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Groundstone Tool Technology

In its broadest sense, material culture encompasses any part of the physical world intentionally altered by humans (Deetz 1977:10). This definition not only incorporates obvious items made of ceramic, stone, bone, metal, earth and plastic. Underlying every act in the creation of material culture, whether it is the manufacture of an arrow point or a toy made by a child, is the expenditure of energy, which is best termed effort.

It can be argued that all material culture has value. Although the term 'value' in the modern sense has become inexorably tied to a monetary scale, it is still applicable to the past. Value can be defined as "that quality [or qualities] of a thing which makes it more or less desirable, useful, etc." (Guralnik 1983) People value objects based on qualities such as utilitarian functionality, cost of manufacture, endurance (Olausson 1983:7), as well as aesthetic appeal and rarity. When dealing with the worth that prehistoric peoples placed upon certain objects, archaeologists are very limited in which aspects of value they can reconstruct because value is predominantly an emic cultural property. Unless a written text or an oral tradition survives from a culture, recording the types of value placed on a particular kind of object, there are no direct forms of evidence that can be used to establish value. There are, however, indirect lines of evidence that lie in the artifacts themselves and the contexts from which they were recovered.

The characteristics of nephrite are static or uniform over time -- the amount of effort needed to alter nephrite today is the same as it was in the past. Modern use of nephrite is largely aesthetic, such as its use in jewelry or carvings because of the polish and luster it will hold. While these characteristics were widely admired by past cultures in various areas of the world, nephrite was also used for tools due to its strength and durability. It is the latter qualities of nephrite that are the easiest for the archaeologist to study.

In this chapter I will examine nephrite as a material for tool manufacture. The main emphasis of this chapter will be to establish the cost-effectiveness of nephrite in comparison to other types of stone material. The purpose of this investigation will be to examine the amount of time needed to shape stone tools of various materials compared with the effectiveness and durability of working edges. The first part of this chapter will summarize the principles of groundstone tool manufacture and use. The second section will focus on the results of experiments undertaken to replicate the manufacture of nephrite implements. Finally, I provide time efficiency models for the use of nephrite in comparison with other materials.

Flaked debitage, in many sites, is the largest artifact class represented. Most experimental lithic studies have, therefore, focused on the reconstruction of chipped stone assemblages. Experimental reconstruction of groundstone tool technologies, on the other hand, has largely been ignored. The research conducted on groundstone tools has been primarily petrological (e.g., Mesoamerican jade studies Foshag 1957; Lange 1993; Wooley et al. 1975) or typological in nature (e.g., Mackie 1992, Duff 1950). Some experimentation has been undertaken, but the overall quantity of this work compared to chipped stone is limited. This is probably due to the lack of evidence left behind from making groundstone tools and to the substantial amount of time and effort needed to simulate groundstone manufacturing processes.

In this section, I will review aspects of groundstone tool technology that relate to the manufacture of nephrite implements. This will include discussions of:the following: 1) principles of groundstone tool technology, 2) theoretical issues pertaining the use of groundstone versus chipped stone technology, 3) various techniques employed worldwide to manufacture jade objects, 4) techniques used to make stone celts, and 5) relevant experimental procedures previously undertaken on groundstone tool production.

Principles and Methods

Unlike chipped stone, groundstone technology is essentially the alteration of stone by techniques that do not utilize the conchoidal fracture pattern. The key mechanism of reduction in groundstone technology is abrasion.

Abrasion is the removal of one substance by friction from another substance and is a type of wear (Barwell 1979). Other forms of wear include adhesive, fatigue, and chemical processes. As a process, abrasion is influenced by material hardness, surface roughness, and the amount of pressure between two contacting materials (LeMoine 1994:320).

Hardness is probably the most important factor in groundstone tool technology. As a measure of a substance's strength (Szymanski and Szymanski 1989), it influences both the occurrence and the rate of abrasion. In order for one material to alter or scratch another, it must be equal to it or greater in hardness. Also, the greater the hardness of one material compared to another, the greater the amount or rate of abrasion that will occur.

Typically, hardness is expressed using the Moh's hardness scale in increments from 1 to 10. Each increment has a well-known associated mineral type: 1-talc, 2-gypsum, 3-calcite, 4-fluorite, 5-apatite, 6-feldspar or orthoclase, 7-quartz, 8-topaz, 9-corundum, 10-diamond. Additionally, fingernails rank around 2, a knife blade or window glass are about 5.5, and a steel file is approximately 6.5. The typical way measurements are taken using the Moh`s hardness scale is by finding which minerals will scratch the test specimen. If a mineral scratches a substance, it is at least equal to or greater in hardness. If a mineral does not scratch the specimen, then the mineral has a lesser hardness. Other more accurate hardness measures, such as the Vickers, Brinnell or Knopp methods, are also used in modern hardness testing (Szymanski and Szymanski 1989). The Moh's scale, however, is still relevant today because of its simplicity, and the proximity of the chosen minerals to the hardness increments in the Moh's system.

In groundstone tool technology, there are two primary reduction techniques: pecking and grinding. Both can be considered abrasive techniques but differ in the manner in which they remove material.

Pecking

Pecking, sometimes known as hammer-dressing (Beck 1970), is when a hammerstone is used to detach minute particles of material from a stone (Figure 4.1). Using a pecking technique, the amount of pressure or load exerted from the hammerstone is just as important as the hardness of the hammerstone. A soft hammerstone will remove material from a harder stone. However, as Dickson (1981) and M'Guire (1892:166-7) found, a hard hammerstone made of jasper or quartzite (hardness of 7) was more effective than one made of a softer material. In the same manner, when pecking different types of material, Dickson (1981) removed the most material per hour from softer rocks such as limestone than from harder rocks like basalt and quartzite.

Grinding

Grinding can be divided into four methods: simple grinding, sawing, drilling and polishing (Figure 4.2). Grinding is usually performed in conjunction with water, which acts as a lubricant/coolant, and as a mechanism to remove expended particles (Beck 1970:72; Callahan 1993:43). Sand/grit may also be used in the grinding process (Callahan 1993:43).

Simple Grinding - a grinding stone is employed to abrade. The grinding stone is usually made of some form of sandstone, but other stone types such as granite (Callahan 1993), siltstones or abrasive volcanic stones can also be used. As a rule, grinding stones tend to have very hard particles incorporated into their matrix.

Sawing - a specialized form of grinding where a saw is used to create a groove to cut through a piece of stone material. The saw can be made out of stone such as sandstone, siltstone, slate, greywacke or schist (Beck 1970), or constructed from thongs of leather, wood (Dawson 1899; Digby 1972:15), string (Digby 1972:15), or in some cases a metal wire (Hansford 1950; Chapman 1892). Generally the saw is used in conjunction with an abrasive and a lubricant, although this is not a necessity with stone saws. The abrasive could be as simple as sand, but may be a more refined sub stance such as crushed quartzite pebbles (Beck 1970), or harder prepared abrasives such as pulverized corundum or garnet (used ethnographically in China, [Hansford 1950:67-8]). The lubricant usually used during the sawing process is water, but oils or grease will also perform the same function (Johnson S. 1975; Hansford 1950).

Drilling - is another specialized form of grinding. In this instance, a drill is rotated to create a hole in a piece of stone material. Some drills, such as those used by the Maori (Beck 1970:75-77), have a hard stone tip, whereas others are untipped or hollow (Hansford 1950; Digby 1972:15). Again, as with sawing, usually an abrasive and a lubricant are used in conjunction with the drill bit. In the case of hollow drills, abrasives are poured into the drill to function as a bit (Hansford 1950).

