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Technology, Flaked Stone Technology, and Risk

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ABSTRACT

Recent theoretical studies of flaked stone technology have identified many factors that affect the ways in which human beings make and use tools. However, these studies lack a unified body of theory that might help to integrate their diverse perspectives. This paper expands recent anthropological discussions of risk as the basis for such a theory. We begin by defining risk, emphasizing two distinct components of this concept–the probability that some problem will occur and the cost of such an occurrence–and argue that technology can be seen as a means of reducing such probabilities in the face of unacceptably high costs. We support this argument using cross-cultural data on hunter-gatherer technology and archaeological and historic data on the construction of defensive works on the northern Great Plains. Next, we consider specific problems in applying this perspective archaeologically, concluding that existing limits on our ability to estimate failure probabilities and costs prevent us from testing the ideas outlined here in archaeological contexts. However, accepting this perspective as provisionally validated by ethnographic data allows us to see how it can illuminate archaeological cases, and we exemplify this by comparing the production of Araya microblade projectile points in the Japanese Paleolithic and Folsom fluted projectile points on the North American Great Plains.

This is a paper outlining a way to think about flaked stone tools, contained in a volume addressing the role of Darwinian theory in archaeological explanation. We think that this volume is an appropriate place for this paper to be, but we also think that the relation between Darwinian theory and stone tools requires some explication.

The version of Darwinian theory which is currently popular in archaeology is often referred to as "selectionist", following O'Brien and Holland (1990) and others. Selectionist archaeologists make two important claims, one regarding the mechanisms by which cultural change occurs and the other regarding the causal forces driving such change. First, selectionists argue that changes in human ways of life occur as the result of the differential persistence of one variant of a pattern of behavior or kind of artifact over another, with successful variants or artifact types "selected" by external, usually environmental, conditions; they often contrast such a pattern with transformational views of change. Second, selectionist scholars argue further that Darwinian forces drive this pattern of change, which means, or ought to mean, that one pattern of behavior or artifact type is selected over another on the basis of its effects on the reproductive fitness of individual human beings.

It is absolutely essential to distinguish these two arguments, because addressing them archaeologically poses very different problems. These problems are most severe in the case of attributing change to the causal force of reproductive fitness, which, no matter how we dance around it, is what Darwinian theory is about. Direct observation, archaeologically or otherwise, of the processes on which Darwinian evolution depends–the effect of differences in reproductive fitness among individuals within a breeding population–is exceedingly difficult, and we would argue that archaeologists who have attempted to look directly at reproductive fitness have achieved ambiguous results at best. For example, Leonard and Reed (1993; also see Larson et al. 1996) take regional population growth as a measure of fitness, despite the fact that Darwinian theory explicitly refers to the differential reproductive success of individual organisms, and that the spread of one phenotype at the expense of another therefore represents evolution by natural selection whether total population increases, decreases, or remains the same. Overall population levels may well measure the overall biological success of a regional population, but they absolutely do not automatically indicate Darwinian evolution in that population.

As Smith (1991: 34) notes, "Reproductive competition among individual members of a population may be such as to confound any generalization we might wish to make about the effect of selection on entire populations: selection might *result* in a decline in population size, an increase in mortality or strife, a decline in mean population fitness, or even extinction, even as it *favors* the individual traits that produce such effects" (emphasis in original). It seems to us that an emphasis on regional population growth comes perilously close to relying, implicitly or not, on arguments based on group rather than individual selection (compare, for example, Leonard & Reed [1993] with Kaplan & Hill [1985]). Group level processes may turn out to be particularly important in cultural, as opposed to biological, change, but such processes will not necessarily be compatible with, and may actually produce results which are quite divergent from, processes of Darwinian evolution (also see Smith 1988: 230-231).

Perhaps because of problems like these, the great majority of selectionist research focuses on the ways in which artifacts or behavioral patterns are likely to enhance fitness under specific conditions and then evaluates the effects of changes in those conditions, but does not address individual reproductive fitness directly. Arguments like these typically show that one artifactual or behavioral variant is particularly efficient or effective under some conditions and not under others, and that changing conditions select for it over other, less efficient or effective, variants; alternatively, some analysts attempt to isolate aspects of artifactual variation which are argued not to be subject to selective forces (i.e., Neff 1992, Neiman 1995).

The distinction we drew above between a selectionist pattern of change and the possibility that differential reproductive fitness drives such change is important here: without showing that fitness differences among individual humans are the ultimate cause of archaeological change, these less direct selectionist arguments use Darwinian theory basically as a heuristic metaphor, applying concepts developed to understand evolutionary changes in organisms as tools to clarify our thinking about temporal changes in material culture. To rephrase our earlier arguments, enhancing the survival of entire populations of humans is not Darwinian evolution, and, to the extent that selectionist arguments pertain to such population-level benefits, the causal processes to which they appeal differ little, if at all, from those of more traditional views which the selectionist program is intended to supplant (also see Schiffer 1996: 647).

Our discussion falls into this latter, heuristically "Darwinian", category of selectionist research, and we therefore proceed with some caution. Stone tools were essential to the ways in which humans coped with the conditions around them for over two million years. Understanding how these tools enhanced such coping is thus important to archaeological interpretation, and our goal here is to outline a framework for analyzing the links between different technological patterns and the context in which they were designed to operate; it will be clear that we view external environmental conditions as particularly important in shaping particular technological stances. However, we suspect that virtually all lithic datasets derive from the collective activities of groups of people and rarely tell us much about differences (reproductive or otherwise) among individual human beings. We are quite comfortable with arguments for selectionist patterns of change, and we believe that the framework we present here is particularly suited to such views. However, we also believe that archaeology is a long way from showing that truly Darwinian forces cause such change: we believe that a selectionist framework helps to make sense out of diachronic change and synchronic variation in lithic technology, but it is not clear to us that such technology tells us a lot about Darwinian process.

Our goal here is to outline a basis for building a body of theory relevant to important aspects of technology, particularly flaked stone technology, in order to address a general lack of synthesis and integration in the archaeological literature on this topic. A recent expansion of the attention given by archaeologists to the interpretive potential of flaked stone tools has clearly increased dramatically the range and sophistication of the archaeological problems that lithic data sets can help to solve. In the past two decades, archaeologists focused on flaked stone tools have derived substantial insights into the relations between technology and such factors as mobility patterns, complex economic organization, raw material availability, and cultural or ethnic preferences (Nelson [1991] reviews much of this literature; also see Andrefsky 1994, Bamforth 1991a; Barton 1991, Chapter 8; Bousman 1993, Carr 1994, Flenniken 1984; Hayden 1981, 1987; Jeske 1992, Kornfeld et al. 1990, Kuhn 1994, Ricklis & Cox 1993, Sackett 1982). Although many issues remain to be settled, there is no doubt that the field has made great strides. However, despite the range of topics lithic analysts have addressed and the progress made over the past decade, Jeske (1996) points out that this branch of archaeological thought seems stalled: studies of mobility and other patterns derived from Binford's (1977, 1979, 1980) work dominate the field, for example, and a single descriptive term-the "curation" concept (Binford 1973, 1977, 1979)-structures virtually every study in the published literature. Furthermore, theoretical lithic analysis is plagued by seemingly unnoticed mutually contradictory arguments, a wide range of distinct definitions for important terms (most notably "curation"), and little or no synthesis.

