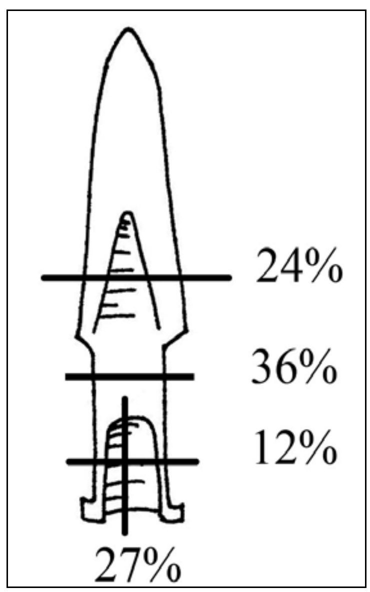

Figure 6.13: Most frequent sites of breakage and damage in socketed valves. All scarfed valves (Figure 5.10 in Chapter 5) were intact.

Roughly half of those with socketed bases, either straight or spurred, suffered breaks or damage but all of the valves featuring a scarfed base were complete. As jutting features, spurs were vulnerable to fracture and 31% of spurred valves were broken, generally in the area where the spur met the body of the piece.

Basal breaks would have been virtually irreparable and probably occurred while the proximal valve was still hafted into the foreshaft. Tip breaks and battering could have been repaired more easily, and the length of valve tips (measured from the tip of the piece to the tip of the countersink) gives an indication of the amount of use-life that remains. Tip lengths ranged widely, from 0 to 66 millimeters (mean = 16 mm, C.V. = 0.747); those whose tips were completely exhausted (tip length = 0 mm) were resharpened down to the tip of the countersink. Many valves were discarded or lost with little or no use-life remaining, while fewer had a considerable amount of tip still present (Figure 6.14).

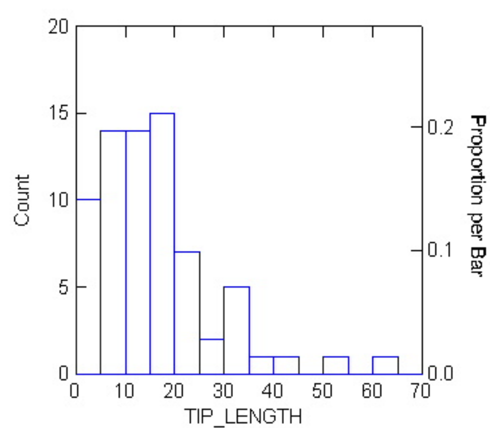

Figure 6.14: Tip lengths of fishing valves (mm).

Figure 6.15: Many harpoon valves were extensively resharpened (top). Fewer have a good deal of usable tip remaining (bottom).

Raw Material Selection

Fracture patterns are not broken down by raw material type because of the overwhelming prevalence use of a single material seen in the collection. Only three of the 112 valves analyzed were made definitively of marine mammal bone, six could not be identified to raw material, and just as predicted, an overwhelming 92% of fish valves were created from antler, as predicted based on material properties.

Awls

Rather then sudden impacts, awls of all types would be expected to undergo steady, slow, and prolonged stresses. Those used for piercing skin and hides would need first and foremost to be stiff, and able to withstand bending and torsional forces without buckling. It is also imperative that they be able to maintain a sharp point, which is most effectively accomplished using compact rather than spongy tissue.

Awls used in basketry and other forms of fiberworking need not possess very sharp tips. Fairly blunt but smooth working ends may in fact be preferable for separating or splitting adjacent fibers without snagging. Both functions, however, call for a material that is stiff and close-grained. *Of the materials whose mechanical properties are currently well-understood, land mammal bone best fits these criteria.* The existing literature, however, suggests bird bones would provide the best material specifically for creating sharp-tipped awls. Proximal wing elements have a particularly high structural stiffness, and are adapted to withstand the strong bending and torsional stresses that are encountered during flight (Pennycuick 1967). As a result, they are well suited to withstanding the pressure and twisting motions entailed in piercing soft materials. The size of bird bones and the thinness of their cortical walls place absolute limits on the size and structural strength of tools that can be made from them. Sharp-tipped awls are small, hand-held tools. Their diameters must be sized appropriately for piercing, and bird bones can be readily splintered to provide sharp and easily maintainable working ends.

Awls of all types were hand-held instruments, used to place direct pressure on the working material. In this crucial way they differ from the arrows, barbed harpoons, and wedges described here. Relatively heavy stresses would be placed on sharp tips, but in a gradual and constant manner; a skilled worker would have a visual and tactile sense of an acceptable magnitude of this pressure. What is more, projectile technologies leave the hand and often the eye, but an awl is used to maintain fine and *continuous* control over the stresses acting on the piece, which can be adjusting at will. The result is a type of loading that is sustained rather than sudden, and adjustable rather than unmodulated.

Raw Material Selection and Breakage Patterns

A total of 61 awls and awls fragments were recovered from the three study locales, only one of which was found at the Russian *artel* site. Most of the artifacts that were determined to be awls were recovered whole (88%) but given their morphological simplicity, more fragments were likely overlooked. Information on wear was not noted. Complete awl lengths ranged widely, from 3.3 – 16.4 cm. Similarly, raw material distributions (based on 82% of the sample that could be identified) revealed a degree material diversity that probably reflects a combination of low selection pressure, researcher error, and their use for a range of functions. For instance, nearly a quarter (24%) of the awls were constructed of antler, which is surprising given its low elastic modulus. Some of these antler implements may well have served other purposes, such as connecting pegs for bentwood boxes, or been used for different functions (Griffitts 2006). Other media include marine mammal bone, the predicted terrestrial animal and avian bone, and a single specimen of ivory. Bird bone representation is in fact striking, comprising 54% of the total identifiable sample (Figure 6.16). These awls often preserve one articular end and a spirally fractured tip. Although awls compose a somewhat artificially constructed category, the extensive use of bird bone is unprecedented among other artifact types.

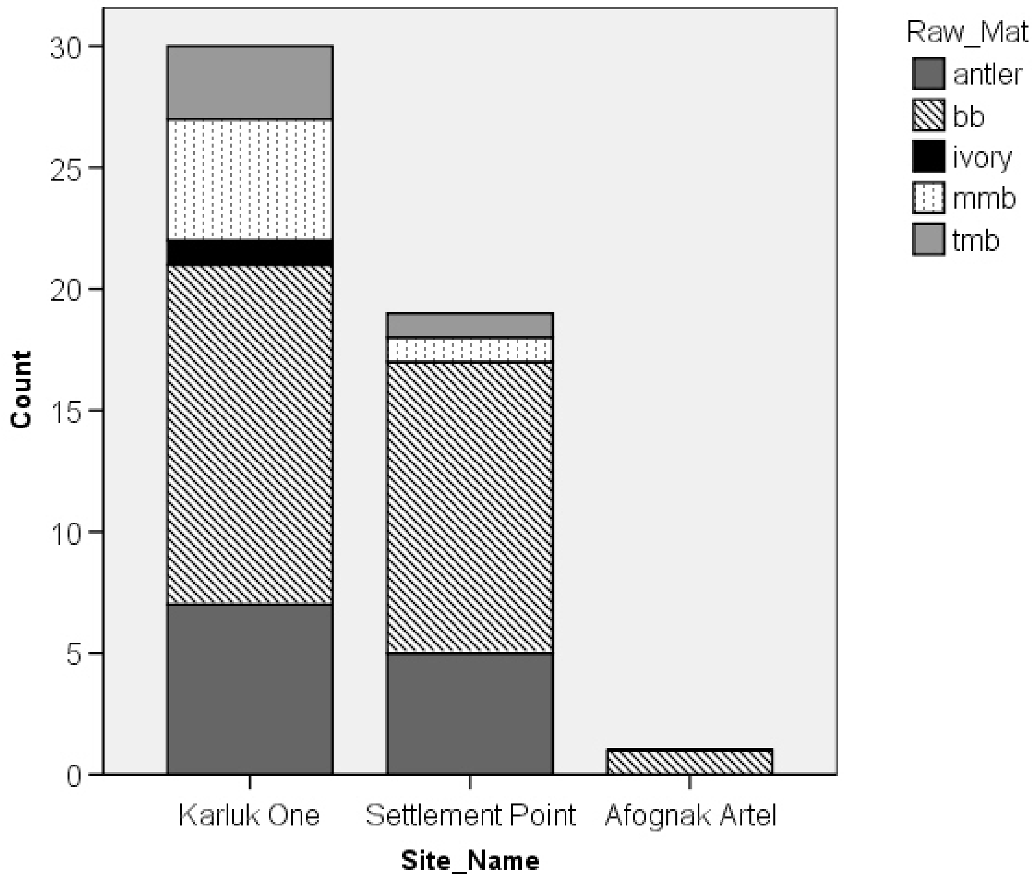

Figure 6.16: Awl raw materials by site.

<u>Woodworking Wedges</u>

Wedges, like awls, remain in the control of the worker during use and would undergo a fairly predictable form of loading. Ideally the blow of a hammer would create a pure compressive force that is diffused across the width of wedge's blade. However, a combination of compression and bending is the more realistic mode of loading in all but the stiffest instruments. Wedges, particularly those above a certain size, pose a mechanical quandary to woodworkers restricted to osseous source materials. To support heavy impacts and successfully penetrate wood substrates wedges must be both strong and fracture resistant, two properties normally at odds in bony tissues. What is more, they must also be stiff so as not to buckle under a striking force, and to successfully relay the striking force into the wood. The materials data presented here show a strong correlation between intrinsic stiffness and bending strength, but that both qualities are sacrificed with increasing degrees of fracture resistance. All three properties would be important to the successful function of wedges, however, so wedges that are constructed of osseous materials represent a compromise, regardless of the chosen material of manufacture. The best way to triangulate between these constraints may be to create a wedge that is large, using a material that is good at resisting fracture. "Building bigger" ameliorates the low intrinsic stiffness and strength of the raw material, and elevates structural strength and stiffness to more easily split apart large driftwood logs. Of the materials whose mechanical properties are well-understood, antler provides maximum fracture-resistance. However, the overall size and especially diameters of tools that could be created from this material are very limited. *Antler is thus put forth as a strong candidate for use in the construction of woodworking wedges, but one whose selection for toughness would represent an unsatisfactory compromise in a wedge's structural strength and stiffness.*

Raw Material Selection and Breakage Patterns

No osseous wedges were recovered from the *artel* site, but those from the two prehistoric sites total 35. All but three of these were made on whale bone, many of them clearly rib segments. Two were shaped from antler, and one could not be identified to raw material. Few wedges were definitively broken, but most showed signs of battering on the butt and blade ends. Pounding caused butt ends to crumple and created longitudinal splits emanating from the blade end which, in a few cases, had completely rent the wedge in two.