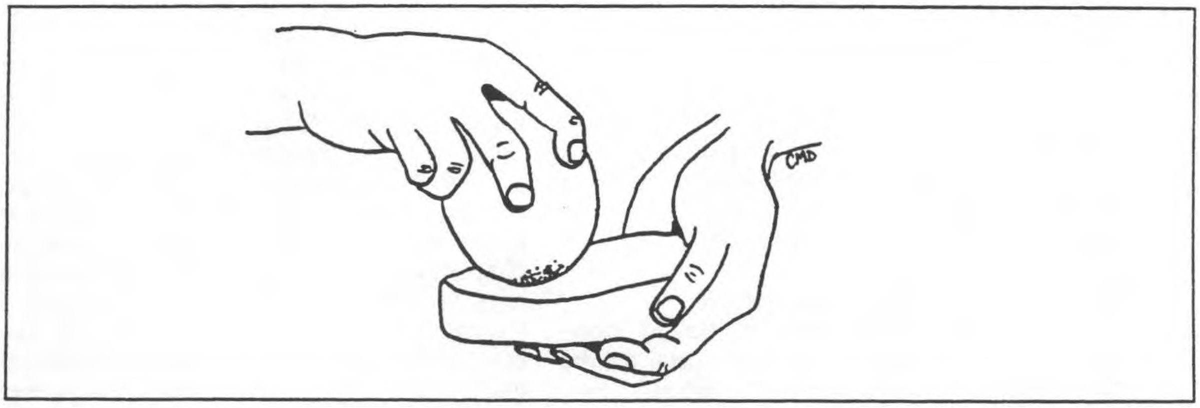
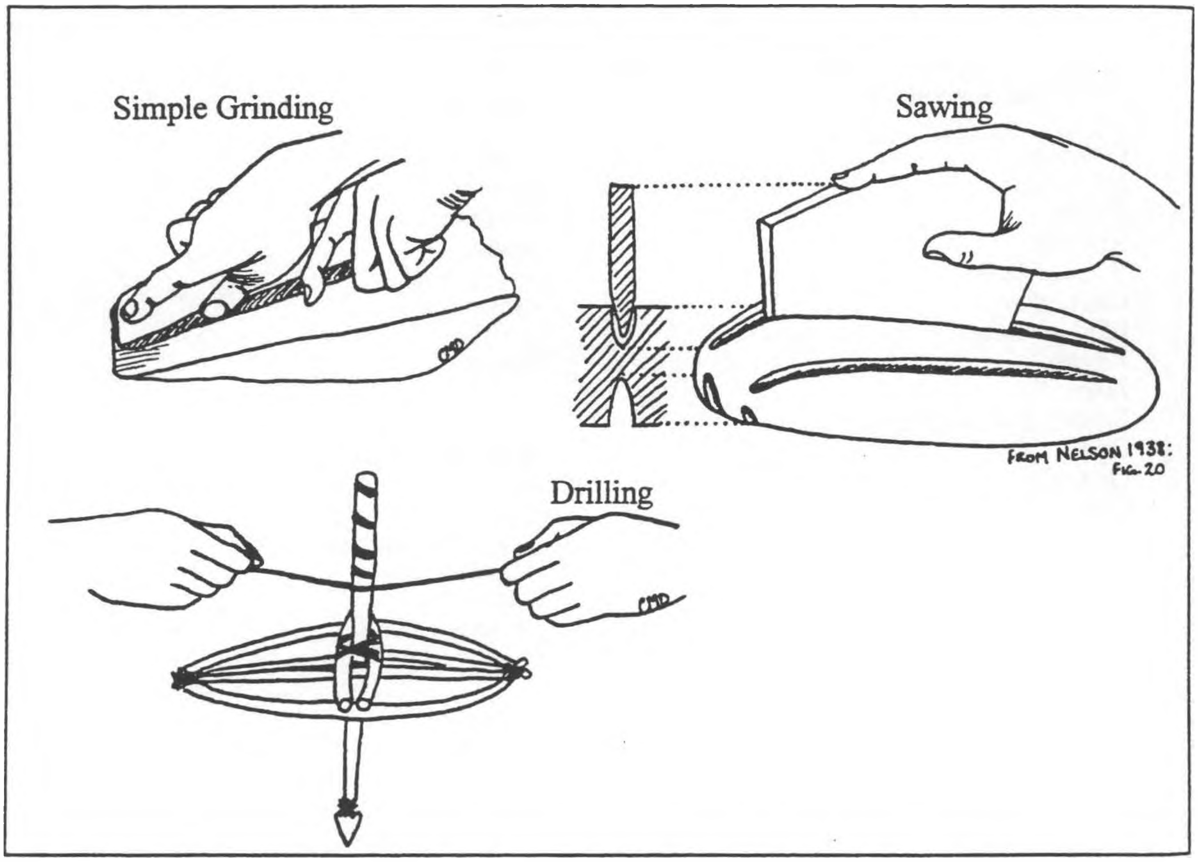


Figure 4.1. Methods Involved in Pecking.



FROM NELSON 1938: FIG. 20

Figure 4.2. Methods involved in Grinding.

Polishing - is very similar to simple grinding, but the objective is not to remove material. Rather, it is to create a smooth surface. Many different techniques can be used to polish stone, ranging from using fine grained abrasive stones to repetitive dunking in a fine slurry of abrasive (Dickson 1981). Other polishing techniques include rubbing with leather or wood in conjunction with grease (Callahan 1993:43), or burnishing with hematite (Digby 1972:15).

Materials Used in Groundstone

Unlike the manufacture of flaked stone tools, almost any type of stone material can be exploited using groundstone techniques. Frequently, stones used in groundstone tools do not flake or break readily or predictably. This is not to say that stone types used for chipped stone cannot be modified using groundstone techniques. There are many instances where both methods are used to create a tool (e.g.., European flint axes and daggers, greenstone adzes on the Central Coast). However, most rock types used for groundstone tools do not break with a conchoidal fracture pattern. Table 4.1 lists the different stone types that are generally exploited by groundstone and flaked stone technology. As will be discussed later in the chapter, one advantage of groundstone technology is that it makes it possible to use very tough, fibrous materials that could not be effectively exploited with flaked stone techniques, and allows for continuous, long-term resharpening without significantly reducing the size.of the tool.

Table 4.1 - Materials Generally Exploited by Flaked Stone and Groundstone Techniques.

Materials Desirable for Flaked Stone Tools (after Crabtree 1982:9)	Groundstone Materials (after Kapches 1979; Callahan 1993)
Obsidian	Amphibole
Ignimbrite	Granite
Basalt	Basalt or Metabasalt
Rhyolite	Gniess
Welded Tuff	Greenstone
Chalcedony	Serpentine
Flint or Chert	Dorite
Agate	Pumice
Jasper	
Silicified Sediments	
Opal	Hornfels/Horneblend
Quartzite	Marble
Quartz	
	Soapstone/Steatite
	Nephrite
	Jadeite
	Greywacke
	Slate
	Sandstone
	Siltstone
	+ all of column one can be modified in using groundstone techniques

Optimization of Lithic Technologies

The types of lithic technologies used by people in the past were systems that operated not only in response to environmental needs, but in conjunction with other strategies which maintained social cohesion (Torrence 1989:2). Current discussions surrounding lithic technology (i.e., Torrence 1983, 1989; Boydston 1989; Bamforth 1986; Bousman 1993; Hayden 1987; Jeske 1992) have focused on applying optimization theory to the dynamics involved within lithic industries. Viewing tools as "optimal solutions" (Torrence 1989:2-3), these authors often attempt to explain stone tool systems in terms of a cost-efficiency or cost-benefit relationship of some form of 'currency'. 'Currency', in this situation, refers to the item of expenditure or value that is to be 'optimized' (Torrence 1989:3). Items such as energy, time, raw material, technical knowledge, stability, risk, uncertainty and security are all potential currencies in stone tool systems (Torrence 1989:3). The underlying principle behind optimizing theory is that past cultures always attempted to maximize returns while minimizing the expenditure of currency.

While all the currencies listed above interact with respect to any lithic system, it can be argued that both time and raw material constraints are the most basic factors to consider within a stone tool industry. Many forms of currency are subsumed under the term effort. Effort, as discussed, as an encompassing concept is difficult to measure (Boydston 1989:71). Some studies use caloric energy as currency (e.g., Jeske 1989, 1992; Morrow and Jeffries 1989; Camilli 1989; Henry 1989) which assume that past cultures had energy budgets or constraints (Torrence 1989:3). Use of this currency, however, can be criticized because it is not clear whether caloric energy is scarce enough in environments to be a selective behavior (ibid.). As Boydston (1989:71) points out, even if an individual spent a whole day flaking and grinding a stone tool, the energy expended would be insufficient to interrupt "biophysical homeostasis". More important than the energy expended for the day is the time lost grinding.