Our discussion begins by considering (briefly) what technology is, and then turns specifically to focus on the range of behavior involved in flaked stone technology. In this first section, we will argue that archaeologists (1) have been too quick to equate technology with tools and (2) have tended to focus on too narrow a range of behavior in their attempts to explain technological patterns. We then turn to build on Torrence's (1989) discussion of the importance of risk as a determinant of patterns of tool production and use as the basis for beginning to develop a more synthetic account of the determinants of technological behavior. This discussion emphasizes the problem of defining "risk" and translating the definition we use into the analytic framework we develop in the first two sections; our arguments here particularly rely on cost-benefit arguments, but point out that there are likely to be situations in which such arguments may not be important. We close by contrasting two specific archaeological examples in light of our arguments.

TECHNOLOGY AND FLAKED STONE TECHNOLOGY

We follow Bleed (Chapter 6) in defining "technology" as a society's "customary means of manipulating the physical environment". In this view, technology encompasses a wide range of complex behavior and knowledge regarding how to appropriately acquire and put tools to use, and is not simply equivalent to those tools themselves: technological options include knowledge both of what kinds of tools to make and of alternative ways to use those tools, alternatives that may involve such factors as work group organization or the geographic location or time of year in which a particular activity is carried out. Thus, for example, the technological knowledge required to make a living as a Late Prehistoric bison hunter on the Northwestern Great Plains included not only that pertaining to the manufacture and use of the bow and arrow, but also that pertaining to the conditions under which to hunt individually or communally. We therefore need to distinguish between what Bleed (Chapter 6) refers to as technological content (knowledge, standards regarding the proper way to carry out a particular activity, etc.) and technological results (material culture and modifications to the environment): as archaeologists, we study the second of these and hope to learn something about the first.

This view of technology has two important implications for our thought. First, emphasizing technological knowledge helps to remind us that all humans have more than one means of manipulating their environment; we know more than one way to accomplish any given goal, and we make different choices from our range of alternatives in different situations. Second, such an emphasis also reminds us that technological knowledge includes not only knowledge about how to use tools but also about how to obtain them, and that this knowledge can be manifest archaeologically (that is, it produces technological results) in the form of material residues generated at all steps along the continuum of behavior involved in tool production and use. In the specific context of flaked stone technology, many archaeologists have pointed out that this continuum includes the procurement of raw material, production of useable tools, use, optional maintenance and/or recycling of worn tools, and, finally, discard (Callahan 1978, Collins 1975, Crabtree 1968, Rick 1978). For present purposes, we follow Jeske (1989) in dividing this continuum into three fundamental domains of behavior: first, raw material from which tools can be made must be obtained; second, tools must be produced from this material; and, third, these tools must be applied to some task or tasks. In this scheme, tool maintenance and recycling fall into the domain of application.

As Nelson and Lippmeier (1993: 286-287) note, "the most fundamental condition influencing tool design is the task for which a tool is expected to be used; all tools must be minimally effective at the task for which they were produced." Recognizing that this is so, most archaeological attempts to theorize about the factors structuring technology have emphasized the domain of application, arguing, for example, that mobile groups are likely to make portable tools in order to minimize transport costs (Shott 1986) or that design differences between functionally identical implements result necessarily from ideational factors (Lemmonier 1986). However, we will argue here that, although it is obviously true that the utilitarian requirements of the task to be accomplished set fundamental limits on possible technological approaches to that task, technological strategies incorporate essential knowledge about the full continuum from procurement to application. Furthermore, the outcomes of choices made in the earlier points along this continuum strongly condition the options available at later points: successful application of a tool relies on successful production of that tool, which relies in turn on successful raw material procurement.

All flaked stone technologies must therefore solve the problems of obtaining sufficient material, producing adequate tools, and accomplishing necessary tasks, and any successful technological adaptation must therefore take advantage of opportunities and cope with constraints in all three of these areas. The problem in deriving general theory that helps to understand why technological behavior varies in time and space, then, is to understand how these opportunities and constraints are balanced against, or perhaps integrated with, each other in specific cases. The failure of most theoretically-oriented lithic analysis to systematically address the importance of technological decisions in the domains of procurement and production (with the major exception of Rick's [1978] discussion of heat alteration) is one of the important factors limiting our understanding of technological variability. Recognizing this, though, introduces the additional problem of finding a conceptual framework within which to analyze the balance (or integration) of technological decisions in the contexts of procurement, production, and application in specific cases. For the remainder of this paper, we attempt to build on Torrence's (1989) discussion of risk as an important factor structuring technological choices to lay the basis for such a framework.

RISK

All tools must meet certain baseline requirements of effectiveness and accessibility, each of which may be buffered by social factors and limits of knowledge. In general, it is likely that these buffers are minor determinants of technological decisions in most situations, particularly in the case of flaked stone technology: they are background and not the main arena of technological design (although there are presumably cases in which this is not so, as we discuss below). We therefore focus here on the practical or utilitarian factors affecting technology. Following Torrence (1989), we will argue that many critical aspects of human technological behavior, with flaked stone technology as a specific example, can be understood as a means of managing risk.

Although the notion of "risk" has a fairly clear intuitive meaning for most of us, it is not always apparent how it can be transformed into a construct that is precise enough for systematic analysis. As Winterhalder (1986a: 383) puts it, "defining risk is like juggling a porcupine: whatever way you throw it up, it comes down prickly". Anthropological interest in risk (see below) grows out of the recognition that the world can be an unpredictable and, sometimes, perilous place, and that an understanding of human affairs ought to take this into account. In common usage, we often refer to unpredictable and perilous situations as "risky", and this term has been carried over into anthropology and other disciplines. However, as is often true for the academic application of intuitively "obvious" concepts, different scholars have operationalized "risk" in a variety of ways that fit their different interests and perspectives: different analysts have applied the term "risk" to different (but related) concepts. As Cashdan (1990a; also see Christenson 1982: 422-423) notes, the existence of multiple operational definitions of the intuitive notion of "risk" is best taken as evidence that the world is unpredictable and perilous in more than one way and that different analytic tools are necessary to examine unpredictability and peril in different contexts. However, this implies that it is important to specify exactly what we mean when we use the word "risk" and why that meaning is relevant to the problem we are interested in solving. The following section therefore addresses this issue.