The use of whale bone for wedge production is not at all surprising. Whale bone offers the greatest package size of all osseous materials in the Kodiak region, especially in terms of width, the limiting variable. Antler offers the same benefit of a solid rather than tubular macrostructure, but cannot offer the material girth of whale bone. The mean width of the wedges is 44.4 mm (n = 32, C.V. = 0.342) (Figure 6.17) which exceeds the maximum shaft diameter of caribou antler by at least a centimeter (Corbin 1975:204, 207 Table 4).

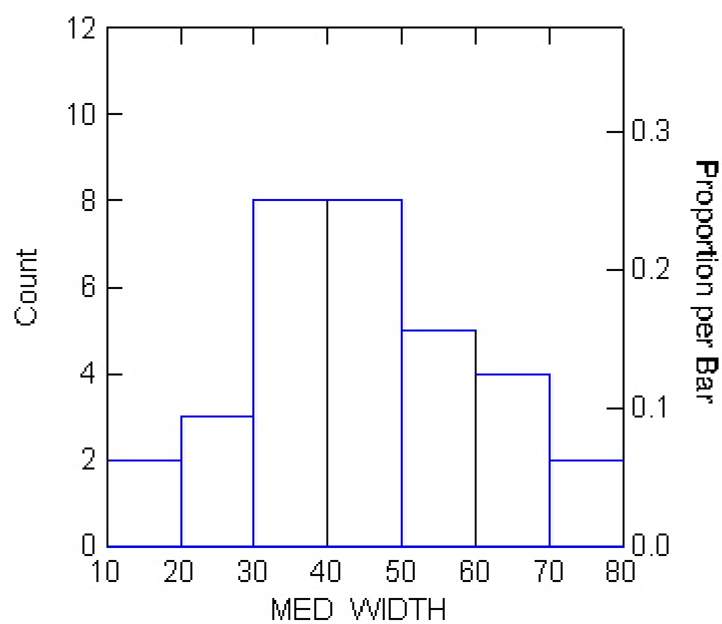

Figure 6.17: Widths (mm) of wedges measured mid-shaft.

Mechanical Properties and Raw Material Selection

Mechanical tests conducted here lead to the prediction that from a mechanical perspective alone, antler should be used to create tool components requiring maximum toughness, and for which flexibility is important or at least allowable. Tools components that must be strong and stiff are less likely to be constructed of antler, and technicians should instead look to land mammal limb bone, or avian limb bone (Chapter 2).

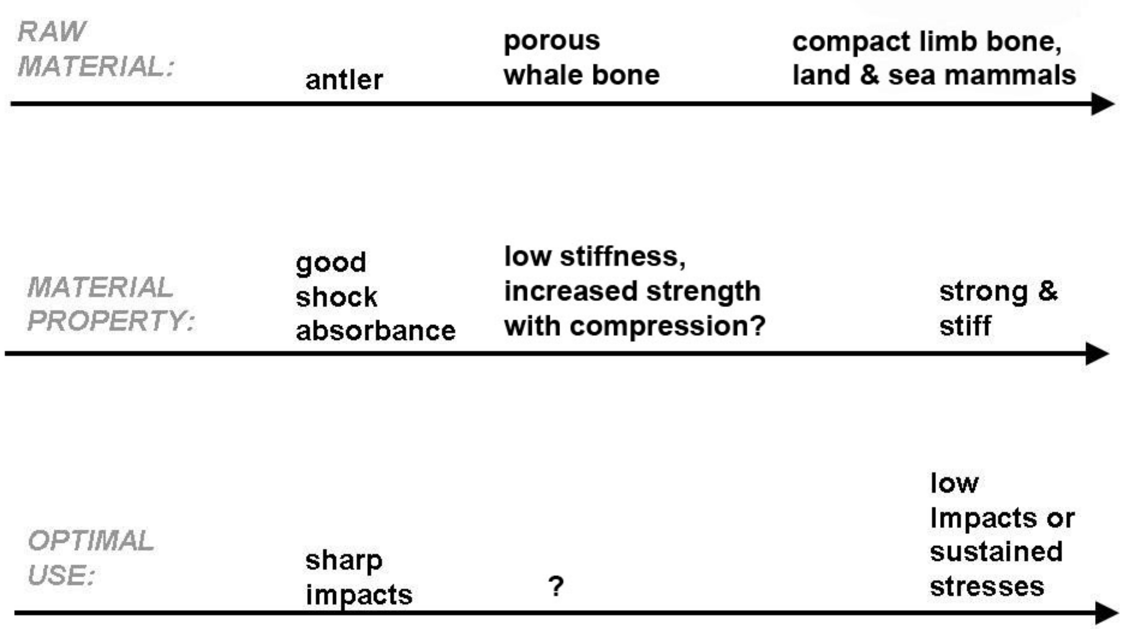

Figure 6.18: Predicted uses of materials based on mechanical parameters.

The five types of tool components studied here ranged in their uses from hunting to fishing to domestic tasks. Consequently, each would have endured distinct types of loading during use. These five tool components can be ordered along a continuum (Figure 6.18) based on their predicted mode and rate of loading, from sharp impacts (left) to low impacts or sustained stresses (right) in order to test how well Alutiiq raw material choices matched the mechanically-based expectations.

Alutiiq raw material choices in many ways fit the mechanical predictions (Figure 6.19). In particular, as the left side of the figure demonstrates, antler use dominates among high impact tools, and decreases relative to other materials as the expected amount of sharp impact also diminishes.

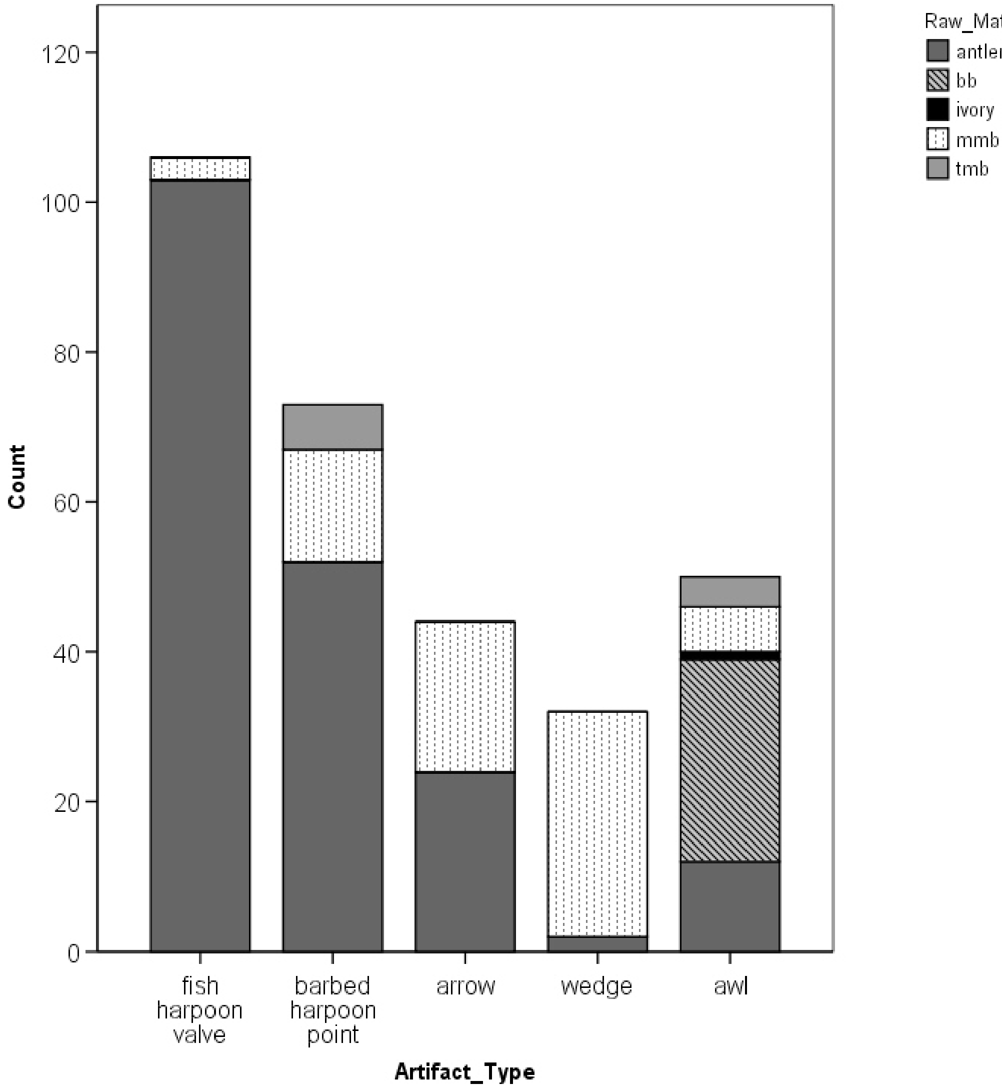

Figure 6.19: Raw material selection by artifact type.

This fact is particularly striking because the caribou that provided the antler are not native to the Kodiak Archipelago. The Russian Orthodox missionary Hieromonk Gideon, who lived on Kodiak island from 1804-1807, recounts the following:

> The northern and western inhabitants of Kad'iak [Kodiak] engaged in barter trade mostly with the Americans of Aliaksa [Alaska Peninsula]…The former obtained from the Alaskans, in exchange for dentalium shell beads and amber, caribou

> antlers used for spear tips [foreshafts], caribou parkas, and also long caribou hair taken from the animals chest…(Gideon 1989:57).