Torrence (1983:11-14) initially explored the concept of time currency and stressed the importance of time budgeting in hunter-gatherer societies. She argues that the scheduling of resource related activities within hunter-gatherer societies was vital to fully exploit a subsistence base. Because the timing involved in harvesting different resources varies, tool designs have to be specific to the risks and needs at hand. Torrence (1983:13-14) argues that scheduling or time budgeting needs affect the composition, diversity and complexity of tool assemblages. As all humans operate under finite time constraints, tool designs reflect the necessity to conserve time. Often logistical hunter-gathering lifestyles associated with high latitudes necessitate large, diverse tool kits that take relatively more time to create and maintain than those affiliated with more residential hunter-gatherers at lower latitudes (Torrence 1983:18-20).

Boydston (1989) has similarly suggested, through the study of functionally comparable tool types, that prehistoric peoples chose tool manufacturing processes based upon time expenditure in relation to perceived or expected benefits. When examining a cost-benefit function for time consumption (Figure 4.3), Boydston (1989:71) hypothesizes four possible cases: 1) high cost, low benefit, 2) low cost, low benefit, 3) high cost, high benefit, and 4) low cost, high benefit. When using the concept of efficiency (benefit divided by cost), the cases can be ranked, except for instances 2 and 3 which are equivalent, as follows:

$$4 > 3; \; 2 > 1$$

Under an optimizing paradigm, the cost benefit function predicts that a tool with a Case 4 efficiency level would supersede a tool with a Case 3,2 or 1 level (ibid.). The costs involved in tool production are procurement time, production time, and maintenance time. The benefits derived from a tool type are measured in terms of operational life and effectiveness (Boydston 1971:71).

The other relevant form of currency, raw material factors, has been explored by Hayden (1987). In reviewing the development of different cutting edges through prehistory, Hayden (1987:41) argues that raw material conservation was a key factor influencing the development of cutting edges. In a progression from hard hammer percussion reduction techniques to the development of metal tools, the amount of effort required to maintain cutting edges increase while there was greater conservation of raw materials. Under this model, the

		COST	
		Low	High
BENEFIT	Low	Case 2	Case 1 - Potential Prestige Function
	High	Case 4 - Optimal Tool	Case 3 - Potential Prestige Function

Figure 4.3. The Cost Benefit Function (after Boydston 1989:71)

need to conserve raw material is important because of the amount of time spent on resharpening/retooling detracts from the primary activity. Hayden (1987:40-41) uses for an example the inefficiency of using chipped stone edges instead of slate knives on the Northwest Coast. Because of the relative weakness of chipped stone edges compared to groundstone edges, the constant need to resharpen or replace chipped edges would have greatly detracted from the number of salmon that could be processed in a day when time was of the essence and therefore waste energy.

Similarly, Bamforth (1986) after examining the stone material used by the !Kung San and two archaeological examples, concluded that raw material availability directly influences the choices of reduction technologies. Looking at the distribution of lithic resources from these examples, he (ibid:41-49) demonstrated that a shortage or restriction of lithic material increases the level of tool maintenance and recycling. He also identified instances where only specific types of material were used for certain tool forms. This distinction was related to the advantage of using particular stone types for certain technologies.

While there is some disagreement concerning the relevance of raw material as a currency (see Torrence 1989:3), I believe that the selection of raw material is generally related to time availability and cost. Different stone materials take varying amounts of time to be reduced. For example, as noted previously, there are great differences between the manufacturing times for stones that can be reduced by flaking compared with those that can only be reduced using groundstone techniques. Thus, the time needed to remove equivalent amounts by chipping chert, as opposed to grinding nephrite, differs greatly.

As with the development of cutting edges, there must be benefits that favor a change from one resharpening method to the next (Hayden 1987). Boydston (1989:71) predicts, using cost benefit (Figure 4.3) function as an evolutionary model, that in any instance where a high benefit/ low cost technology is present, it will be chosen over other alternatives for practical technological purposes. In situations of high cost/high benefit or low cost/low benefit, there may be no incentive to change technology. It is assumed that high cost/low benefit technology will be replaced in the face of other alternatives. The advantages vary -- what may be needed by a mobile residential hunter-gatherer group is not necessarily beneficial for a more sedentary logistical group (Boydston 1989:75). For some lifestyles, the advantages of using crude chert choppers that may take half an hour to make and a short time to expend are greater than spending days creating a groundstone adze that will last considerably longer. In this situation, the time needed to make a groundstone adze would detract from other more important activities. If chert was hypothetically abundant in the area, there would be little need to conserve material. Hayden (1987) also suggests that heightened sedentism in the past increased woodworking demands, requiring the use of materials that were more advantageous for these tasks due to lower replacement rates. In this case, the use of expedient choppers not only would waste chert resources but also would detract from the time spent on woodworking. Use of tougher groundstone edges would allow for greater efficiency in woodworking tasks due to lower replacement rates. In both of these instances, raw material and time, interchange with each other as the currency being optimized.

Surplus and Non-Utilitarian Functionality

While optimizing theory in many ways is a powerful tool for explaining lithic use in prehistoric cultures, there is the simple problem that not all human behavior in the past was optimized. As demonstrated by a paradox illustrated by Olausson (1983:7), a tool's value can be dependent on "two opposing factors". A tool can be valued on its ability to perform its practical functions with high benefits and low costs, or it may be a factor of its inability to effectively perform its intended utilitarian function. There are many instances in prehistory where an item has evolved away from its original intended use,

> [to] serve some [other] purpose in society -- to mark status, religious affiliation, etc. The value of such an object *increases* the *less* it is able to fulfill a practical function. The amount of time or effort spent on the manufacture of such an object represents an investment *beyond* what is required for subsistence -- a surplus. Therefore the more time spent in the manufacture of such an object, the more valuable it is as a symbol of wealth (Olausson 1983:3).

A major criticism of optimizing theory is that it is incapable of explaining behavior beyond a subsistence level. As cultural complexity increases the most optimal decision on an economic level may not be the best choice on a social level.

Olausson (1983), in the above passage, brings up two important concepts that cannot be explained by optimizing theory: surplus and non-utilitarian functionality. Surplus is the result of excess effort used to create a stone tool. For example, grinding/polishing a celt beyond the working edge may be considered surplus because of the limited benefits that the effort imparts to the practical function of the tool. Non-utilitarian functionality is the process where a practical tool is elaborated or modified to the degree where the modification hinders the performance of the implement. With celts, the typical elaboration is to increase the size to unwieldy or easily breakable proportions. In both cases, these concepts are not apparently wise economic choices. If an exorbitant amount of effort is spent in making a practical tool (i.e.., enhancing the aesthetic appeal), it may have high benefits, but it would also have high costs. If the same amount of effort is spent on a non-utilitarian tool or item, it would have high costs and low practical benefits. Both of these, especially the latter, are non-desirable in terms of optimizing behavior.

In her study of flaked versus groundstone axes, Olausson (1983:7-8) felt that the best approach to identifying surplus energy expenditure was to derive minimal criteria for the effort/time needed to make strictly functional woodworking tools. To do this, she examined three aspects of groundstone flint axe use versus greenstone axe use in Scandinavia: 1) differential access to raw material, 2) ease of manufacture, and 3) differential use of material types for specific tasks. The results of her investigations demonstrated that groundstone axes made of greenstone were easier to manufacture and resharpen than those made of flint. Despite this, the greenstone axes were equivalent, if not superior, to those made of flint in performing woodworking tasks (Olausson 1983:60-1). Olausson concluded that the additional effort expended upon the flint axes was an "'extra' touch not required for function; i.e., value." (1983:60) The incentives behind making flint axes were associated more with the desire to display or confer status rather than any utilitarian need.