"Risk" in the Dictionary and Elsewhere

Webster's New Collegiate Dictionary presents a complex definition of "risk", the most general aspect of which defines the term as "Hazard; peril; exposure to loss or injury". A second, more precise, section of the definition derives from the insurance industry: "a. The chance of loss or the perils to the subject matter of insurance covered by the contract; also, the degree of probability of such loss. b. Short for amount at risk, that is, the amount which the company may lose." The first, more general, of these clearly refers to the common usage of the word "risk" to refer to the possibility that something bad may happen, while the second distinguishes clearly between two components of this usage: the probability of a bad thing occurring and an estimate of just how bad that bad thing is.

Systematic usage of the concept of risk in a variety of disciplines (including economics [Jones-Lee 1989], insurance [Hammond 1968], environmental hazards assessment [Sewall 1990, Suter 1993, Westman 1985], and others) generally focuses clearly on the importance of assessing both the probability and the magnitude of hazards in evaluating levels of risk. This literature has developed substantially as a basis for specifying decision rules on which to base financial and policy decisions, and, as a result, has developed a variety of highly quantitative approaches to operationalizing and analysing this interaction, approaches that are generally designed to help to identify the course of action that most effectively balances risks and the costs of avoiding them (Rescher [1983] presents an extended conceptual, as opposed to mathematical, discussion of many of the essential issues and debates that research in these areas has identified). Among the outcomes of work in this area is a widely (although not universally) applied distinction among risky situations, in which the possible outcomes of a choice (both negative and positive) and their respective probabilities are known, uncertain situations, in which the possible outcomes are known but their probabilities are not, and situations of incomplete knowledge, in which the range of possible outcomes is unknown (Mishan 1971).

Economic/business forecasting relies on assessments of investment risks which distinguish clearly between probabilities and costs, but often recasts the notion of cost in terms of "utility", or "the strength of our desire for something" (Bernstein 1996: 71). Although this branch of research has produced important insights into human responses to risk, it is worth noting that the equation of cost and utility blurs the distinction between the probability of obtaining some desired benefit and that of incurring some undesired harm. For example, Bernstein (1996: 71) quotes an anonymous seventeenth century author who wrote that "Fear of harm ought to be proportional not merely to the gravity of the harm, but also to the probability of the event", but goes on to argue that "We could turn this assertion around and state that a decision should involve the strength of our desire for a particular outcome as well as the degree of our belief about the probability of that outcome". Distinguishing clearly between costs and benefits, between losses and gains, is analytically particularly important because research into the psychology of risk-taking (see Bernstein 1996: 269-283 for a lucid summary) indicates that people make systematically different choices in relation to situations of loss than of gain, even when the outcomes of these situations are mathematically identical.

Evolutionary ecology has also attended to issues of risk. Limited early attention to the topic (i.e., Horn 1968) addressed the "predictability" of resource distributions, and more abundant recent work has explicitly applied the term "risk", resulting in important refinements of optimal foraging models (Real & Caraco 1986). However, although ecological applications of the risk concept generally begin from the commonsense observation that all organisms inhabit a world in which bad things may occur, and often note issues like the distinction between risk and uncertainty (i.e., Real & Caraco 1986: 373, Stephens 1990), ecological analyses tend to operationalize "risk" in a distinctive way. Such analyses deal almost exclusively with two kinds of risks: inadequate food intake and predation (and sometimes with both of these simultaneously-see, for example, Bednekoff & Houston 1994, Bulmer 1994: 112-116, Oksanen & Lunberg 1995). Not surprisingly, studies of predation generally take the magnitude of the hazard at issue-death-as fixed, and examine organisms' reponses to the varying probabilities of encounter with a predator; as we might expect, such studies (i.e., Bouskila 1995, Kennedy et al. 1994, Suhonen 1993) typically find that organisms alter their behavior to avoid contact with predators when predators are present.

In contrast, studies of dietary risk generally proceed by treating food availability as fluctuating, and considering the ways in which organisms' foraging decisions vary in response to these fluctuations; increases in the magnitude of resource fluctuations are seen as increases in risk. In general, theoretical analyses of "risk-sensitive foraging" suggest that an organism should act in ways that reduce the variance in foraging yields when resources are abundant relative to that organism's needs (that is, they should be "risk-averse") and should act in ways that increase variance when resources are scarce (that is, they should be "risk-prone"), and a number of studies have confirmed these predictions empirically (Bird, Chapter 16; Bulmer 1994: 111-112, Caraco et al. 1980, 1990; McNamara & Houston 1992, Real & Caraco 1986, Stephens & Charnov 1982). Alternatively, Stephens (1990) points out a second kind of variance that can be referred to as risk, variance in the degree to which return is delayed, and notes that experiments show that animals often select more variable over less variable delays. A few analyses (Caraco & Chasin 1984, Houston & McNamara 1986) have also examined the effects of the direction of skewing in the distribution of resource fluctuations. These studies complicate this issue somewhat, suggesting that positively skewed distributions should be favored when nutritional reserves are either low or high, while negatively skewed distributions should be favored in intermediate situations.

We discuss the difference between ecological usage of "risk" and the usage of this term in other fields below, in the context of a summary of anthropological usage of the term. However, it is worth noting that at least some of the analyses that simultaneously consider predation and dietary risks (see Bulmer's [1994: 112-116] discussion for an example) move quite close to the emphasis on both probabilities and costs in fields like insurance and hazards assessment

Risk in Anthropology and Archaeology

Both anthropology and archaeology have recognized the importance of addressing the role that risk plays in structuring human ways of life, although virtually all discussions of risk in our discipline have focused on subsistence risk (the risk of failing to obtain sufficient amounts of food) to the exclusion of other risks that humans may encounter (war, disease, accidents, etc.). In some cases (Gould 1991, Halstead & O'Shea 1989, Jochim 1981, Minnis 1996), anthropologists and archaeologists have used terms like "risk" and "uncertainty" without defining them, relying on our common intuitive understanding of these terms; in others, the substance of the risk concept–the possibility of encountering problems–enters into analyses under a different label (i.e., "predictability" or "reliability"; Bamforth 1988, Heffley 1981, Hayden 1981, Lee 1968, Tanaka 1976, Wilmsen 1973). However, other writers have variously drawn explicitly from usage in the literature in insurance/economics and evolutionary ecology.