Were fishing tips not expected to support sharp impacts, the range of effective materials for their manufacture might be more loosely bounded. As it was, impact stress was the prevailing factor in raw material selection, nearly always superseding the problem of material availability. Only rarely was marine mammal bone substituted for antler in valve construction. Although material substitutions can be the visible result of experimentation in new media, whale bone was widely available in the Kodiak region, and was a material with which Alutiiq people were intimately familiar. Its restricted use for this particular tool type speaks not to experimentation and innovation, but to a concentrated focus on the use of non-local antler as a prized resource. The case of harpoon valves, in which maximizing toughness was the ultimate goal, bookends the range of raw material compromises inherent in all tool designs.

Sea mammal harpoons show a similar, if slightly less dramatic, preference for antler, which was used to create over 70% of the barbed harpoons, harpoon blanks, and fragments of identifiable raw material recovered from the two prehistoric sites of Karluk One and Settlement Point. The suggested compromise in their design was one of maximizing piercing effectiveness, best achieved by selecting stiff and strong land mammal bone, or maximizing durability through the use of antler. Clearly the latter trait was of primary importance to prehistoric Alutiiq engineers. Alutiiqs at the Afognak work camp also eschewed land mammal bone for barbed harpoon manufacture in favor of a material with a low degree of stiffness, but this material was whale bone rather than antler. It's pattern of use for bared harpoon tips and other tool components (as will be discussed below) strongly suggests that the intrinsic mechanical properties of antler and whale bone are more closely allied with each other than they are to the corporeal bones of land mammals.

On the other end of the chart, the awls form a very mixed group. As Griffitts (2006) has noted, awls are an understudied set of tool types. Morphology and function are often conflated, disguising the diversity of tasks for which awl-like instruments were often used, including the use of a single instrument for multiple activities throughout its use-life. Although some types of Kodiak products that were likely manufactured using awls were remarkably preserved at the waterlogged Karluk One site, including grass, feathers, hair and basketry items (R. Knecht 1995), an analysis aimed at linking awls in the assemblage to the specific task or tasks for which they were once used was beyond the scope of this study. It is likely that the wide array of materials used to construct awls in large part reflects functional diversity, in addition to loose raw material constraints.

Nonetheless, awls are the only tool form showing a significant use of bird bone. As strong slender rods suited to the twisting and bending motions used when piercing supple materials, bird bone serves as a valuable reminder that not only material-scale mechanical properties, but also whole-bone morphology and structural properties can be key factors in the selection of one material over another.

Moving toward the middle of the chart, it is evident that nearly all of the wedges are made of whale bone. This too must be linked to the material's gross morphology, as whale bone is simply more massive than other available materials save the wood it was used to strike. The largest wedge (AM 193.95.735) has a width of nearly 74 cm, but the bit end is only about 2 cm wide. The example illustrates the scaling-up principle to increase stiffness, even when a wide working end is not necessarily desired. A second factor in whale bone selection for wedge construction may relate to its dense yet porous texture. When subject to compressive forces, wet cancellous tissue becomes stronger before it becomes weaker, as structural cells collapse to form a more solid architecture (Gibson and Ashby 1997:439). Accrued strength through use would surely have benefited wedge performance, at least until compressive or bending stresses would exceed the structural strength of a wedge causing it to crack or buckle. Both size and elevated strength are compelling factors that likely stood behind the use of whale bone for woodworking wedges, but neither offers a satisfying explanation for why this material was frequently selected to create the final artifact category analyzed here: arrows.

Although it was predicted that simple, unbarbed arrows would ideally be constructed of land mammal bone, a stiff and strong material, not a single arrow conformed to this prediction. Instead, arrows were made roughly evenly from antler and marine mammal bone. Antler arrows numerically dominated at Karluk One; antler's representation was bolstered by several antler arrows obviously reworked from another type of tool, demonstrating a wide tolerance in accepted arrow shapes.

The fact that land-mammal bone was eschewed in favor of antler supports the notion that arrows were used primarily for stunning rather than for penetrating prey. Stunning would require toughness to resist impacts with both birds and the substrate below, so that durability, rather than strength or stiffness would be of primary importance. Great penetration power, in contrast, might call for a degree of stiffness or strength that antler does not carry. Salmon harpoons were used to penetrate all the way through the prey, but the soft bodies of fish would offer little resistance to the weapon tip. If Alutiiq fishers valued piercing effectiveness over durability for their tools, then fish harpoon valves, like arrows, would likely have been constructed from land mammal bone rather than overwhelmingly from tough materials.

Most arrow tips are strongly tapered like the farthest left piece pictured in Chapter 5 (Figure 5.3), but even the best preserved specimens lack the kind of sharp point which stone arrow tips are capable of holding (Ellis 1997). The arrows are also circular or semi-circular in cross-section rather than thin and sharp-edged. It is possible, but awaits verification through testing, that antler is simply less capable of holding a sharp point than is land mammal bone. Even so, both antler and land mammal bone can be shaped into blunt points. Differences in raw material availability also offer no compelling explanation for the preferred selection of antler for arrows. Most land mammals native to the Kodiak Archipelago prehistorically were fox-sized or smaller, which would limit the size of articles that could be constructed from their bones. Nonetheless, while caribou antler was obtained through trade, little or no economic importance was apparently placed on the corporeal bones of these same animals. Durability through toughness, then, seems to have been the key mechanical goal in the design of arrows, just as it was for fish harpoon points.

The use of antler for arrow construction offers not only a compelling contrast to the predicted use of land mammal bone, but also insight into its alternative medium in arrow construction, marine mammal bone. Several times throughout this work it has been noted that whale bone, antler's rough equivalent in arrow manufacture, is not well understood in mechanical terms. If toughness was the guiding principle in its selection for arrow construction, as the alternative use of antler suggests, then the relatively even use of the two materials suggests that whale bone possesses a degree of fracture resistance that rivals, if not equals, that of antler.

In sum, antler proved to be the material of choice for constructing those tool components for which fracture resistance was maximized, despite antler's restricted availability. For arrows, expected to receive slightly more moderate impacts, Alutiiq engineers relied on antler and whale bone interchangeably. Perhaps for the purposes of arrow, barbed harpoon, and fishing valve manufacture, whale bone was considered a sort of "poor man's" antler: a material that was locally-available, with a degree of resilience ranking below that of antler but nonetheless superior to that of land mammal limb bone (Figure 6.20).

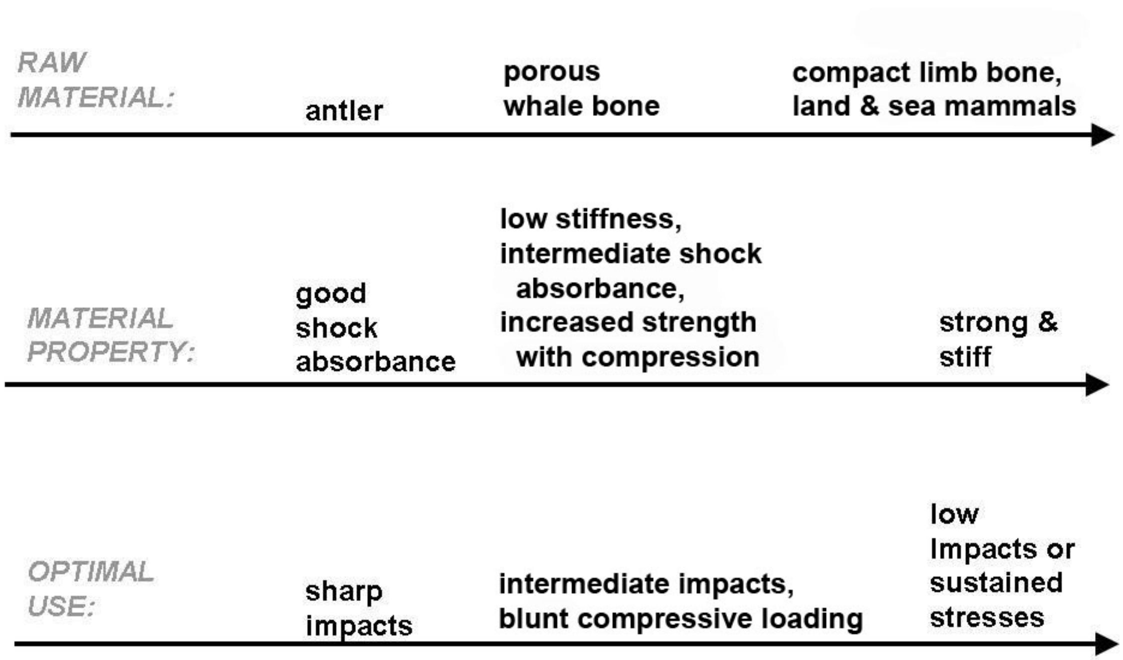

Figure 6.20: Measured and inferred properties of whale bone relative to other osseous media.

It is also worth considering patterns of whale bone use outside of the strictly functional realm. The special regard given to whaling in Alutiiq society (Chapter 5) conjures McGhee's (1977) suggestion that modern Inuit's Thule ancestors dichotomized the realms of the land and the sea, reserving the use of sea products such as marine mammal bone and ivory for marine hunting gear, while caribou antler's only appropriate use was for tools used for hunting on land. This was not the case among Alutiiq groups, however. Sea mammal bone as well as antler was used to create implements utilized both on land and in riverine and marine contexts. Alutiiq use of materials derived from land

and sea, while judicious, cross-cut ecological boundaries -- at least those easily recognizable by the modern researcher.

The Longevity of Osseous Tool Components

Stone is brittle, while all but the most hyper- mineralized osseous materials are tough, antler being the foremost example. The concept of toughness, or fracture resistance, is central to this analysis of osseous tools from the Kodiak region, emerging as a key concern for Alutiiq engineers who constructed weapons tips required to withstand sharp impacts. Tough and brittle materials call for different methods of working, however, and Chapter 4 discusses the potentially great time and labor expenses involved in manufacturing osseous tools. (Morphologically complex tools are no doubt the most difficult to produce, and the state of the raw material – whether it is dry or fresh – can have a profound effect on ease of working.) It waits to be seen if antler can be effectively rehydrated in a way that corporeal bone cannot, thereby lowering antler tool blank production costs. Nonetheless, several of the technological strategies that have come to light in this chapter involving osseous raw material choices and artifact designs converge around the theme of *maximizing tool longevity.*

Individuals can increase the longevity of tools by choosing raw materials that prove durable in the contexts in which they are put to use, as well as by building into tool components the potential for their reworking and recycling. A third strategy for keeping artifacts in circulation, applicable most directly to osseous tools, is to extend their use-lives by staving off the natural forces of drying and lipid breakdown to which biological materials are susceptible, and which can lead to mechanical failure. With potentially high manufacturing costs associated with bone and antler as materials, keeping osseous components in circulation, even in the guise of recycled objects, might offer real benefits to time-stressed technicians (c.f. Torrence 1983).