Although not addressed by Olausson (1983), there are many prehistoric instances where stone tools have been elaborated to the point where they are essentially not practical for utilitarian functional (e.g., Mesoamerican, Mississippian, Northwestern Plateau obsidian eccentrics and stone bowls). Usually in these situations, the energy and time needed to manufacture an implement is beyond that needed to make a utilitarian counterpart. The point at which items cross over between utilitarian and non-utilitarian function is not always apparent and sometimes investigators arbitrarily set limits. For instance, in New Guinea ceremonial axes are distinguished by their size, which are generally over 25 cm, from the working axes that are usually under 15 cm in length (Sherratt 1976:567). Similarly, thin-butted flint axes in Scandinavia and northern Germany are at times more than 40 centimeters in length and weigh around 4 kg. This, as Sherratt states, "[is] clearly in excess of ergonomic requirement." (1976:567) While it appears that the most exaggerated forms are probably non-utilitarian, I am not aware of any studies that have determined the point where the size of a celt becomes a hindrance to performance.

One of the major risks in using such exaggerated implements is breakage. As has been found during experimentation with adzes, even normal sized celts are susceptible to bending/compressive (Olausson 1983), or side-slap (Kinsella 1993:41) fractures. This weakness is amplified by the extended body length of an exaggerated celt which makes it even more prone to damage. Risking a celt of this type to breakage could result in the loss of a large amount of time and effort. Therefore, with European axes, the symbolic function of an exaggerated implement form must override its utilitarian function (Sherratt 1976:567).

Another component of non-utilitarian function is mimicry. If an object is being made specifically for non-practical purposes, alternate materials that lower manufacturing costs but imitate the final appearance of the functional original may be utilized. Thus the value of the object is gained with a lower time investment. In Mesoamerica, for example, serpentine is often used in forgeries of artistic pieces made from jadeite because of the relative speed in which it can be worked (Foshag 1957:32). Conversely, if the lower quality item was ever used for practical purposes, its performance would be substandard.

Summary

To understand the nature of nephrite use on the British Columbia Plateau it will be necessary to establish the cost benefits of nephrite use in comparison to other available material types. A strong emphasis will be placed upon establishing manufacturing costs in terms of time needed to reduce various material types. Some attention will be also devoted to the use life of various tool forms. By examining these aspects, it may be possible to determine whether surplus or excess effort was expended manufacturing nephrite implements, compared to their advantages as working tools

Examining all the issues of non-practical functionality is beyond the scope of this thesis. There will be no attempt to define at which point a nephrite implement becomes too large to be functionally effective as an adze or celt. There will be some investigation into the possibility of substituting serpentine for nephrite in Chapter 5.

Celt Manufacture

Because celts are the main type of nephrite artifact manufactured on the British Columbia Plateau, I will focus my discussion on the cost-efficiency of nephrite for celt technology. Other types of artifacts, such as knives, are exceedingly rare.

There are three basic reduction strategies used to manufacture celts: 1) pebble modification, 2) flaked blank reduction, and 3) sawn blank reduction (Hanson 1973; Mackie 1992). The following discussion is based on Hanson (1973:228-230), Mackie (1992:127-140) and Kapches (1979).

Pebble Modification

The simplest celt reduction technique is pebble modification. With this method, a pebble that is roughly celt shaped is either pecked or ground. Depending on the proximity of the stone to its final shape, this can be the fastest method of producing a celt. When completed, the cross-sections of such celts are usually oval and they may or may not have some of the original pebble shape or cortex. Pebble celts can be manufactured on virtually any stone type.

Flaked Blank Modification

Using this celt reduction technique, the blank is initially shaped using flaking reduction. Any combination of hard hammer or soft hammer techniques may be used to form the blank, including the bit. The blank is subsequently finished by either pecking or grinding, although the celt may be functional without further modification. When completed, such celts typically have a bi-convex cross-section and may have remnants of flake scars depending on the degree of grinding. The types of materials exploited using this technique at least marginally break in a conchoidal pattern (e.g., chert or flint, basalt, greenstone, jasper, tuff, etc..). Although not used with great effectiveness, it is also used to reduce tougher rock types such as nephrite, serpentine, granite, hornblende, slate, etc. The results of such breakages are often unpredictable and waste a large amount of material. The time needed to manufacture a celt with this method varies depending on the raw material and amount of abrasion used after the initial flaking -- it can be the fastest method if no further grinding is performed after the blank is flaked, but it is generally slower than pebble modification.

Sawn Blank Modification

This celt reduction technique is the most specialized and is usually only performed on a limited number of non-brittle rock types. The blank is sawn out of a larger rock with a groove and snap approach. The bit may be formed during the sawing process or done through pecking and grinding. Sawn blank celts usually have a rectangular cross-section and may have manufacturing grooves present on the margins or faces. The sawn blank modification is by far the most time consuming method of celt production and is usually only utilized on materials where flaking is ineffective (e.g., nephrite, jadeite, serpentine, hornblende, soapstone, slate).

Previous Observations and Experiments on Nephrite Manufacturing Time

Only a limited amount of ethnographic observation and experimentation has been published on the amount of time needed to work nephrite but it does indicate that a considerable amount of time is required to cut that material. In this section I will review the ethnographic and experimental literature relating to the time needed to manufacture nephrite implements.

Ethnographic Information on Nephrite Manufacturing Times

The closest parallels to Plateau nephrite manufacturing come from Maori jade working in New Zealand. Here a range of nephrite artifacts, including adzes, knives, weapons, fish hooks and ornaments (Beck 1970), were made using methods similar to those in British Columbia.

During the 1800's, several explorers made observations on Maori greenstone working methods (Chapman 1892). Two of these explorers, Heaphy and Brunner, reported (Chapman 1892:498-499) their observations on the manufacture of a *mere* or stone short sword out of *pounamu* or nephrite:

> The Arahura natives [Maoris] lay in a large stock of thin pieces of sharp quartose slate, with the edges of which, worked saw-fashion, and with plenty of water, they contrive to cut a furrow in the stone, first on one side, then on the other, until the piece may be broken at the thin place. . . . With pretty constant work -- that is, when not talking, eating, doing nothing, or sleeping -- a man will get a slab into rough triangular shape, and about 12 in. thick, in a month, and, with the aid of some blocks of sharp, sandy-gritted limestone, will work down the faces and edges of into proper shape in six weeks more (Major Heaphy to Chapman 1892:498).

Beck (1970:74) estimates that initial sawing of this *mere* would have involved minimally 50 square inches (325 cm^2) of sawn area based on the average *mere* size of 15 inches (450 mm) long and 4 inches (100 mm) wide. In other words the total distance sawn, based on the circumference of the cross-section of a *mere* blank, was 225 millimeters. Assuming that 160 hours were minimally spent during the month the *mere* was manufactured, the craftsperson was sawing at a rate of approximately 1.4 mm/hr.

Jade working in China has been undertaken since the early Neolithic (Huang 1992). The craft, in its long development, has produced some of the best artistic carvings. The tools and abrasives used in Chinese jade carving are considerably more sophisticated than those used on the British Columbia Plateau. The lapidaries in China used a variety of metal (usually iron) tools in conjunction with numerous hard abrasives including corundum (hardness of 9) (Hansford 1950:67, 81). Diamonds were also used but usually just for drill points.

Despite the advanced nature of the tools and abrasives in Chinese jade working, cutting speeds were still slow. In describing the bisection of a jade cobble (I estimate to be 20 to 30 centimeters in diameter) using a metal wire, abrasive, and water, Hansford (1950:79) stated that the operation would require several weeks to complete. Other processes, such as hollowing bowls and jars, inscribing writing, creating relief, are described as being laborious, but Hansford offers no further time estimations.

Experimental Data on Jade Manufacturing

One of the earliest investigators to study aboriginal lapidary was M'Guire (1892). During his research, M'Guire attempted to reconstruct prehistoric technology by simulating reduction techniques. In one experiment, he (1892:166-167) manufactured a grooved axe of nephrite. Beginning with an irregular shaped fragment of a nephrite boulder, he repetitively pecked and ground the piece into a grooved nephrite axe in a total of 66 hours. Most time was spent on pecking the axe into shape (55 hours). During this experiment M'Guire estimated that he delivered approximately 140 blows per minute for a total of over 460,000 strikes for the whole procedure. Also during the process he destroyed 40+ hammerstones until he found one tough enough to withstand the pounding. After pecking (which was curtailed after breaking a section of the celt), the axe was ground for 5 hours and polished for 6 hours. M'Guire considered the amount of time needed to complete the axe to be excessive. With tougher hammerstones (e.g., one made of nephrite) he felt that he could have cut the amount of work needed to complete the axe in half. Likewise, he believed that aboriginal craftspeople would have chosen pebbles to reduce that were closer to the desired form.