Not surprisingly, definitions of risk in economic anthropology (Calavan 1984, Cancian 1980, Cashdan 1985; Weissner 1982a, 1982b; Wharton 1971) follow those in economics and business, emphasizing "risk" as the probability of loss (generally the loss of subsistence resources, particularly agricultural produce, due to environmental or other factors). In contrast, anthropological work grounded in evolutionary ecology often shows important definitional ambiguities. For example, Keene (1981: 179) defines risk as the probability of loss, but then uses the term in contexts that clearly emphasize only loss probabilities, with no attention to loss magnitudes (i.e., Keene 1981: 179, 180). Similarly, Winterhalder (1981: 94) refers to "species with low short-term risk of capture failure" and Smith (1981: 46) distinguishes between "low-risk, low-return resources . . . [and] relatively high-risk (erratic) resource types", clearly equating risk with loss probabilities in both cases; more recently, Baksh and Johnson (1990: 195) make the same equation in referring to estimates of the "risk" of rocket failure in the NASA space shuttle program during the 1980's that ranged from "1 in 100,000" to "1 in 70". Tainter (1996: 15) also seems to see risk primarily in terms of probabilities, distinguishing between "stress" ("the consequences that arise when the energy needs of a human population are not met") and "risk" ("the likelihood that energy needs will not be met), and Rautman (1996: 200) follows this usage in asserting that "Regional social networks extending beyond the local group reduce the risk of resource stress"; "stress" in this sense is essentially the same as the "loss" component of the economic definition of risk. However, many recent analyses draw explicitly on the specific approach taken by theoretical ecologists, and formal examinations increasingly equate risk explicitly with variance in resource availability (Bettinger 1991: 118-127, Hegmon 1996, Kelly 1995, Kohler & Van West 1996, Smith 1988; Winterhalder 1986a, 1986b; also see most of the authors in Cashdan 1990b). In one particularly clear example of this usage, Larson et al. (1996) measure subsistence risk in the precontact Southwest by examining temporal patterns in year to year variability in rainfall reconstructed from tree rings; however, these authors supplement this measure by also focusing specifically on years in which rainfall was below-average.

All of these studies address the means that humans have devised to prevent, or at least minimize, shortfalls in the food supply, and a common (although not universal) conclusion is that resource sharing within communities, and variability in the degree to which such sharing occurs, is related to the level and geographic homogeneity of subsistence risk in the environment; the emphasis on fairly abundant and spatially predictable plant foods among many hunter-gatherer groups is also regularly attributed to attempts to reduce subsistence risk (although this is often referred to as increasing subsistence reliability). Furthermore, the classic arguments that many hunter-gatherer groups maintain long-distance social ties in order to have access to distant resources during times of scarcity (i.e., Burch & Correll 1972, Gould 1991, Lee 1976, Smith & Boyd 1990), although not generally explicitly grounded in the literature on risk, clearly link important components of social relations to unpredictable subsistence problems. Archaeologists have also recognized the importance of unpredictable problems as factors structuring human adaptations (although they have not always used the word "risk" to describe these), but have tended to emphasize larger-scale, more archaeologically visible adaptations: for example, Smith (1995; also see Flannery 1986) attributes the rise of food production to hunter-gatherers' attempts to get through lean years, and a number of authors (Nicholson 1988; Rautman 1993, 1996; Spielmann 1991) emphasize interregional exchange as a means of evening out resource shortfalls over large areas .

Risk and Lithic Technology

As this discussion illustrates, and as Torrence (1989: 59) and Bousman (1993: 69) point out, anthropological discussions have tended to focus on social rather than technological responses to risk (such as sharing or exchange), although at least some authors (Cashdan 1985, Weissner 1982) have considered the conditions under which storage may help to reduce subsistence risk. However, there are excellent and obvious reasons for arguing that considerations of risk should be important in making technological choices. As Torrence notes (1989: 58-59), human beings use technology to manipulate the environment in such a way that they satisfy their needs. Because the environment varies in time and space and because this variation is only partially predictable, it is always possible that something may go wrong and either complicate or prevent human actions. Specific problems that do not create major difficulties do not necessarily require adaptive responses, but more significant problems do. That is, most human activities have some probability of failing and in many cases such a failure can have high costs, which is one way to say that some level of risk is built in to most human enterprises. Where risk is unacceptably high, it can be reduced either by lowering costs or by reducing failure probabilities, and, as we argue below, archaeologists seem generally to agree that that technology plays an important role in such reductions, particularly in the latter area.

However, relatively few archaeologists have specifically discussed the relation between risk (or "reliability"; Hayden 1981) and technology, including flaked stone technology. All of the studies that explicitly link risk and technology refer to Torrence's (1989) discussion, making her work an important starting point (note that we focus here on Torrence's definition of risk; we discuss her specific arguments regarding risk and technology in a later section). Torrence explicitly recognizes the importance of both failure probabilities and failure costs, defining risk in the context of subsistence activities as "the probability of failing to meet dietary requirements". She then argues from this definition that risk in this sense is not simply determined by the probability of failing to capture an animal, but by the cost of such a failure, and makes the essential point that this cost depends on the availability of alternative sources of food. However, although she stresses failure costs in portions of her discussion (i.e., Torrence 1989: 63), her cross-cultural analysis (see below) treats risk almost entirely as the probability of failure, as is indicated, for example, in assertions that "people do not attempt to minimize the expenditure of time for its own sake, but because the length of time a resource is available is an important measure of the probability of failing to capture it, i.e., of the degree of risk involved" and that tools used to procure aquatic resources are complex (have many parts) because of "the higher probability of loss for a resource captured in the water as opposed to on land" with no reference to the cost of such a loss (Torrence 1989: 60, 61).

Similarly mixed use of the term, as well as the equation of "risk" levels with estimates of probabilities, is evident in other studies of risk and technology. For example, Myers (1989) does not explicitly define risk, but he clearly uses it primarily with a similar emphasis on probabilities: for example, he argues that "the mobility of animals introduces risk through the capacity of the resource to avoid detection and capture. By the same token, plants are incapable of significant motion and cannot avoid capture once detected" (Myers 1989: 84). Myers focuses on a shift from Early to later British Mesolithic weapon technology from relatively simple, unstandardized stone projectile points and regular use of bone and antler points to complex, highly standardized stone barbs with almost no use of antler and bone points, explaining this as a response to a shift from an environment in which game animals migrated in large herds regularly between predictable locations to one in which these animals moved erratically in small groups. In this view, Myers sees the technological changes as enhancing weapon function, ease of repair, and accuracy, all of which became more important given the increased difficulty of locating mobile prey and thus the increased importance of ensuring a successful kill when such prey was sighted.