Longevity through Raw Material Selection

Raw material choice is a toolmaker's first defense against anticipated fracture and failure of tools, and their resulting demise as usable objects. Original laboratory studies (Chapter 3) and those conducted elsewhere demonstrate that antler's fracture resistance is superior to that of the land mammal and bird limb bone alternatives available to Alutiiq toolmakers. As discussed earlier, the maximization of fracture resistance (at the expense of higher raw material acquisition costs) is exemplified most dramatically in the Alutiiq sample by fish harpoon tips. Salmon harpoon valves, the most numerically dominant artifact type included in the study, were constructed nearly exclusively from antler. It is clear that as a non-local resource, antler was highly-valued by Alutiiq technologists, and many fish harpoon valves were resharpened until little or no use-life remained.

Barbed sea mammal harpoons were also created most frequently from antler, followed by marine mammal bone. Although land mammal bone is stiff, a characteristic important for the weapon tip's initial penetration into a tough sea mammal hide, the fact that Alutiiq engineers preferred fracture-resistant materials over stiff ones for barbed harpoon manufacture similarly indicates design for longevity through raw material durability.

<u>Longevity through Structural Design</u>

Alutiiq tool designs also demonstrate how, in addition to choice of building material, the structure, or "architecture" of tool components can be used to maximize their use-lives. Two non-exclusive strategies can be used to increasing artifact longevity through their structural design. The first is to design tool components with anticipated stresses in mind, building in the ability to channel strains safely to preclude fatal fractures from ever occurring. The second is to maximize the repair or recycling potential of tool components, in the case that fractures or damage should occur.

The first strategy, minimizing a tool's anticipated need for repair, accords with Bleed's (1986) notion of the design of reliable tools. Along a continuum from reliability to maintainability, tools that are most reliable are highly specialized and over-engineered. Minimizing tool repair requirements is a risk reduction measure exemplified in the Kodiak assemblages by the design of barbed sea mammal harpoons. Unlike simple unbarbed arrows, barbed harpoons have complex contours. Their shape in fact flies in the face of the rules of sound structural design in that it incorporates two textbook stress accumulators, fissures (line holes) and notches (barbs). A consideration of the specific types of stresses to which barbed harpoons would have subjected during use reveals, however, that holes, as essential design elements, were placed in the least risky region of the harpoon body possible. Specifically, the consistent placement of basal line holes along the single barbed edge would have directed local stresses (that developed as result of tension on the connecting line) into the area of the base that was widest, and where the structural strength of the harpoon was greatest. Analogous harpoon designs linking line hole and barb placement can be found cross-culturally (Julien 1982; Stewart 1996:104-105) and strongly support this functional interpretation.

Durability can also be built into tool designs at even greater scales of structure. Alutiiq engineers designed harpoon valves to work in tandem, "giving" somewhat upon impact in order to protect the entire composite tip from fracturing (R. Knecht 1995:205). Most designs also ensured that only one valve of two (or three) made contact with a rocky substrate, thereby protecting the ensconced inner valve from damage.

A second strategy for obtaining tool longevity is to ensure that even when damage does occur, its effects can be ameliorated through either repair or recycling. While ease of repair is a criterion for "maintainable" tools (sensu Bleed 1986) recycling is a separate (although not exclusive) strategy that can be applied to tools that fall anywhere along the maintainable/reliable continuum, thereby extending their circulation times. Thus, tool longevity is a goal that cross-cuts the concepts of maintainability and reliability, as well as across analytical scales. Stemmed arrows exemplify how both repair and recycling potentials can be included in structural design strategies. A wide tolerance in arrow blade lengths supports the notion that arrows could have easily been reshaped to repair tip damage. Like awls, the design of arrows also allowed for considerable morphological variation: not only were blade lengths highly variable, but arrows were occasionally constructed from a range of obviously recycled tool forms, including fish harpoon valves.

Tools with the simplest morphologist may lend themselves to the greatest ease of repair and may make ready recycling products, but recycling potential is not limited to these tool types. Barbed harpoons represent a "donor" form in the recycling chain.

Barbed harpoons were recycled into (but not reworked from) a variety of other tool types, the original tool still recognizable by its distinctive shouldered and pierced base. The products of these transformations include an awl-like instrument and possible foreshaft for a toggling harpoon head, and from the Alutiiq Artel, a knife handle stained with traces of an inset iron blade (Figure 6.21).

Figure 6.21: Implements recycled from sea mammal harpoons found at Karluk One, Settlement Point, and the Afognak Artel (left to right).

<u>Longevity through Conservation</u>

Finally, the longevity of osseous tool parts can be extended by conservation measures, in the sense of deliberately maintaining bone and antler's fresh state to avoid drying and cracking. As noted in Chapter 2, dry antler is three times tougher than dry bovid bone, while *wet* antler provides a degree of fracture resistance otherwise unequalled in the realm of osseous materials tested to date. The mechanical properties of all bony tissues when tested in a laboratory setting vary dramatically according to whether the materials are wet or dry (Chapter 2). Dry compact bone accrues strength and stiffness at the expense of fracture resistance (toughness). Previous researchers have also noted that antler retains its three-fold degree of fracture resistance over bovid bone whether the two materials are tested in the same state of either fresh or dry. Perhaps not coincidentally, the two types of artifacts which Alutiiq workers produced in greatest frequencies from antler were fishing valves and barbed sea mammal harpoons. Both types of tool tips were required to withstand sudden impacts, and both were used specifically in aqueous contexts.

Ethnographic accounts of other cultures also describe the manual addition of fats to maintain the “freshness” of osseous media with presumed mechanical benefits (e.g., Guthrie 1983:280-282; Steinbring 1966:579). Although the long-buried Kodiak artifacts were no longer greasy to the touch, fresh bones of sea mammals are naturally oil-rich. This too may have been a factor in the selection of marine mammal bone for certain technological purposes. The oils present in fresh whale bones would act as a useful lubricant for wedges, reducing friction between wedge and wood as well as prolonging the life of the tool. Natural oils present in the bone could be supplemented or maintained by reserving fat in the special concavities located along the face of some wedges (Chapter 5, Figure 5.12), which local oral history credit with this purpose.

In sum, longevity is used here a highly generalized goal which can be reached through design for durability during use, design for recycling and reworking potential, and through tool conservation. These strategies are exemplified in different ways in the osseous tool components studied here, underscoring that raw materials whose mechanical properties are highly divergent, as are those of stone and most skeletal materials, can be used to meet very different technological goals.

Stone weapons tips used in hunting encounters, for example, are likely to be more lethal than osseous tips. They are able to hold sharper tips and edges than osseous points, and are more likely to fracture in a wound, causing more damage to the prey (Ellis 1997:52). But as Ellis points out, although stone tips may be individually quicker to manufacture than those of bone or antler, frequent breakage of lithic points would rapidly raise *cumulative* manufacturing investments (Ellis 1997:57).

Weapons tips used in aquatic hunting or fishing contexts typically require durability over lethality, as a harpoon's primary purpose is to aid in prey capture by maintaining a physical attachment between the animal and hunter.   Another instrument such as a lance, club, or firearm is used to deal the final blow. It is not surprising then that Alutiiqs chose osseous materials to construct harpoons used for fishing and sea mammal hunting, as these are naturally highly durable, and are maximally so when used wet rather than dry (Currey 1979; MacGregor 1985; Yamada 1970). Moreover, Alutiiq engineers overwhelmingly selected the "toughest of the tough" for these purposes: antler, and marine mammal bone.

The longevity of osseous tool components and the working costs associated with creating those tool components are closely intertwined. Due to their relative toughness, corporeal bone, and especially antler, require time-consuming blank production procedures, and only reluctantly fracture upon impacts. All else equal, maximizing the length of time that osseous tool components can be kept in circulation surely reduces the costs of manufacturing new components from scratch (Torrence 1983). However, the mechanical properties that lead to high production costs among osseous tools and tool components are likely the same properties that lend them their superior toughness and durability during use.

If maximizing the longevity of osseous tool components was indeed a widespread goal of prehistoric technologists, then evidence should indicate long circulation times of complexly shaped pieces with high production costs. Such pieces should show considerable reworking, recycling as one form was transformed into another, and evidence of special treatment to avoid drying and cracking -- even when it can be judged that the raw materials to make these osseous implements were widely-available.

Osseous Technologies at the *Artel*

The Afognak Artel site yielded only a relatively small proportion of the artifacts analyzed for this study. Nonetheless, the patterns of raw material selection and use noted in the assemblage, combined with qualitative observations of manufacturing techniques, offer a glimpse into the shifts in Alutiiq technological strategies that followed Russian incursion into the Kodiak Archipelago and the establishment of the *artel* system (Chapter 5). The brief discussion that follows underscores how a broader understanding of forager technological strategies can shed light on the dynamics of technology transfer in culture contact scenarios, including those in which osseous tools have played a central role.

The site of Settlement Point and the Afognak Artel are separated by only a few kilometers (Partlow 2000:Figure 4.07; Woodhouse-Beyer 2001:Figure 5), but the raw material selection patterns and tool types, and working techniques seen at the sites are quite different. The range of tool types recovered from the Afognak *artel* site was more restricted than that from nearby Settlement Point. Of the five tool components included in this analysis (representing those found in the greatest frequencies across the three sites), the *artel* site yielded only barbed harpoons and awls. Many of the harpoons were unfinished, and were accompanied by manufacturing waste. The restricted range of tool forms likely stems from the narrow range of activities Alutiiq workers carried out on-site as well as its short span of occupation.