M'Guire (1892:175) also attempted to measure the rate at which nephrite could be sawed. He first attempted to saw nephrite with a sheet of native copper, sand and water. Subsequently, he tried both chert and jasper in conjunction with sand and water. With all three saws M'Guire reported that "great difficulty was experienced in making satisfactory progress." (1892:175) Only when using a saw made of "jadite" was a greater rate achieved. When using "jadite", with or without sand, in association with water, he recorded "cutting a groove one-fourth of an inch deep in about an hour." (1892:175)

Johnson S. (1975), in a study of Mesoamerican jade working, investigated the rate at which jadeite can be sawn. In her experiments, Johnson S. (1975:6) achieved a cutting speed of 1 millimeter per hour using a blade or sheet of wood in conjunction with crushed granite and water. In a similar experiment she found that sawing rates could be increased to 2 mm per hour using grease or fat, instead of water, as a lubricant.

In his studies of Maori jade working, Beck (1970:70-72) performed some experiments on nephrite. In these investigations he tested the efficiency of saws made of different materials in creating cutting grooves and their effectiveness after the groove was established. Beck (1970:72) determined that sandstone saws are superior in both circumstances compared to those made of quartzose schist, greywacke spalls, and slate. Unfortunately, he does not record the rates achieved with the different materials.

Finally, Barrow (1962:254) observed the manufacture of a nephrite *hei tiki* using semi-aboriginal techniques by a jade worker known as Mr. Hansson. For the most part, modern tools and abrasives were used to create a *hei tiki* that measured 6.5cm x 3.3 cm x 8 cm. Some aboriginal drilling and grinding techniques were used, however, to shape and finish the pendant. Despite the use of synthetic carborundum abrasives and an emery wheel, the *hei tiki* still took 350 hours to complete. Barrow concluded that this would probably be the minimum amount of time a skilled Maori craftsperson would need to complete the same item using only traditional methods.

Manufacturing Experiments

This section deals with a series of grinding experiments that were undertaken to establish the effort needed to make nephrite tools compared to other material types. As discussed earlier in the chapter, I believe time and raw material are the most important factors involved in making and using stone tools. The following experimental procedures were designed to gauge the relative time needed to cut nephrite, serpentine, greenstone, chert, and steatite using similar techniques to those utilized prehistorically on the Plateau.

Experimental Procedures

The experimental approach undertaken in this thesis to emulate Plateau jade working technology was to cut grooves in various specimens of rock with a sandstone saw in conjunction with sand and water. Following the ethnographic information recorded by Emmons (1923) and Teit (1900), and my observations of nephrite artifacts, I believe that this method, as opposed to the use of a thong or reed, was probably the primary means of reduction.

I decided to use a sandstone saw partly from Emmons' (1923) descriptions of Plateau nephrite working and from Beck's (1970) endorsement of sandstone saws over other material types for effectiveness in cutting. The saws used in the experiments were approximately 20 cm x 10 cm x 1.5 cm in size and were made from a pink sandstone tile. Although saws were sought from natural sources in British Columbia, commercially obtained sandstone tiles were used because of their uniform thickness. The composition of the particles in the sandstone is largely unknown. I had hoped that a large number of the particles were pink quartzite (hardness of 7) but many may have been feldspar (hardness of 6). The particles were approximately 0.25 millimeters in size and had a partially rounded shape.

Two types of sand were utilized during the procedure. Due to the location of my experiments, both came from the Missouri area and were a mixture of different particle types. Again the types of materials in the sand were not identified, but quartz crystals were present in both. The first kind of sand had particles approximately 0.5 to 0.25 millimeters in size and was not as coarse as the second type with particles up to a 1.0 millimeter in diameter.

The tests were carried out on specimens of nephrite, serpentine, greenstone, chert, and steatite, which are all available in the interior of British Columbia (Leaming 1978). Three samples of nephrite were tested -- two from the Dease Lake area (Specimen #1 and # 2) on the Cassiar segment and one from the Skihist area on the Fraser River (Specimen # 3). The serpentine (Specimen #4) and steatite (Specimen #7) were purchased in a Vancouver lapidary and probably came from the interior of British Columbia, although this is uncertain. One sample of greenstone (Specimen #5) was tested and it was collected from the Bella Coola valley (Breffitt 1993: personal communication). The chert sample (Specimen #6) used was Burlington chert from Missouri and served as a replacement for a broken piece collected in British Columbia. For three of the material types (nephrite, serpentine, and greenstone), samples of various sizes were cut to determine what factors the length of the groove played in cutting time.

The following procedures were followed for every test:

1. An initial cutting groove was established in each specimen before the start of the experiments. This was to facilitate direction of the saw and effective dispersion of sand and water.

2. The depth of both ends of the cutting groove were measured to the nearest 1/10 th of a millimeter and recorded before each test.

3. All specimens were held in place with the use of a large vice ("Black and Decker Workmate").

4. Only one saw was used for each test.

5. The saw was moved repetitively through the groove at a rate of approximately 150-170 strokes per minute. Some downward pressure was exerted while moving the saw but not an excessive amount.

6. Sand and water were liberally added when needed. Only one type of sand was used per test. In some situations, sand was recycled after being used once.

7. All sawing was timed -- usually in 1 or 2 hour increments. Any time sawing was halted the timer was stopped.

8. After the grinding was completed, the depth of each groove end was again measured to the nearest 1/10th of a millimeter. Rates were calculated by averaging the distance cut on each end of the groove.

Results

Of the samples tested, the lowest cutting rate was achieved on the chert specimen. After spending a large amount of time trying to establish a groove and additionally sawing one timed hour, only a minimal amount of headway was made (0.15 mm/hr). Sawing was curtailed after 1 hour because of the lack of progress. The reasons behind the slow rate directly correlate with the hardness of the material (Table 4.2).

The second slowest sawing rate was associated with the nephrite specimens, which had an average cutting speed of 1.455 mm/hr. A number of groove lengths were tested during the experiments. It was found that groove length had only a minor influence on cutting speed. The longest groove (402 millimeters) did have the slowest cutting rate (1.31 mm/hr). When comparing it, however, to grooves half the size, the difference only amounts to between 0.20 mm/hr and 0.365 mm/hr. The second lowest cutting speed was on Specimen #3 which had the shortest groove length, at 1.375 mm/hr. This variation between specimens can likely be attributed to slight differences in hardness.

The greenstone sample followed nephrite in cutting speed with an average of 2.52 mm/hr. Rates achieved for the serpentine specimens were over double those for nephrite and averaged 3.15 mm/hr. This is not unexpected due to the fact that the serpentine is approximately half as hard as nephrite. The differences in groove length for both the greenstone and serpentine samples reflect the same trends seen in the nephrite specimens. Only minimal differences (if any in the case of greenstone) were found between different groove lengths. Not surprisingly, the fastest sawing rate was recorded for the steatite specimen. At 20.95 mm/hr, the sample was nearly bisected before an hour

Table 4.2. Results of Experimental Sawing.