Similarly, Nelson (1996) cites an early version of the present paper in distinguishing between the probability of loss and the cost of that loss, and argues for important differences in technological strategies resulting from efforts to reduce subsistence risk by specializing on a small set of resources (which she argues should result in reliable [in Bleed's [1986] terms; see below], efficient, and specialized tools that require high investments of production time) and strategies resulting from efforts to reduce such risk by diversifying resources (which she argues should result in reliable, versatile, and portable tools that require low investments of production time). However, she follows Torrence in shifting from a recognition of the importance of both probabilities and costs to a primary focus on probabilities in assertions like "specialization and diversification are economic decisions intended to ameliorate stress or reduce the risk and cost of shortfall", that "the risk in production of cultigens is less than the risk in hunting", or that "while people engaged in hunting a wide variety of game during some time periods, this practice may not have been effective as a risk-reducing strategy in times of food shortage or anticipated risk of shortages" (Nelson 1996: 111, 134).

In contrast to these, Bousman (1993) explicitly refers to both the insurance/economic and ecological uses of the term as part of a more general discussion of hunter-gatherer mobility and technological change: "Risk is defined as the probability of economic loss, and perhaps it is best conceived in terms of unpredictable environmental variations that influence getting enough food to support a given population" (Bousman 1993: 64). However, his use of the term in reference to technological choices follows Weissner (1982a) and clearly adheres to the probability of loss definition: he argues that technology reduces risk primarily by preventing loss, and that increased variability in access to food should result in (1) increased discard of worn but still-usable tools, to reduce the chances that worn tools will fail in use, and (2) more intensive repair/maintenance of tools, for the same reason. Bousman's usage of "risk" then, links technology fairly specifically to attempts to control the "probability" component of the "probability of loss" definition.

Hiscock (1994: 276) makes this link somewhat more explicitly, equating risk with "a low probability of foraging success" which he notes can "incur large energy costs on any group but, in some instances, may endanger individuals or groups". Focusing on the mid-Holocene appearance in Australia of "highly retouched, finely shaped implements" (Hiscock 1994: 277), he argues that the technological patterns he discusses develop during times of rapid environmental change and when humans were in the process of colonizing new territory (see also Webb & Rindos, Chapter 13). Under these circumstances, Hiscock follows Kelly (1988; also see Parry & Kelly 1988) in arguing that humans know less about specific resource distributions than when conditions are stable or when they have a long acquaintance with a region, and therefore find it difficult to predict when and where they will move. In such a context, designing tools for easy transport, multiple uses, and relatively long use lives should help to minimize the possibility of running out of tools with no replacements available.

The probabilities that these authors implicitly or explicitly emphasize refer to the chances that tools either will not be available or will fail to perform as needed, resulting in failure of the activity in which they are used. We will refer to these as "failure probabilities". Despite a lack of overt references to "risk" in the great majority of the literature on flaked stone technology, a close analysis of most of the arguments that archaeologists have made in this literature indicates that they rely ultimately on some consideration of failure probabilities and thus, however incompletely or implicitly, on considerations of risk.

For example, maintaining access to raw material (Bamforth 1986) is essential to any viable technological strategy in order to ensure that it is possible to manufacture replacement tools, without which activities requiring those tools may fail. Similarly, Bleed (1986) discusses two aspects of tool design: maintainability, or the degree to which a design emphasizes features that make it easy and quick to return a broken tool to useful condition, and reliability, or the degree to which a design ensures that a tool will operate effectively under a range of conditions. As Bleed's discussion makes clear, emphasizing one or the other of these alternative (although not mutually exclusive) strategies amounts to selecting a way to ensure that useful tools will be available when they are needed, which is to say that these are different ways of reducing the probability of technological failure. Hayden (1981) argues along very similar lines to Nelson (1996), referring to "resource reliability" rather than risk; in particular, he predicts that specialization on a few highly productive resources to increase reliability should be accompanied by complex and specialized tools, while strategies that increase reliability by diversifying the diet should be accompanied by "complex and diversified" tools, although he sees somewhat different links between subsistence patterns and technology than Nelson (Hayden 1981: 526). Jeske (1989: 35) also links the complexity and diversity of tools used to procure food to the need to reduce "activity failure rates" (in our terms, failure probabilities), and, like Nelson (1996) and Myers (1989), points out that mobile resources (particularly aquatic resources) are likely to have substantially higher failure rates than immobile resources like plants.

In fact, the logic of virtually all of the theoretical literature on flaked stone technology (see Nelson [1991] for a useful review) rests on the assumption that the central problem that technological strategies have to solve is that of ensuring that the tools on which humans rely are available and in useful condition when they are needed, and links variability in these strategies to variability in the conditions under which different human groups live and have lived (Jochim 1981, Nelson 1991). There is, in effect, essentially universal implicit agreement among archaeologists that technology reduces risk (in Wiessner's [1982a] terms) by preventing loss, or at least reducing the probability that loss will occur (Bousman 1993: 68-69, Jochim 1981: 114, Torrence 1989: 64), implying that the risk concept may offer the basis for building a useful synthetic conceptual framework for work in this area. We therefore turn to discuss some of the implications of the varying definitions of risk we have outlined here, as a basis for assessing how risk might be useful in the study of technology.

Why Definitions Matter

It is clear that incorporating risk into anthropological and archaeological analyses has expanded our understanding of the determinants of human adaptations in important ways. However, varying definitions of risk in general and inconsistent use of chosen definitions limit the possibility of building on existing work and complicate synthesis. As we have noted, technological studies have rarely appealed to the "risk-as-variance" perspective, making the basic distinction in the non-archaeological literature between this view and the "risk-as-probability-of-loss" view less of a problem here, but it is still important to consider the differences between them.

Smith (1988: 231) refers to the risk-as-variance definition as "technical", and argues that it subsumes the "colloquial" probability of loss definition. We disagree. Using a measure of variance to define risk is certainly mathematically convenient, and thus may be technical (but see Larson et al. [1996] for an equally rigorous, and equally "technical", measure of risk based on frequencies of drought years in the pre-Contact American Southwest), and it does subsume losses, at least in the sense that the mathematical variance of a distribution encompasses both positive and negative deviations from the mean. Nevertheless, equating risk with variance includes within the operationalized definition of the term both unpredictable shortfalls and unpredictable windfalls, and few people would view the latter as contributing to risk under most circumstances. The "surprising" (Cashdan 1990, Stephens 1990) conclusion that organisms should be "risk-prone" under certain conditions derives from this, and this conclusion is much less surprising from the probability-of-loss view: "risk-prone" behavior is sometimes adaptive because, when expected returns are below the levels required for survival, seeking out variable returns introduces the possibility of obtaining unpredictable windfalls, thereby reducing the probability of suffering a loss. We might therefore clarify important issues somewhat by accepting the "probability of loss" definition and referring to "variance-prone" and "variance-averse", rather than "risk-prone" and "risk-averse", foragers.