Antler use at the *artel* was also more limited. Barbed harpoons of marine mammal bone are twice as numerous as those of antler at the *artel*, while at Settlement Point, antler harpoons are nearly four times more prevalent than those made of sea mammal bone. The trend suggests that trade networks with mainland caribou hunters were truncated as a result of work and travel strictures imposed by Russian fur traders. With the exception of these harpoons, however, few tool types which the prehistoric assemblages would predict to be created from antler were found at the *artel*. In particular, neither fish harpoon components nor arrows of any type were recovered. The site instead yielded twelve sockets or socket fragments into which harpoons or smaller harpoon darts would have fit. All of these were of some variant of marine mammal bone, and some were very dense, suggesting the use of *oosiks* (pinniped bacula).

Based on mechanical predictions outlined earlier, it is not surprising that bone woodworking wedges were not found at the *artel* site, as metal could provide the rare combination of stiffness, strength, and resistance to fracture required of this type of instrument. Metal implements were indeed found at the site, including at least one file and several Russian-style metal axes (Woodhouse-Beyer 2001). Bone-working debitage speaks to the use of metal tools and associated techniques by Alutiiq workers – but in some cases for the continued production of traditional tool forms.

Evidence of Working Tools and Techniques

Traditional groove and splinter, and saw/chop and snap techniques were used for the production of tool blanks at the nearby prehistoric settlement at Settlement Point. Bone segments and articular ends were partially separated from a blank using a sawing or chopping technique applied circumferentially or from a single surface. The piece was then snapped off, leaving ragged edges along the snap line or interior region (Figure 6.22).

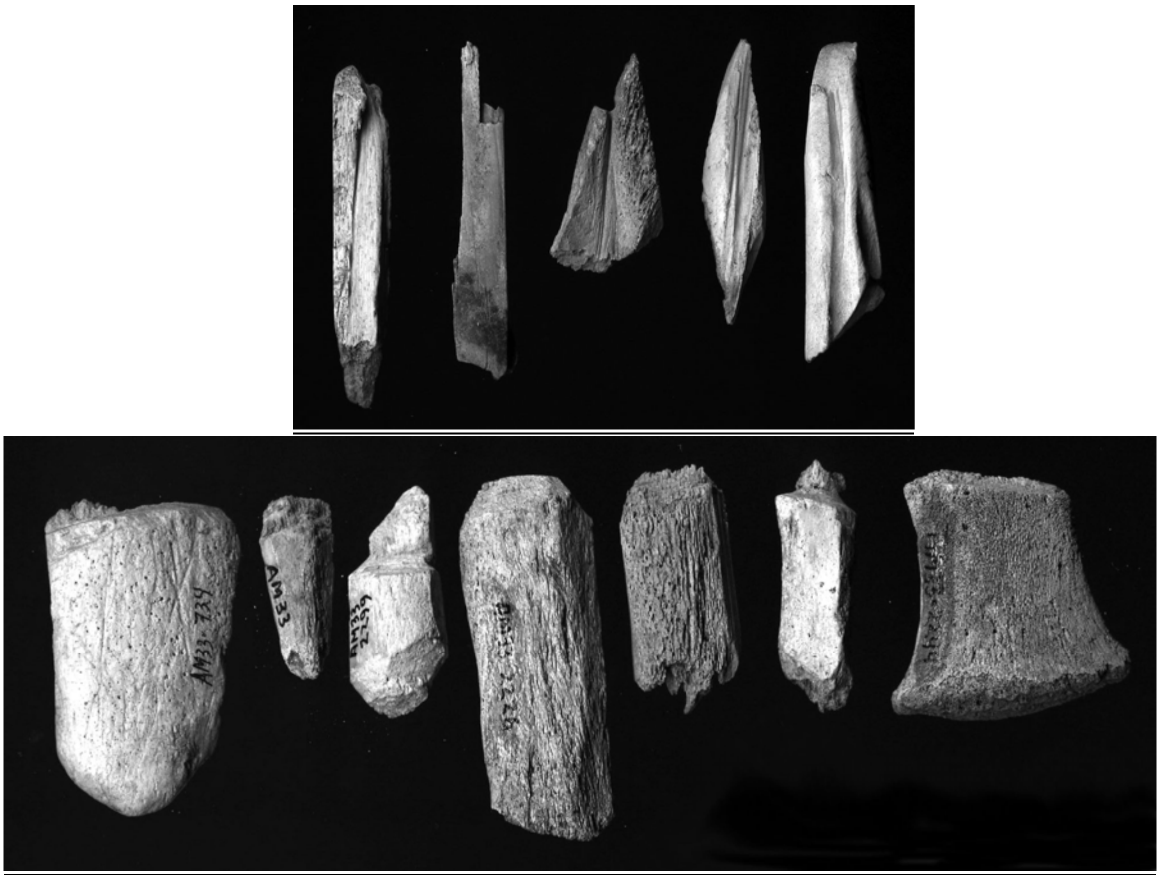

Figure 6.22: Manufacturing waste from prehistoric Settlement Point. Groove and splinter (top) and saw and snap techniques (bottom).

Different working methods are evidenced in the historic bone and antler assemblages. Most large debitage and tool blanks recovered from the *artel* site were prismatically-shaped: flat-faced and sharply cornered. Chatter and ripple marks along the worked surfaces evidence the use of a wide, thin blade. Numerous thin shavings were also preserved at the *artel*. Lacking experimental data, it is not possible to identify with certainty the precise type of implement used to create these shavings, although the debris is reminiscent of the waste shavings that are created using modern woodworking tools (Figure 6.23). The debitage style suggests that metal Russian-style axes recovered from the site were used for rough chopping. Tool shaping and planing work might have been accomplished with a smaller tool, or by using finer axe strokes.

Figure 6.23: Manufacturing debris from the Afognak Artel witnessing the use of metal manufacturing tools.

Waste from groove and splinter manufacture techniques was not recovered from the *artel* site. At both locales, some large blanks were prepared for removal from the larger core or blank by circumferential chopping or sawing. At the historic site, this radial work was followed not by snapping, but by cleanly severing the segments using minimal strokes. My impression is that like the largest artifact pictured in Figure 6.23, circumferential preparation was less invasive at the Afognak Artel than at Settlement Point.

The technical differences at the two sites are exemplified by two very similar pieces of marine mammal bone waste, which are possibly remnants from the manufacture of ulu handles. Ulus are knives with broad, curved, semi-lunar shaped blades which, in the Kodiak region, were made of slate or metal. Both pieces were grooved to accommodate a blade, and chopped transversely to remove the piece from a larger blank. Different methods and probably tools were used to accomplish these tasks at the two sites, however.

The groove in which the blade would have been inset into the prehistoric artifact from Settlement Point is V-shaped (Figure 6.24, left), and in fact still retains fragments of a purplish fine-grained silicious material, a likely remnant of the cutting implement itself (Figure 6.25, left). In contrast, the blade groove of the early historic piece has a greater and more uniform width, and is U-shaped in profile.

The two objects were also made using different methods and instrument types. The prehistoric segment was detached from a cylindrical blank by first narrowing one end's diameter through a series of circumferential chops. Figure 6.25 (left) shows that multiple strokes were used to reduce the piece's diameter along a single side. In this case, it was not possible to determine how the transverse cutting used to finally detach the piece was accomplished. Nonetheless, the parallel piece from the historic site tells a different story. Here, the *artel* worker was able to chop through the segment very cleanly along both ends, perhaps because a metal blade could offer a sharper cutting edge than slate, the typical prehistoric lithic medium for tool blade (and whaling lance) manufacture.

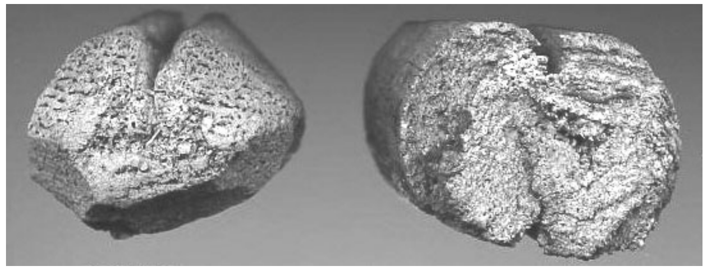

Figure 6.24: Transverse view of marine mammal bone manufacturing discard from Settlement Point (left) and the nearby Afognak Artel site (right).

Figure 6.25: Plan view of manufacture discard from Settlement Point (left) and the Afognak Artel (right).

Raw Material Changes and Continuities

Despite the differences in working implements and associated techniques evidenced in the example above, the similarities between the two discard objects are striking. Most obvious is the simple fact that osseous materials continued to be worked and used into the historic period. The most prominent examples are the fourteen barbed osseous harpoons and harpoon blanks recovered from the site (Figure 6.26) and ten or more whole and broken split-base bone sockets, which were designed to hold darts or harpoon arrows in their distal tips (K. Knecht 1995:260). However, it is not clear to what extent antler use may have declined relative to that of locally-available whale bone. The evidence from barbed harpoon points suggests a proportional increase in the use of whale bone for tool manufacture at the *artel*, but due to limited sample sizes at the site, few inter-site comparisons of raw material selection for other types of osseous tools can be made.

Figure 6.26: Harpoons and harpoon blanks from the Afognak Artel, demonstrating continuity in forms and some materials into the historic period.

Interestingly, the Afognak *artel* excavation contained bone and ivory artifact types found neither at Settlement Point nor at Karluk One. Examples include a disc-shaped hair decoration of whale bone, which was both pierced and incised, and two fragments of bird bone, possibly from a swan (Figure 6.27). These hollow bone tubes were also decoratively inscribed, and may have been used as needle cases. Finally, a tiny ivory figurine, possibly a gaming piece, was also recovered at the *artel*. Only 23 mm tall, it depicts a whale tail raised upright in the water. Walrus are rare in the waters near Kodiak, and like similar ivory pieces recovered from Karluk One, the sculpture was probably obtained through trade (R. Knecht 1995:563), perhaps from the Bering Sea region. This lovely piece offers a small reminder of the importance of marine technologies and materials in Alutiiq toolkits, even into the historic period.

Figure 6.27: Whale bone, bird bone, and ivory objects found at the Afognak Artel.