Specimen	Trial Number	Sand Type	Groove Length	Side A	Side B	Time Elapsed	Increase in Groove Depth
No 1 Nephrite	1	1	202 mm	4.05 mm	2.65 mm	2 hrs	1.675 mm/hr
	2	2	202 mm	4.1 mm	1.95 mm	2 hrs	1.51 mm/hr
	3	2	402 mm	2.85 mm	2.4 mm	2 hrs	1.31 mm/hr
No 2. Nephrite	1	2	114 mm	2.5 mm	3.2 mm	2 hrs	1.43 mm/hr
No 3. Nephrite	1	2	94 mm	1.6 mm	1.15 mm	1 hr	1.375 mm/hr
Hardness: 6-6.5							Ave - 1.455 mm/hr
No.4 Serpentine	1	1	170 mm	6.55 mm	6.3 mm	2 hrs	3.21 mm/hr
Hardness : 4-5	2	2	170 mm	6.05 mm	5.8 mm	2 hrs	2.96 mm/hr
	3	2	101 mm	4.0 mm	2.7 mm	1 hr	3.35 mm/hr
							Ave - 3.17 mm/hr
No. 5 Greenstone	1	1	160 mm	5.3 mm	4.85 mm	2 hrs	2.54 mm/hr
Hardness : ~5	2	2	160 mm	7.9 mm	3.95 mm	2 hrs	2.96 mm/hr
	3	2	106 mm	2 mm	2.05 mm	1 hr	2.05 mm/hr
							Ave - 2.52 mm/hr
No. 6 Chert	1	2	94 mm	0	0.3 mm	1 hr	0.15 mm/hr
Hardness : 6.5-7							Ave < 1 mm/hr
No.7 Steatite	1	1	111 mm	20.3 mm	21.6 mm	1 hr	20.95 mm/hr
Hardness : ~2							Ave -20.95 mm/hr

of sawing was completed.

Several other observations were made during the experiments. There was, at times, a considerable amount of attrition noted on the sandstone saws - particularly when sawing nephrite. During one test, the saw decreased 6.3 mm in size whereas the nephrite's groove depth only increased by 3.35 millimeters. Also, the working edges of the saws tended to become concave or bowed as the experiments proceeded. This was also reflected in the grooves which tended to be shallower in the middle. The only exception to this was the nephrite specimen with a groove length of 402 millimeters where the opposite conditions were observed; the groove was deeper in the center.

During the experiments, I discovered that water and sand needed to be added continually. Although I never precisely measured the quantities of either material, it was not uncommon to use at least 4 litres of water and 1 litre of sand over a 2 hour test period. Increased pressure placed on the saw during the grinding process resulted in greater loss of sand and water. These were literally 'pushed out' of the groove.

Only a minor amount of physical exertion was needed to operate the saw. Never was the procedure physically rigorous and the overall caloric expenditure was likely quite low. In no way could this procedure have upset "biophysical homeostasis" (Boydston 1989:71) by its caloric consumption (unless carried on for excessive periods of time).

I also noted that the serpentine sample would not have been suitable for strictly functional tools. It is doubtful that a celt could even be successfully made out of this specimen of the material. During the experiments, I observed that the serpentine subject became pervaded with cracks and pieces of the material simply fell off. If this piece is indicative of serpentine in general (although this is probably not the case), then this material would not even be suitable for mimicking nephrite.

Critique of the Experimental Results

The results gained from the experiments should only be taken as an approximation of cutting rates achieved by prehistoric stone workers. This is especially the case when looking at the variables involved in the sawing process. These include:

1. Hardness of the material being sawed
2. Hardness of the saw
3. Hardness of the abrasive
4. The amount of pressure exerted downward on the saw
5. The shape and size of the particles in the saw
6. The shape of particles in the abrasives
7. Rate of sawing strokes

Hardness of the material being sawed can only be varied to a limited extent (e.g., nephrite can only be between 6-6.5 in hardness; one can choose pieces in the lower part of the range), whereas other factors also can be controlled to some degree. Throughout the experiments, I did not try to maximize the effects of the other factors. This would have entailed finding harder, more angular abrasives (e.g., pure quartz sand); saws with harder particles such as garnet; applying more downward thrust; and possibly increasing the number of sawing repetitions per minute. If prehistoric Plateau stone workers maximized these factors, they may have been able to saw at an increased rate. There are indications that the Maori tried to maximize the hardness of their abrasives and saws (Beck 1970) and in China a whole industry arose to supply lapidaries with effective abrasives (Hansford 1950:67-69). Nevertheless, despite some limitations of the experiments, they do provide valuable information.

Comparison of Reduction Techniques and Materials

Table 4.3 is a summary of the manufacturing times recorded by other researchers for making celts using different blank types. The figures for sawing nephrite were derived from the experiments conducted for this thesis, using probable reduction sequences inferred from nephrite artifacts from the plateau and ethnographic references discussed in Chapter 5. When comparing the times needed to make celts with different techniques, the flaked blank approach has the fastest mean time of 5.2 hours. This is followed by the pebble modification technique at 29.8 hours and sawn blank at 82 hours (using average times calculated using maximum speeds). The reason for this large variation is that the materials modified by the pebble and sawing techniques cannot be effectively reduced by flaking. It should be noted that the excessive time needed to reduce nephrite and greywacke siltstone inflates the average rate for the pebble modification and sawing techniques. If these two materials are

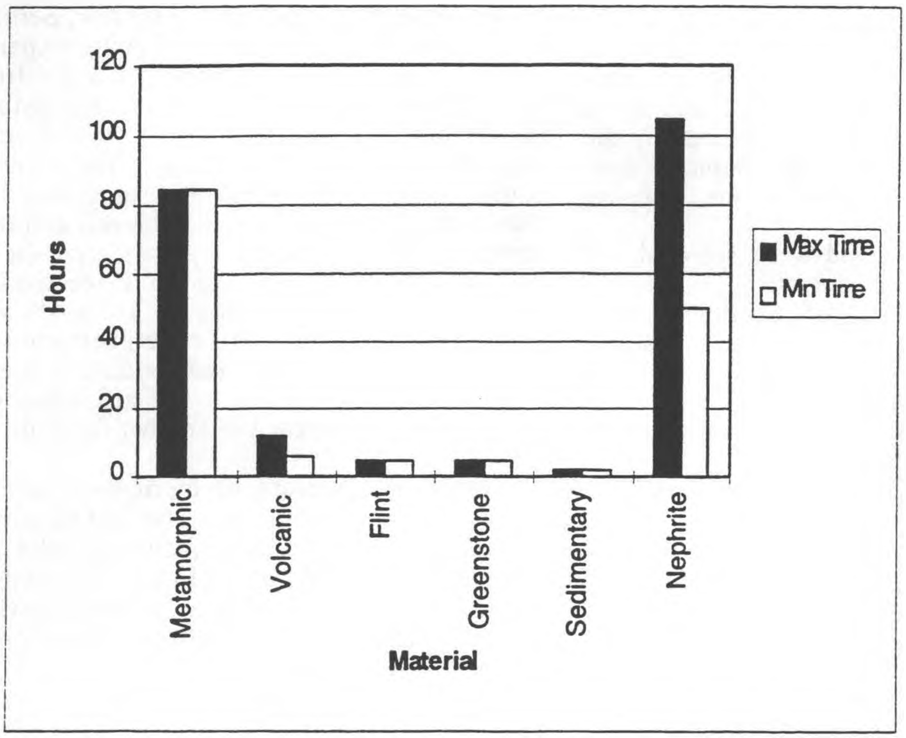


Figure 4.4. Time Needed to Manufacture Celts from Different Material Types.

removed from the sample, the average time decreases to 3.3 hours.

It is quite apparent that celts made of different raw materials have varying manufacturing times (Figure 4.4). Some of the materials have been grouped by similar geologic origin. Metamorphic rocks (greywacke, siltstone, and slate) and nephrite clearly have the greatest manufacturing times. This is particularly the case with the total for nephrite which underrepresents the actual time required.

Cost-Benefits

Since the cost of manufacturing nephrite adze bnlades is so high, there should in theory be very high benefits, unless those objects were created for non-utilitarian or prestige purposes. One potential benefit that nephrite tools may have bestowed upon their users was increased speed in cutting or chopping wood. To evaluate this aspect of nephrite celt use, a series of chopping experiments was undertaken using a nephrite celt to gauge the cutting efficienncy of the tool compared to celts of other materials.

Wood cutting experiments were conducted using a nephrite celt mounted in an axe haft. Nephrite from the Dease Lake region of northern British Columbia was cut into a celt using a diamond saw. The celt measured 270 mm x 60 mm x 20 mm and had a bifacial working edge to 38°. Because of its size and weight, the implement tended to readily induce fatigue. Its use, unfortunately, was necessary due to the inadequacy of two smaller celts also manufactured for experimention. Due to flaws in the material, that were probably inhanced by the heat and vibrations from the diamond saw, those two celts fractured before the chopping experiments could begin.