Regardless, the work that is most important here clearly is most compatible with risk conceived as probability of loss. However, reliance on this definition requires explicit attention to its two distinct components: the probability that a loss will occur and the magnitude (or cost) of that loss are fundamentally different things, and risk in this sense results from the interaction between them. Rescher (1983) discusses this interaction at length, but it can be clarified by a simple example: the probability of falling from a tightrope is much the same whether the rope is one foot or 100 feet above the ground, but the cost of falling, and thus the risk entailed by walking the tightrope, is much higher in the latter case than in the former. Analysing risk and its relation to technological decision-making thus requires attention to both costs and the probabilities of bearing these costs and, although Torrence (1989) has made this point, archaeologists have yet to integrate it into our analyses. This is particularly important because, as Torrence (1989) points out, events with similar probabilities of occurrence may results in very different costs in different situations, and may therefore select for very different technological responses.

Focusing on definitional issues therefore highlights two particularly important points. First, it seems clear that at least one important component of risk, the probability of failure, is central to most current approaches to the study of flaked stone technology. Second, though, it is also clear that archaeologists have rarely explicitly attended to the importance of the second component of risk, the costs of such failure. Following Torrence (1989), we will therefore argue for the remainder of this paper that explicitly attending to failure costs as well as to failure probabilities will greatly help to expand our current understanding of technological variability. In addition, we will also argue, (1) that a second kind of costs, the costs of making particular technological choices (which we will refer to as "technological costs"), must also be built into our discussions (also see Bleed 1986), and (2) that it is necessary to assess failure costs, failure probabilities, and technological costs not only in the domain of application but throughout the continuum of tool production and use defined above.

RISK, COST, AND TECHNOLOGY: A CONCEPTUAL FRAMEWORK

> Only the pathologically risk-averse make choices based on the consequences without regard to the probability involved . . . only the foolhardy make choices based only on the probability of an outcome without regard to its consequences (Bernstein 1996: 100).

At the most basic level, common sense obviously suggests that high failure costs ought to select for technological responses to reduce failure probabilities: if an event would have truly awful results, it is to our benefit to ensure that it does not occur, and designing technology to this end is one effective way to do this. Again, this is, in effect, the logic most archaeologists have followed in discussing technology, but it is important to note that this assertion also implies that low-cost failures do not have this selective force and that, as Torrence (1989) notes, the same activity may have different associated costs when it is carried out under different circumstances. In this view, Jeske (1989), Myers (1989), and Nelson (1996) are incorrect in arguing that hunting unpredictably mobile animals is necessarily riskier than gathering immobile plants or relying on cultivated plants: hunting is likely to be more failure-prone than gathering and, in at least some circumstances, than cultivation, but the cost of hunting failure, and thus the risk of hunting, depends not on the chances of killing an animal but on the likelihood that failing to kill an animal will cause the hunter to starve (although, as Christenson [1982: 422] points out, hunting is often riskier than plant-gathering or farming in the sense that wounded or threatened animals may injure or kill the hunter). If there are abundant alternative resources available, this cost is low; if there are no alternatives, this cost is high (Torrence 1989: 64).

To generalize beyond the domain of tools used to obtain food, the degree to which it is important for technology to reduce failure probabilities should vary with the costs of those failures. However, humans live in a world with limited time and resources, and we therefore have a limited ability to "invest" in technology. Making tools takes time and energy in procurement and production, and choosing to spend large amounts of time or energy producing tools, organizing labor, etc., makes it impossible to spend that time or energy doing something else-there are "opportunity costs" (Rescher 1983, Winterhalder 1987) entailed by investing in technological solutions to problems. Furthermore, much of the recent attention to risk management in environmental hazards work (i.e., Jones-Lee 1989, Rescher 1983, Sewall 1990, Westman 1985) has observed that greater reductions in the probability of encountering such hazards often require greater investments of resources, and that, while it may be technologically feasible to reduce such probabilities to zero, it is often not economically feasible. We should thus expect humans to vary in the degree to which they can afford to bear technological costs, and situations may exist that preclude a reliance on high-cost technology even when such technology would reduce the probability of high-cost failures.

In brief, then, technological strategies should be linked to risk by their ability to reduce failure probabilities in the face of high failure costs, but a group's ability to bear the costs of relying on such strategies is likely to limit potential technological options. Arguments that search for a balance between costs and benefits, as ours obviously does, follow the logic of optimization reasoning. A number of recent authors (i.e., Bettinger 1991, Bousman 1993, Kelly 1995, Nelson 1996, Torrence 1989, Winterhalder 1987) have discussed this logic at some length, and it is unnecessary to reiterate these discussions here. However, it is important to make one point in this context. Optimization models rely on idealized views of likely adaptive responses to limited sets of variables, and all optimization reasoning incorporates the unspoken caution that optimal predictions refer to a situation in which the behavior being studied is not influenced by any important factors that are not included in the optimization model at issue. The great value of optimization models is their ability to clarify our thoughts and direct our attention to specific aspects of the world; they offer a clear baseline against which to assess the world, which is almost never completely consistent in detail with those models. As Winterhalder (1987: 313, 315) notes, "optimal foraging models are valuable. . .not as lawful statements about reality but as structured forms of inquiry, more interesting to stalk than to live by. . . We seek, then, models that are good to think".

Cultural anthropologists, faced with the spectacular complexity of day to day human activities, are generally very clear that optimization predictions are guides to help us investigate the real world, and focus explicitly on both the fit between models and reality and the likely factors that produce differences between models and reality. However, archaeologists are often not clear in this sense, and sometimes treat untested optimization predictions as facts; such predictions are sometimes then taken as rules that allow us to interpret patterns in archaeological data as evidence for specific kinds of adaptive responses. This is a mistake: theoretical arguments like those presented here, no matter how plausible, require empirical support. Furthermore, it is extremely difficult to test such arguments adequately against purely archaeological data. Most tests of optimization predictions, even those that ultimately focus on archaeological situations, therefore examine those predictions in an ethnographic context (i.e., Bamforth 1988; Bird, Chapter 16; Jochim 1976). We follow this procedure by examining cross-cultural data on recent hunter-gatherer technology in light of our discussion so far. However, some archaeological data are easier to deal with than others, and we also provide a case study of technological change that relies on reasonably clear archaeological data before turning to deal specifically with flaked stone technology.

RISK AND TECHNICAL OPTIONS: CROSS-CULTURAL AND ARCHAEOLOGICAL DATA

As have a number of other studies of technology (Bousman 1993, Shott 1986; Torrence 1983, 1989), we turn to a set of data on hunter-gatherer subsistence technology compiled by Oswalt (1976) to illustrate the general relations we have proposed between risk and technology; our additional analysis here builds primarily on Torrence's work. These data, which include information on the number of tools used to acquire food (technological diversity) and number of parts in each of these tools (technological complexity) for a series of hunter-gatherer groups, provide at least some basis for examining the relations we have suggested above and thus documenting empirically that there is indeed an interesting relation between technology and risk. Our analysis has three parts. First, we consider Torrence's specific use of these data to examine the link between technology and risk and show that sampling problems in the data make this link at once both more complex and somewhat more problematic than she asserts; particularly, her arguments depend on equating risk with failure probabilities, and this is incorrect. Second, we show that considering the "cost" component of risk helps to eliminate some of these problems and, third, we argue that that integrating information on technological costs helps to eliminate them as well.