By the late 1780s, Alutiiq social networks were severely disrupted as Russian traders removed young men from their home villages, enforcing their intensive focus on a few activities which had previously occupied only a portion of the Alutiiq seasonal round (Black 2004:128). In order to obtain great numbers of sea otter pelts, the *promyshlenniks* were wholly reliant on Native technology, here in the full sense of their knowledge, expertise, and equipment (Black 2004:127; Gibson 1969:31). Hunting at sea was critical to Alutiiq survival and identity, and while Russian incursion introduced radical social changes, it somewhat ironically also allowed for the persistence of some Alutiiq technological traditions.

At the same time, evidence from the Afognak Artel shows that Alutiiq *artel* workers began to make use of new metal tools and at least some novel accompanying working techniques. While restructuring technological sequences, the adoption of metal manufacturing implements had a practical logic, allowing Alutiiq workers to continue the production of some traditional bone tools, but in a more efficient fashion.

Wake (1997,1999) has noted a similar pattern at Colony Ross in California, the eastern-most extent of the Russian empire. Here, Native Alaskans (including Alutiiqs), who were forcibly removed to this southern encampment in order to procure sea otter pelts for the fur trade, continued to create traditional fishing, sea otter- and sea mammal-hunting gear from such materials as whale bone, antler, and terrestrial mammal bone (Wake 1999:193-195). The workers abandoned their traditional manufacturing tools made of stone, however, in favor of sharp-edges metal ones (Wake 1999:199). Interestingly, at least one manufacturing technique remained constant despite changes in the actual tools used for the process. Manufacture discard show that rather then employing newly-available metal saws to cleanly sever lengths of bone, the Native workers used small, hand-held metal tools to score and snap the bone, as they did in the past using stone-bladed tools (Wake 1999:197-198).

As with the Native laborers at Colony Ross, Alutiiq know-how regarding the functional constraints of diverse raw materials was not of course sparked by their forced labor under the Russian *artel* system. It should be clear from the analysis presented here that Alutiiqs of the Kodiak Archipelago possessed a long-standing and highly nuanced appreciation for the mechanical properties of a wide range of raw materials available to them both locally and from afar. In fact, the insights obtained from modern laboratory experiments conducted on at least one such material, whale bone, have yet to approach those gained by Alutiiq technologists. The growing battery of materials testing and characterization techniques available in materials science and engineering can contribute greatly to our understanding of how raw materials “work”, but largely in isolation from human encounters. Laboratory studies can complement, but never substitute, for investigation of how raw materials were actually obtained, worked and used by prehistoric engineers.

CHAPTER 7:
CONCLUSIONS

Raw Material Mechanics

This dissertation demonstrates how the study of osseous tools and materials can greatly expand our understanding of the technological strategies practice by past forager groups. To date, models of forager decision-making regarding raw material selection and how tools should be manufactured, used, recycled, or discarded have been derived largely from studies of the life-histories of lithic tools. Osseous materials offer a powerful and revealing contrast to lithic media because as biologically- rather than geologically-derived materials, skeletal tissues have evolved to solve a range of problems *in vivo*, serving roles variably in locomotion, structural support, and buoyancy control. The legacy of such divergent functional adaptations is that the resulting innate mechanical properties of osseous tissues (such as strength, stiffness, and fracture resistance) also cover wide ground. Thus, osseous materials offer a much richer context than stone in which to study how raw material properties can affect technological organization.

This study began by laying out some of the most technologically relevant mechanical properties of a range of osseous tissues, synthesizing data from existing studies and original laboratory research. The biomechanics literature, for example, yields important information on avian wing elements. Though thin-walled, bird bones achieve a high degree of stiffness and strength at the structural (whole bone) scale as a result of their slender build. The flight motions to which avian proximal limb elements are also adapted make them especially useful for awl-like instruments, while the overall size of these bones places some limits on how they can be used technologically.

Structural properties are rooted in material ones, a major focus of this study. The known material properties of common osseous technological materials are book-ended by land mammal bone, which is strong and stiff, and antler, which is neither strong nor stiff but which exhibits a remarkable level of toughness (fracture resistance). In addition to the uses of antler described in this dissertation, its fracture resistance may help explain why antler is often employed for soft-hammer percussion and pressure flaking of chipped stone.

The mechanical properties of compact marine mammal limb bone were also investigated here – one of the few such studies, as little compact tissue is present along their skeletal elements for performing mechanical tests. It was found that despite the semi-aquatic adaptation of California sea lions, their intrinsic compact bone properties overlap those of cervid limb bone. It must be noted, though, that the same paucity of marine compact tissue that limits its mechanical testing potential also placed strictures on how it could have been used by prehistoric artisans.

Blank Production and Labor Costs

A second tier of analysis was undertaken to investigate the working properties of bone and antler. Once removed from *in vivo* contexts, skeletal tissues are subject to processes of biological and chemical alteration that can act in more-or-less rapid time frames. The timing of bone or antler blank production may thus be critical. Late Dorset ivory workers on Little Cornwallis Island in the Central Canadian High Arctic, for instance, performed their activities primarily in the spring and summer, which coincided with the period when walrus were hunted, suggesting that fresh material was preferred (LeMoine and Darwent 1998:81).

Preliminary experiments conducted here on the time investment required to produce and refine tool blanks of antler and land mammal bone were strongly influenced by the drying process. It is currently unclear, however, how quickly drying begins to slow the rate at which tool blanks can be created or their shapes can be refined through abrading. Likewise, we do not know if these effects accumulate rapidly at the early stages of drying or if they continue to accrue over time. Simple longitudinal experiments in which materials are worked at successive stages of drying would demonstrate the ideal temporal windows in which different working procedures should take place. Similarly, bone and antler can be systematically soaked after variable periods of drying to reveal if and when the materials can be "rejuvenated." If dried and rewetted antler can recapture some of its original toughness while land mammal cannot, as the results obtained here and by other researchers suggest, then the most opportune window for antler working should be much wider than that for working land mammal bone. All else equal, choosing antler for blank production would allow for more flexible work schedules.

Other research could profitably address the effects of rapid freezing or thawing on osseous material properties, and the pace at which exposure to salt water might alter the mechanical properties of bony tissues through collagen destruction (DiNiro and Weiner 1998).

Alutiiq Tool Design Strategies

"Since the invention of Fibreglass and other artificial composite materials we have been returning at times to the sort of fibrous non-metallic structures which were developed by the Polynesians and the Eskimoes (Gordon 1978:21)."

The mechanical data and insights on the working properties of osseous media were brought to bear on the actual tool design strategies practiced by protohistoric Alutiiq foragers of Alaska's Kodiak Archipelago. Over 300 osseous tools and tool blanks were classed to raw material type, such as land or sea mammal bone, antler, or ivory, and raw material distinctions were used as a basis to explore the material and structural designs of five types of tool components whose uses have been well established. The patterns of raw material selection were striking, and often fit the mechanical predictions.

Popular notions tie migrating caribou herds to a pan-Arctic landscape, but prehistoric Kodiak residents had access to caribou antler only through mainland trade. Nonetheless, they selected antler to create over 100 of the 112 recovered fish harpoon tips, for which fracture resistance would have been at a premium. For these and other implements, most notably barbed sea mammal harpoons from the Karluk One site, the need to obtain a material with superior fracture resistance clearly outweighed the costs of obtaining it.

Antler was clearly a highly prized material, although like any construction medium, its formal properties were not desirable for all purposes. Antler use by tool type declined with required degree of high-impact fracture resistance, giving way to the selection of marine mammal bone (almost certainly whale bone, given the tool sizes). Birding arrows represent a nexus where antler and whale bone use met in similar frequencies. It is possible that such arrows were conceived ideally to be both stiff and resistant to impacts, explaining the variable use of antler and marine mammal bone for their construction. What might appear to be functional trade-offs may also be explained by restricted access to more distant antler, seasonally, or among some members of the Alutiiq community.

Finally, harpoon barb breaks and barb damage were common in the Alutiiq harpoon assemblages. It is not clear if the observed barb damage could have been remedied by reworking multi-barbed harpoons into simpler, single barbed harpoon variants. Although basal dimensions of the two harpoon types overlap to the extent that recycling would have been possible, considerable variation in these measures both within and between harpoon types suggests that *individuals*, rather than communities, set the standards for basal harpoon dimensions. The dimensions of interchangeable tool tips were, in other words, potentially standardized against the dimensions of a single tool, and not against what would be recoverable archaeologically as a larger tool assemblage.

Other problems remain to be addressed. For instance, how well can antler, whale bone, and the corporeal bone of land mammals hold a sharp point? If antler is more easily blunted than more highly-mineralized land mammal bone, then workers would sometimes be expected to choose terrestrial mammal bone for piercing tasks, even if toughness was also desirable. Indeed, although antler is tough, its relative weakness and lack of stiffness make it poorly suited for some tasks. Even when readily available, one would expect antler’s use to be restricted to implements requiring maximum toughness, and not to tools such as awls and wedges, where stiffness would be of central concern.

The Curious Case of Whale Bone

In addition to toughness, most raw materials considered in this study were characterized according to their degrees of strength and stiffness. Direct laboratory testing to determine the mechanical properties of whale bone has been limited, however, despite the widespread geographical use of cetacean and other marine mammal bone in forager toolkits. Insights gained from both laboratory and "field" data have helped to piece together the elusive properties of this important raw material type.

Mechanical tests conducted on whale bone demonstrate that its tissue-scale stiffness is low, a formal property no doubt born of its macroporous structure. Whale bone's strength has not been tested directly. Other cancellous tissues have been the subject of intense research, however, especially as they pertain to osteoporosis which primarily affects skeletal elements possessing significant portions of spongy tissue. If whale bone indeed behaves mechanically in the same fashion as other cancellous tissues, then when it is fresh (wet), its structural strength should increase in response to compressive loading, as pores collapse forming a more solid structure. Woodworking wedges of whales bone, for example, should initially grow *stronger* through the force of pounding, although over time they will of course fracture if larger loads than they can bear are placed upon them. Finally, the pattern of overlap in antler and whale bone use in the Kodiak assemblages, which is not limited to arrows, suggests that whale bone's capacity to resist fracture approaches that of antler, while exceeding that of land mammal limb bone, and are thus book-ended by two types of tissues whose mechanical properties have already been well-established. Although the results obtained here strongly suggest that compact antler bone and porous whale bone tissue are both tough raw materials, their properties are arrived at through very different sets of functional adaptations.