Three types of wood were selected and gathered for the experiments -- sycamore, poplar, and a form of juniper. Sections of these tree types were held in a large vice (Black & Decker workmate) in a horizontal position for cutting. Both the sycamore and juniper trees are considered hardwoods, whereas the poplar specimen was softwood.

Each wood specimen was chopped at a rate of between 45 to 50 blows per minute. The amount of force exerted on each swing was less than would be used with an iron or steel axe blade because of the brittleness of stone edges (Olausson [1983] forewarns of this problem). Each experiment was timed using a stop watch. When chopping ceased (usually to adjust the position of the log), the timer was stopped. After each procedure, the distance proceeded into the specimen and the volume chopped were recorded. Volumes were obtained in a similar manner used by Olausson (1983:41) by measuring the amount of wet sand needed to fill the cut area.

The results obtained during the chopping experiments were mixed (Table 4.4). Most of the cutting speeds obtained are relatively slow when compared to the results obtained by Olausson (1983) in her experimental proce dures and by ethnographic observations listed by Boydston (1989:73) using groundstone implements. In Figure 4.5, the cm2/minute of wood chopped (based on the diameter of the tree being cut) for my experiments are compared to those listed by Boydston (1989:74) for ethnographic observations for other groundstone edges. As can be seen, the rates achieved in this study are far below Boydston's average figures for general groundstone axes for both hardwood and softwood. However, these rates fall within the standard deviations that Boydston (1989:73) listed for both his hardwood (12.6 cm2/min) and softwood (22.5 cm2/min) averages.

Few conclusions can be drawn from these experiments. Nephrite edges appear to be neither superior nor inferior to other forms of groundstone edges for cutting efficiency. Although all the chopping results obtained in the experiments in this study were low, Semenov (1964) also conducted chopping experiments using a nephrite adze on a fir tree (considered to be softwood by Boydston [1989:73-4]) and achieved higher rates of cutting efficiency (See Figure 4.6). The slower cutting speeds achieved in this study may be due to the oversized nature of the celt and the horizontal position of the logs being cut (it is difficult to gauge when exactly a tree would fall and the values presented in Table 4.6 are only estimates). Until more experimentation is completed under standardized conditions, there can be no conclusions as to the efficiency of one material as opposed to another for cutting edges.

Three observations of merit were noted during the experimentation. The first of these is the importance of manufacturing celts of nephrite with very few or no flaws. In the case of the two smaller celts that were used briefly, both implements broke immediately along previously existing flaw lines. The celt that was used also sustained some minor damage along a previously existing crack while being used on a hardwood sycamore specimen.

The second observation was that the cutting edge of the nephrite celt, except for a minor break on one end of the blade, essentially retained its sharpness throughout the chopping experiments. Although the experiments could hardly be considered an arduous test of the strength of nephrite edges, this observation does suggest that nephrite edges are enduring.

Table 4.3. Time Involved in Celt Manufacturing Techniques for Different Materials.

Manufacturing Technique	Material	Time Expended	Reference
Pebble Blank (pecked and ground)	Nephrite	66.16 hrs	M'Guire 1892
	Kersantite	2 hrs	M'Guire 1892
	Sandstone	3.75 hrs	Treganze & Valdiva 1955
	Greywacke Siltstone	~ 126 hrs *	Chapell 1966
	Metabasaltic Pebble	1.8 hrs	Dickson 1981
	Porphyry	5 hrs	M'Guire 1891
	Gabbro	4.16 hrs	Evans 1897
	Method Average	29.8 hrs	
	without nephrite & greywacke	3.3 hrs	
Flaked Blank (flaked,pecked,ground)	Catoctin Greenstone	3.16 hrs	Callahan 1993
	Amphibolite	3.55 hrs	Olausson 1983
	Catoctin Greenstone	4.5 hrs	Olausson 1983
	Catoctin Greenstone	5.1 hrs	Olausson 1983
	Catoctin Greenstone	5.87 hrs	Olausson 1983
	Flint	4.25 hrs	Olausson 1983
	Flint	5.1 hrs (6.03 hrs)	Olausson 1983 est.
	Flint	5.63 hrs (6.36 hrs)	Olausson 1983 est.
	Diorite	~18-24 hrs* †	Bordaz 1970
	Granite	4 hrs †	Pond 1930
	Rhyolite	5 hrs	Dickson 1981
	Limestone	0.5 hrs	Dickson 1981
	Basaltic Pebble	2 hrs	Dickson 1981
	Flint (just flaked)	0.25 hrs	Coles 1973
	Method Average	5.2 hrs	
Sawn Blank	Fine Grained Slate	43 hrs	Roberts 1975
	Nephrite	~ 34 to 145 hrs	this thesis - see Figure 5.2
	Serpentine	~16 to 60 hrs	this thesis - see Figure 5.2
	Method Average	max - 82 min - 31	

~ means estimated   * estimated by Kapches (1979)   † estimated by Boydston (1989)

The third observation was that the large size of the celt probably decreased its efficiency as a chopping tool. This was mainly due to unwieldly weight of the implement that tended to fatigue the chopper reducing the number of swings per minute and weakening the force behind them. Further experimentation will be needed in the future to determine what size of celt is more manageable.

In a project to reconstruct prehistoric structures at Cahokia, celts similar to those found in the area prehistorically were used to perform some of the woodworking tasks. Callahan (1993:38) recorded the life history of one celt made of Catocin greenstone. In total it was used for 29.39 hours to fall and trim cedar trees before it was broken. In total it underwent 14 resharpenings and only was abandoned when damage from an accidental drop on a large stone was too severe to warrant a major resharpening. If the celt had not been broken prematurely, it may have had a much longer life. One could expect even longer duration from nephrite celts.

The two measures of a stone's strength are hardness and toughness (Brandt et al. 1973). Hardness is the measure of its resistance to scratching or abrasion, while toughness is its resistance to fracture. Both attributes figure-heavily in the use-life of a stone tool. Harder substances are more resistant to abrasion (noted in my sawing experiments). In theory, a chert celt should remain sharp longer than a nephrite celt because of its greater hardness. However, chert is a brittle substance and this seriously affects its performance. Returning to the surface fracture energy and the fracture toughness measures in Table 2.1, chert has similar toughness values to glass and quartzite. The values for nephrite are 52 times higher for fracture surface energy and 11 times higher for fracture toughness. In practical terms, a nephrite celt should be able to absorb the impact of a blow 11 times stronger than a chert adze.

When modeling the cost-efficiency of different material types, it becomes apparent that nephrite is a 'high cost-high benefit' material for manufacturing celts. In Figure 4.6, the estimated time for manufacturing celts of different materials is compared to the resistance of the material to breakage. The costs and potential benefits of nephrite far exceed any other material. Theoretically, a nephrite celt will withstand seven times the amount of fracture energy than chert. However, the major manufacturing costs would demand either the need for a strong tool, or the *luxury* of having an enduring implement.

Table 4.4. Results of Chopping Experiments.

Specimen	Extent of Cut	Cutting Time	Distance Cut	Volume of Wood Removed	Estimated Tree Falling Time†
Poplar (softwood) 10 cm diameter	cut through	13.68 minutes	10 cm	450 ml after 10 minutes	~ 8.8 minutes
Poplar (softwood) 10 cm diameter	cut through	9.5 minutes	10 cm	500ml	~ 7.7 minutes
Sycamore (hardwood) 11 cm diameter	groove only	10 minutes	4 cm	200 ml	~ 27 minutes
Sycamore (hardwood) 11 cm diameter	groove only	6.3 minutes *	3 cm	200 ml	~ 17 minutes
Juniper (hardwood) 8 cm diameter	groove only	5 minutes	3cm	150 ml	~ 10 minutes

* Experiment stopped due to edge damage

† Based on removing two wedges of wood that would leave a 2 cm rib - based on personal experience, the tree should fall at this point. These estimates may be slow.