Table 7.1 Technological and Dietary Data on 20 Hunter-Gatherer Groups (from Torrence [1983, Table 3.1] and Murdock [1967]).

In columns 2 through 6, the first number refers to the total number of tools in the category and the second refers to the total number of parts that make up those tools; the average number of parts per tool can be obtained by dividing the second number by the first.

Group	lat.	instr.		weap.		tended facil.		untended facil.		total		% aqu. res.
Tiw	12	3	6	6	6	2	2	0	0	11	14	10
Andamanese	12	4	8	4	31	3	12	0	0	11	51	40
Ingura	14	3	3	6	19	3	8	1	2	13	32	20
Chenchu	16	7	13	7	26	6	16	0	0	20	55	5
Naron	19	2	5	5	19	3	3	2	11	12	40	0
Aranda	24	4	7	4	21	7	10	1	4	16	42	0
Owens Valley Paiute	37	4	9	9	44	10	30	5	24	28	107	10
Surprise Valley Paiute	42	7	15	9	27	19	41	4	14	39	97	30
Tasmanians	42	3	3	3	3	4	8	1	1	11	15	20
Klamath	43	9	18	7	35	22	70	5	28	43	151	50
Twana	48	4	7	12	70	19	96	13	64	48	237	60
Tlingit	58	4	7	8	25	8	34	8	55	28	121	60
Tanaina	60	7	13	16	83	3	17	14	111	40	224	50
Ingalik	62	6	14	13	64	15	61	21	157	55	296	50
Nabesna	63	1	1	8	36	8	23	8	45	25	105	20
Caribou	63	3	12	10	39	13	37	8	30	34	118	40
Angmaksalik	66	4	18	18	151	9	20	2	13	33	202	80
Iglulik	69	3	8	20	142	8	27	11	48	42	225	50
Copper	70	4	16	8	53	11	36	4	17	27	122	60
Tareumiut	71	1	3	18	133	10	41	6	28	35	205	70

Latitude, Diet, and Technology

Torrence (1983) initially showed that several characteristics of the individual tools and assemblages of tools used by hunter/gatherers to procure subsistence resources vary on a global scale with latitude. Following Oswalt (1976), Torrence recognizes four distinct classes of tools: instruments (used mainly to procure immobile resources, particularly plants), weapons (used to procure mobile resources, including aquatic and terrestrial resources), tended facilities (such as fish weirs or hunting blinds, that are used to take animals but that function only when humans are present), and untended facilities (such as dead-fall traps, that take animals whether humans or present or not).

Torrence finds several important world-wide patterns in her data. First, instruments dominate the tool kits of low-latitude groups, being replaced, first, by weapons and then, successively, by tended facilities and untended facilities as latitude increases. Second, both the total number of tools used by a group (technological diversity) and the number of component parts per tool (technological complexity) increase with latitude (Pearson's r between latitude and diversity is 0.69 [df = 18, .001 > p] and between latitude and complexity is 0.75 [df = 18, .001 > p]). In addition, untended facilities tend to be the most complex class of tools, followed by tended facilities, weapons, and implements. Finally, tools used to procure aquatic resources are more complex than tools used on land. In a later publication, Torrence (1989) explains these patterns by arguing that, for hunter/gatherers, subsistence risk increases with latitude, and that the trends she identifies are adaptations to this increase.

In this view, risk increases with latitude because increasing seasonality reduces the period of the year during which resources are available, because potential resources tend to be fewer and less abundant towards the poles, and because high latitude hunter/gatherer groups tend to rely on mobile (animal) resources whose ability to escape potential predators makes them inherently riskier resources than immobile resources such as plants. Under these conditions, Torrence argues that it is optimal to use tools that are carefully designed to acquire specific resources and that therefore reduce the probability that an attempt to obtain a resource will fail. As risk increases, this should lead to a reliance on a diverse set of specialized tools, each of which is intended for a specific purpose and is therefore poorly designed for other purposes. Similarly, she argues that complex tools, or tools with many parts, increase the speed with which tasks can be accomplished and, possibly, the ease with which broken tools can be repaired; such tools should also be used in riskier contexts. Finally, the complexity of tools used to procure aquatic resources reflects the risk inherent in a reliance on such resources: fish and sea mammals are more difficult to attack than terrestrial fauna, and cannot be tracked as a wounded land mammal can be; fishing tackle and other gear used to take aquatic resources are often specialized (i.e, are useful for a limited range of tasks) and complex (i.e., have many parts) because retrieval mechanisms are built into them (Torrence 1983: 20-21). Thus, the global trends in Oswalt's data can be explained as technological means of reducing risk.

These data seem to provide relatively strong support for the argument that risk strongly conditions technology. However, Torrence's analysis nowhere explicitly considers the cost of technological failure for the societies in her sample, and this is a problem because of a serious sampling bias in Oswalt's data: these data include a highly selected, non-random sample of hunter/gatherer societies (Eskimo groups, for example, are dramatically overrepresented relative to other groups), and there is a serious bias in them when they are considered in terms of latitude. This bias derives from the relationship in the sample between dependence on aquatic resources and latitude: virtually all of the high latitude groups in Torrence's sample rely heavily on aquatic resources, and there are very strong correlations between the percent of such resources in the diets of the groups in her sample (Table 7.1, data from Murdock 1967) and technological diversity ($r=0.61$) and complexity ($r=0.76$; also see Bousman 1993: 73). As might be expected, there is also a very strong correlation between latitude and the percent of aquatic resources in the diet ($r=0.72$).

This is very important, because Torrence explicitly distinguishes betwen risk resulting from increasing seasonality at high latitudes and failure probabilities inherent in the pursuit of aquatic resources. As just noted, Torrence follows Oswalt (1976) in noting the relationship between dependence on aquatic resources and complex tools, and this fact is essential to interpreting the patterning in these data. That is, it is possible to argue that tools in Oswalt's data set that are used to take aquatic resources are complex not because they are used under riskier conditions but because capturing fish and sea mammals requires complex tools. Because the available data confound dependence on aquatic resources and the many aspects of environmental variation measured by latitude, Torrence's analyses do not allow us to to determine whether differences in technological diversity and complexity reflect differences in risk due to (1) such global factors as seasonality, (2) the requirements of the specific tasks that the tools at issue were designed to accomplish, or (3) some combination of the two.