A Multi-Scalar Approach to the Analysis of Tool Design

Other studies concerned with explaining diversity in forager technological strategies have used as their units of analysis whole assemblages or toolkits (e.g., Torrence 1983), complete tools (e.g., Oswalt 1976), or "systems" (Bleed 1986). Ensuing classification schemes, like those of maintainable or reliable systems (Bleed 1986), are conceptually appealing and valuable in their attempt to place design strategies within their larger ecological contexts. However, operationalizing such schemes can be difficult. Complete multi-component tools, used either individually or in suites, are not typical units of archaeological analysis simply because tools are rarely preserved in their entirety.

By altering the analytical scheme proposed by Oswalt (1976), however, it becomes clear that the individual barbs on a harpoon (or other distinctly functioning morphological regions of an artifact) can be conceived as separate techno-units, each contributing to tool complexity. Similarly, multi-barbed harpoon tips in and of themselves display characteristics of both "reliable" and "maintainable" systems (sensu Bleed 1986), in that a series of barbs represents redundancy in like parts (over-design, a trait of some reliable systems) as well as a modular design, allowing the tip to function even after a portion of it has failed (a feature of reliable ones).

My point here is not to obviate the criteria by which previous researchers have attempted to analyze the economic significance of artifact types, assemblages, or other analytical units. The goal instead is simply to draw attention to the interconnectedness of artifact design at multiple scales, as it was conceived of and carried out by engineers of the past. Although a complete structure (a tool, machine, building, etc.) is designed to meet certain functional requirements, each component or element within the structure must also function well, and its ability to do so derives in part from the materials from which it is created. Thus, investigations into tool designs can -- and should -- be approached at multiple scales.

In this study I have taken an explicitly multi-scalar approach in the analysis of tool design and artifact variability, and one that is rooted in the raw materials of manufacture. This is because material and structural properties of tools are intertwined, although not in any simplistic fashion. Instead, the material and structural properties of a tool can be deliberately well-matched, or alternatively, one can be used to compensate for undesirable but unavoidable limitations of the other.

Particular raw materials can be selected according to their abilities to contribute to the preferred mechanically-based performance characteristics of whole tools. Desirable material properties can then be bolstered through the higher-level design of entire implements or components. This is clearly demonstrated in the Alutiiq's ingenious design of fish harpoons valves, which doubly insured the working tip against fracture: not only were valves constructed of durable antler, but they were also nested to further protect inner, ensconced valves from encountering the direct force of blows.

Raw material and structural properties can also appear to be at odds, when design at one scale is used to compensate for a perceived but unavoidable limitation at another. For example, as a trade-off for lowered procurement or manufacturing costs, an engineer may select a raw material whose properties are considered less than ideal for a given intended use. The overall size and shape of the tool can then be designed to counteract or compensate for sub-par raw material properties. Such was almost certainly the case for Alutiiq woodworking wedges, which were most frequently created from segments of large whale ribs. Wedges require toughness, strength, and stiffness, three properties that do not tend to co-occur in osseous tissues. At the tissue scale, whale bone is likely tough, as was desired, but is also weak and flexible. It is, however, naturally available in sufficiently large package sizes that great *structural* strength and stiffness could be arrived at by "building big," as wedges often were, even if at the tissue scale whale bone's degrees of strength and stiffness are quite low.

Conversely, a raw material can be selected in order to counteract unavoidable structural limitations in a tool. This was the case for sea mammal harpoons, whose barbs and basal line hole are natural stress accumulators. Choosing antler for their construction, as Alutiiqs nearly always did, helped to minimize the likelihood of fracture that followed from a mechanically risky, but functionally effective, structural design.

Maximizing Tool Longevity

Employing multiple analytical scales, this study has also shown how activities directed toward different stages in tool use-lives can contribute together or separately to a generalized goal of maximizing tool longevity, or circulation time. The fracture potential of tools, for example, can be reduced through both raw material selection and overall tool design. The examples presented above demonstrate how a plan for durability can be implemented by choosing raw materials that are tough, and can also be built into higher structural scales through the incorporation of stress-reducing designs, or ones promoting "reliability," in Bleed's (1986) terms. Alutiiq designs for longevity include the nested arrangement of fish harpoon valves, and the off-set line holes on unilaterally barbed harpoons.

Circulation times can also be extended through special care of tools to prevent damage and wear. Osseous tools are particularly subject to naturally destructive actions as they age, and tool conservation, through the manual addition of fats or other hydrating or protective agents, can help to minimize the deleterious effects of drying. According to oral histories, special concavities located along the faces of Alutiiq woodworking wedges once contained lubricating fat, which would help to guard the wedges against brittle fracture as they were struck forcefully with a hammer stone.

Finally, even when some types of tools have been damaged, their circulation times can be extended through repair, or their recycling into other tool forms (Binford 1977). Four of the five artifact types examined for this study were interrelated through recycling chains, through which complex and highly-specialized tool components were reworked into simpler and more generalized ones: spent fishing valves were recycled into arrows, and sea mammal harpoons were transformed into several other forms, including an awl, a handle, and a foreshaft. These insights could only have been revealed by investigating tool design along a hierarchical scale, and by treating the relatively fine-grained Kodiak assemblages as reflections of interrelated technological systems (Schiffer 2005) rather than as mere assortments of various tool forms.

They also draw attention to how the life cycles of individual tool components may be asynchronous with those of the larger assemblies they help to comprise. Some parts are built to last, even to be passed down to future generations. Others are designed to withstand only one or a few uses, their brief life spans compensated, for example, by low production investments. There is good evidence that the production of osseous tool parts is a more time-consuming and laborious task than the creation of most tools of brittle stone. However, as this study has demonstrated, there are several means by which high initial tool production costs can be offset, all leading to the increased circulation times of implements. Because the current focus in hunter-gatherer technology studies is on lithic rather than osseous resources, our perspective on the range of strategies practiced by these groups surrounding patterns of tool manufacture, use, recycling, and discard, as it currently stands, is likely severely truncated. Examining how technology is organized around an alternative suite of materials: bone, antler, and ivory, can widen the field of view.

Applications to the Study of Technology Transfer

As argued at this dissertation's outset, incorporating osseous materials into a larger theory of tool design has the potential to shed light on European colonial interactions with indigenous groups, in which the introduction of new possible alternatives to osseous raw materials and products was a common theme. The dynamics of past colonial interactions have varied widely, but functional considerations of the tools and raw materials which entered into these interactions can be more readily generalized.

This study has only begun to further our understanding of the effects of Russian contact on Alutiiq culture, including Alutiiq technological repertoires. However, the tools and working debris from the Afognak Artel work station do offer some initial insights into the technological changes -- but also continuities -- that followed the arrival of Russian fur traders in the Kodiak Archipelago in the late 18th and early 19th centuries. In short, sea mammal hunting harpoons and sockets found at the *artel* site were manufactured with the use of recently adopted metal implements. Metal tools likely provided sharper cutting edges than slate or other local lithic raw materials could provide. They could not, however, substitute for the resilient and well-designed osseous artifacts that formed durable components of high-stakes aquatic hunting paraphernalia. Thus, Alutiiqs at the *artel* chose to construct old forms, but with the use of new and more efficient tools and working techniques. Carefully crafted of bone and antler, the preserved remains of sea mammal hunting gear recovered from the Afognak Artel evidence the perseverance of some Alutiiq tool traditions well into the colonial era, and speak to the savvy of Alutiiq engineering.

APPENDIX A:
COMPARATIVE MECHANICAL PROPERTY DATA FOR ANTLER AND BOVID BONE

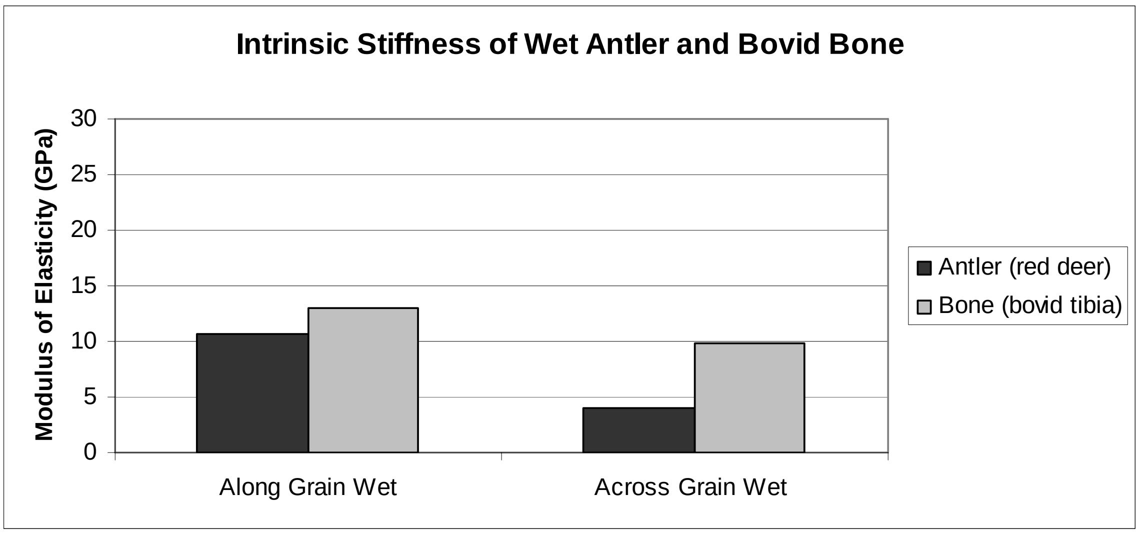

Figure 1: Wet stiffness data from MacGregor (1985).