The practical functional benefits of nephrite are not equal, however, for all celt sizes. This is demonstrated by the model in Figure 4.7. At some point, an optimal size of celt exists which has maximum functional utilitarian benefits, while at the same time it is large enough to endure multiple resharpenings. Simply put, if one makes a short celt, it will have a limited use life. However, there is a maximum length for optimal benefits. After this juncture, an excessive celt length becomes a liability for bending/compressive fracture. This decreases the practical benefits because of the potential to lose the time invested in manufacture. Since this does not represent optimal behavior in a strictly utilitarian sense, the motivation behind making such an artifact probably resides in either symbolic or social value. At present, it is not clear where the optimal length for nephrite celts is located. New Guinea axes (some of which are nephrite) can be divided, based on metric attributes, into ceremonial and utilitarian implements (Phillips 1975:110). This division is approximately between 15 and 25 centimeters in length (Sherratt 1976:567). Using this analogy, nephrite celts greater than 15 to 25 centimeters may not have functioned as effectively as smaller implements

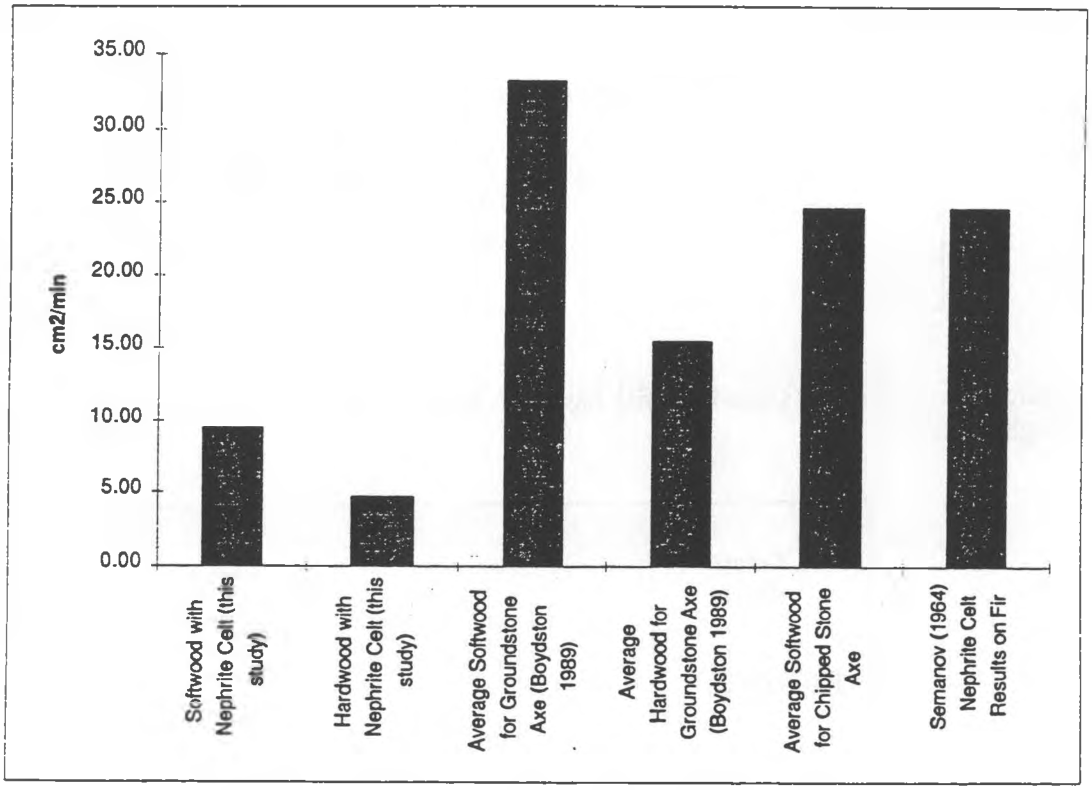


Figure 4.5. Comparison of Areas Chopped to Averages Presented by Boydston (1989).

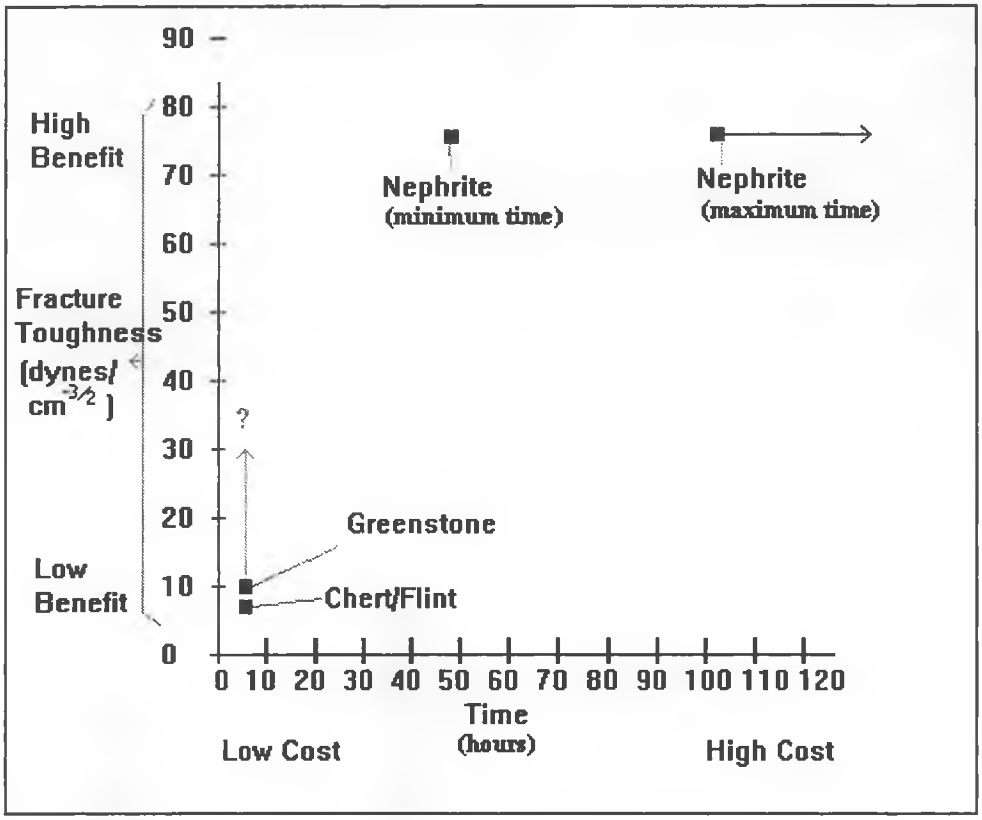


Figure 4.6. Estimated Cost-Benefits based on Manufacturing Time and Fracture Toughness.

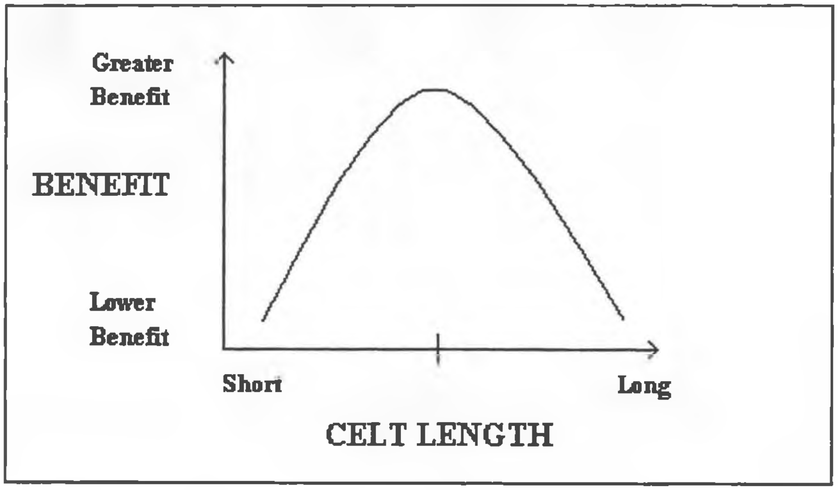


Figure 4.7. Model of Benefits for Nephrite Celts based on Length.