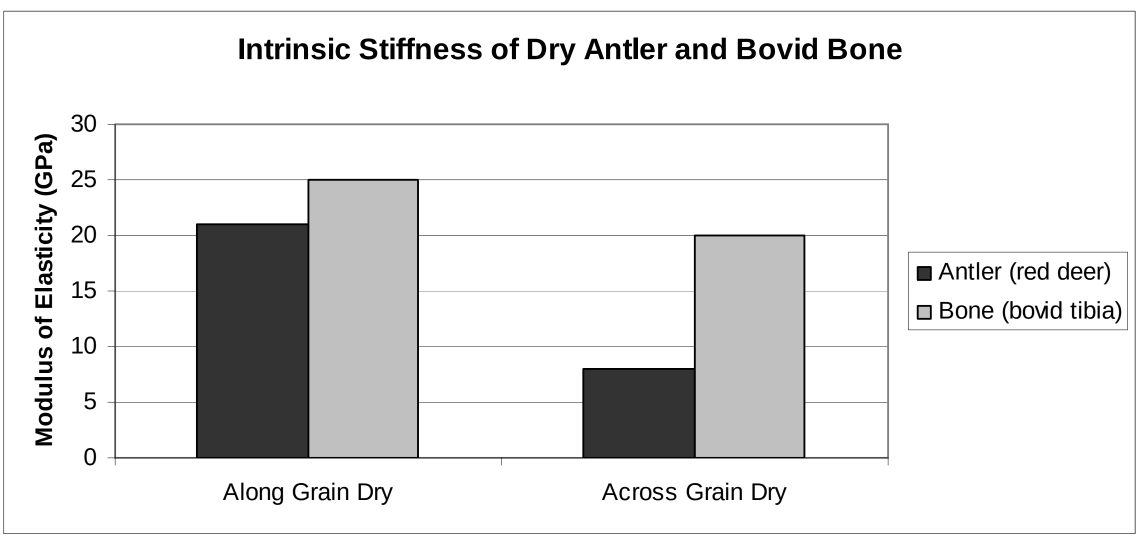

Figure 2: Dry stiffness data from MacGregor (1985).

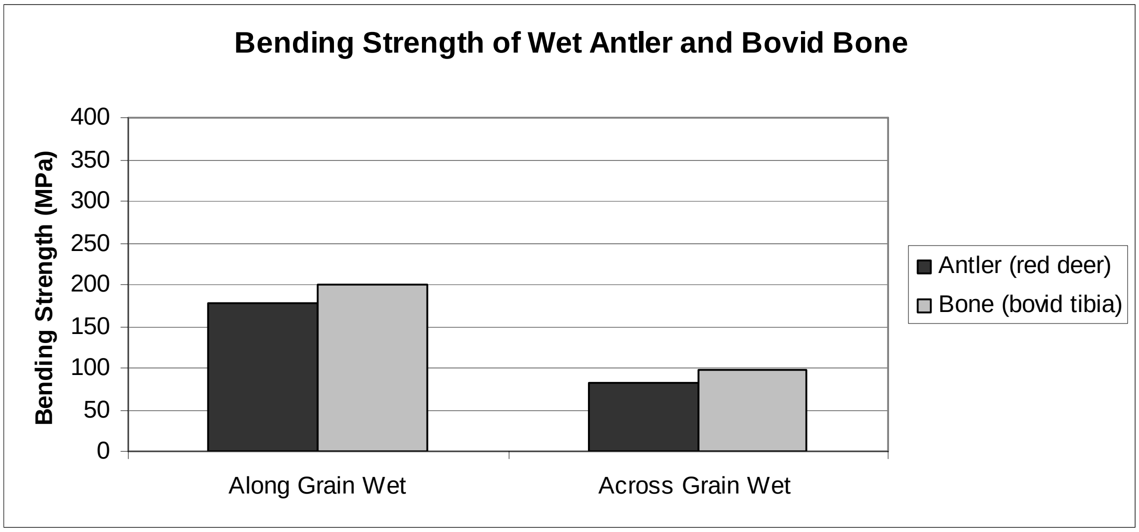

Figure 3: Wet bending strength data from MacGregor (1985).

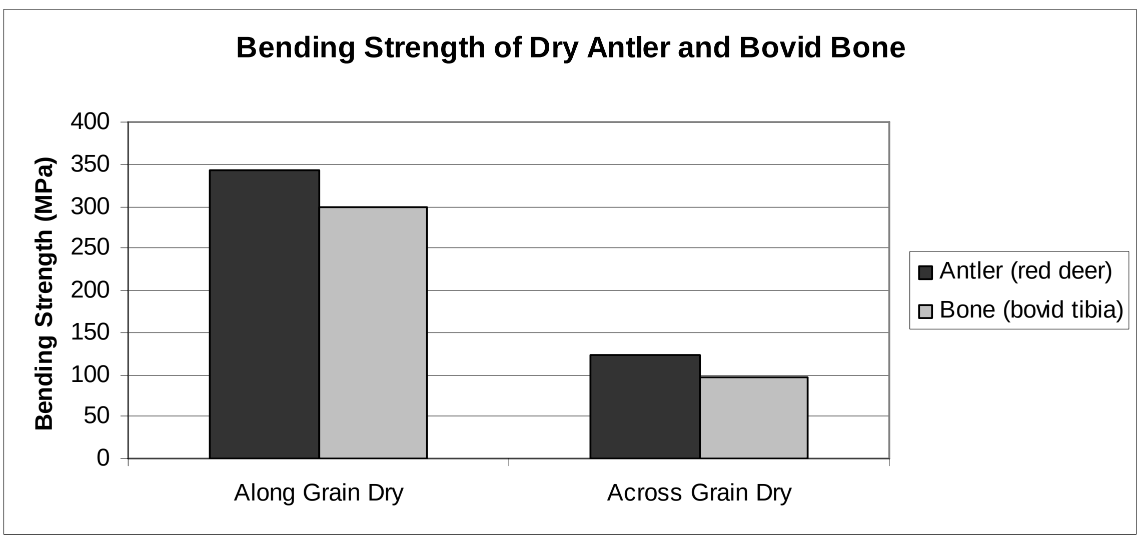

Figure 4: Dry bending strength data from MacGregor (1985).

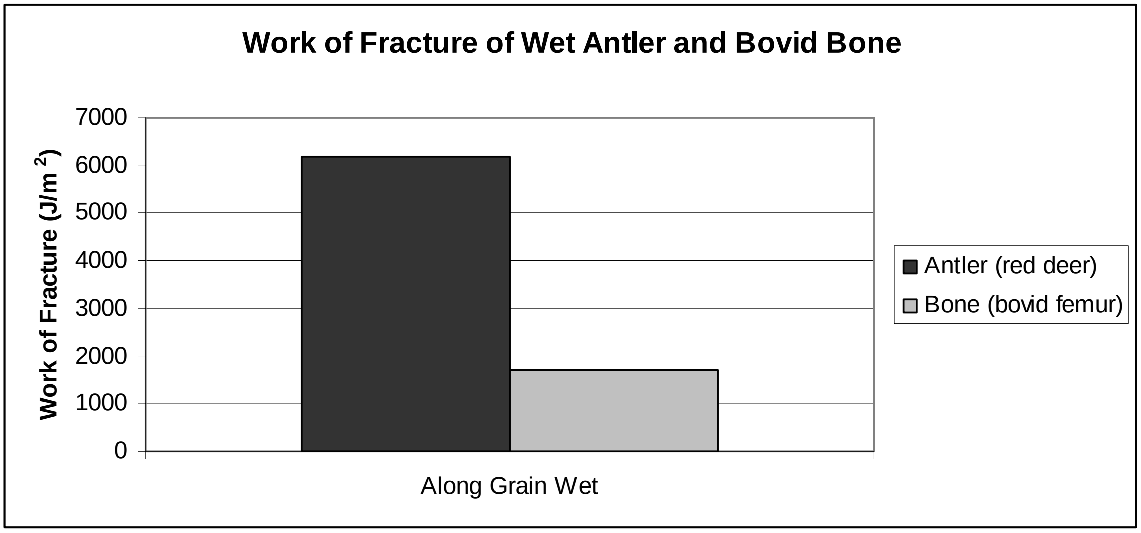

Figure 5: Wet work of fracture data from Currey (1979). No data provided on work of fracture across the grain.

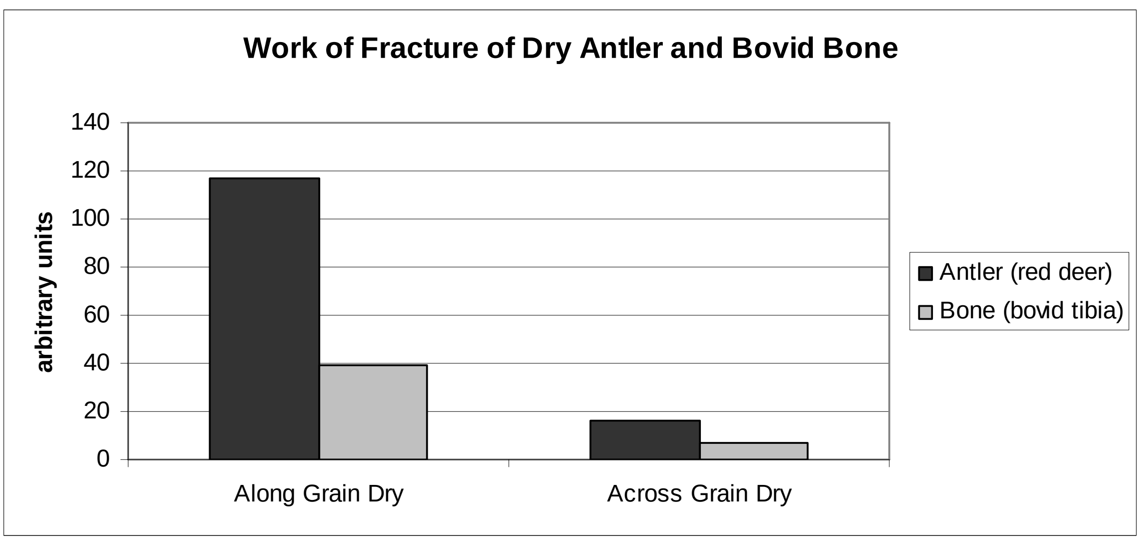

Figure 6: Dry work of fracture data from MacGregor (1985). Note that the dry data are expressed in arbitrary units.

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