This problem can be addressed quantitatively by computing the first-order partial correlations between latitude, percent of aquatic resources in the diet, and the two technological variables. First-order partial correlations measure the degree of relationship between two variables when the effects of a third variable have been removed; statistically, they represent the correlation between the residuals of these two variables when each has been regressed against the third. They therefore make it possible to identify spurious correlations resulting when two variables are related not because one determines the other but because they are both determined by some third variable, and they thus make it possible to control for the bias in the dataset and distinguish between the effects on technology of reliance on aquatic resources and of seasonality, at least as it is monitored by latitude.

Table 7.2 summarizes the results of this analysis both for the measures of overall toolkit diversity and complexity and for each of the four specific classes of tool defined above. Torrence measures complexity as the total number of parts in the overall set of tools used by a society, a measure that clearly increases as toolkit diversity increases whether the tools being used have many parts or not; the average number of parts per tool measures complexity more directly than total number of parts, and we use this measure for the remainder of this section.

Blalock (1960: 337-343) discusses the interpretation of partial correlations in some detail. Following his discussion, the results in Table 7.2 reduce to five patterns of interaction. First (and simplest), the diversity of instruments is uncorrelated with both latitude and depen-

Table 7.2 Simple and First Order Partial Correlations Between Latitude, Percent Dependence on Aquatic Resources, and Technological Diversity and Complexity.

Variable	1	2	3	4
All Tools				
diversity	0.69	0.60	0.47	0.19
complexity	0.67	0.76	0.28	0.53
Instruments				
diversity	-0.09	0.03	-0.17	0.15
complexity	0.48	0.52	0.18	0.28
Weapons				
diversity	0.72	0.68	0.45	0.33
complexity	0.42	0.59	-0.01	0.46
Tended Facilities				
diversity	0.41	0.35	0.24	0.09
complexity	0.48	0.62	0.07	0.45
Untended Facilities				
diversity	0.63	0.45	0.49	-0.01
complexity	0.41	0.43	0.14	0.19

1 simple correlation with latitude
2 simple correlation with percent dependence on aquatic resources
3 first-order partial correlation with latitude, controlling for percent dependence on aquatic resources
4 first-order partial correlation with percent dependence on aquatic resources, controlling for latitude

dence on aquatic resources whether we compute simple or partial correlations. Second, in three cases (overall complexity and the complexity of weapons and of tended facilities), partialling greatly reduces the correlation between latitude and technology but leaves a substantial correlation between dependence on aquatic resources and technology, indicating that latitude is essentially irrelevant in these cases once diet is taken into account. In three cases (overall diversity and the diversity of tended and untended facilities), the situation is reversed, with latitude important and diet irrelevant.

The remainder of the results (the complexity of instruments and untended facilities and the diversity of weapons) have a more complex interpretation. In these cases, partialling reduces both of the correlations, a pattern that is generally expected when the relationship being examined involves an independent variable affecting a dependent variable through an intervening variable. Controlling the independent variable in this case should reduce the correlation between the intervening and dependent variables (Blalock 1960: 342). In the present case, the reduction in both partial correlations suggests that there is a complex interaction between the many environmental characteristics measured by latitude and the subsistence.patterns measured by percent dependence on aquatic resources, with the effects of each mediated by the other and, probably, by other variables as well. Because of the high correlation between latitude and diet in the available data, it is probably not possible to sort this interaction out using these data.

These results reveal a complex pattern of interactions that varies with the specific category of tool being considered and that suggests a somewhat different set of conclusions than was indicated by Torrence's initial analysis. Overall, these data suggest that increasing latitude seems generally to lead human beings to produce more kinds of tools but not necessarily more complex tools. In contrast, increasing dependence on aquatic resources seems generally to lead human beings to produce more complex tools as well as more different kinds of tools, although there appear to be important but presently uninterpretable interactions between these variables that affect some aspects of both toolkit diversity and complexity.

Integrating Failure Costs

As we note above, latitude monitors many aspects of environmental variation, making it difficult to attribute the increased diversity of tools at higher latitudes to any one of these. However, the seeming absence of a connection between technological complexity and latitude merits a closer evaluation. Taken at face value, this result would seem to refute Torrence's argument regarding the importance of complex technology in reducing risk, and, given the higher technological costs of more complex tools, would also seem to pose problems for our aguments here. However, Torrence's arguments linking both technological diversity and technological complexity to risk treat this concept primarily as probability of failure, and our arguments explicitly require attention to failure costs, which the analysis above does not consider. One important reason for the great dependence of high latitude groups, particularly arctic groups, on aquatic resources is the relative paucity of alternative resources at high latitudes. To demonstrate that the patterns in the available data relate to the risk associated with exploitation of aquatic resources, instead of simply to the mechanical problems of retrieving such resources, it is necessary to consider failure costs. As Torrence points out, in the context of subsistence, the risk entailed by dependence on aquatic resources derives not only from the the practical problems of capturing them but also from the abundance of alternative sources of food. Considering this issue puts the data in Tables 7.1 and 7.2 in a somewhat different light.

The narrow range of resources available to most high-latitude hunter-gatherers provides one key to doing this. This observation suggests that risk increases towards the poles not because of increases in reliance on mobile prey, which increases the probability of procurement failure, but, rather, because of the absence of alternative sources of food, which raises the costs of failure when attacking mobile prey. More diverse toolkits at high latitudes, then, can be seen as attempts to reduce higher failure probabilities because of high costs. In support of this, we can measure dependence on mobile prey as the proportion in the diet made up by hunting and fishing. This measure correlates almost perfectly with latitude ($r = 0.96$), obviously indicating that the abundance of plants in the diet drops directly with latitude (Lee 1968). The simple correlation between the number of weapons in a toolkit and dependence on mobile resources is 0.73, suggesting that reliance on mobile resources requires a diverse set of tools. However, holding latitude constant by computing a partial correlation reduces this value to 0.29, implying that reliance on mobile prey–that is, reliance on resources that are inherently difficult to capture–does not by itself predict technology very accurately. This suggests that it is also necessary to consider the effects of the decreasing availability of alternative foods, and therefore the increasing costs of procurement failure, with increasing latitude.

Oswalt's data do not offer any obvious means of doing this, but we can examine this issue further by considering the complexity of a specific class of weapons and comparing some of these data to information on a group not included in his sample. One means of considering the effects on technology of failure costs is to examine the characteristics of tools used in the same activity when it is reasonable to infer that the costs of that activity differ. Although it is difficult to ensure that activities carried out by different societies are indeed "the same", it is reasonable to infer that they are nearly so in at least some cases. The case that we consider here is hunting sea mammals from a boat in open water. The most complex weapons in Oswalt's sample are harpoons used for this purpose by northern Eskimo groups such as the Iglulik, Tareumiut, and Angmaksalik, that average 20 to 25 parts and range as high as 33 parts (Oswalt 1976: 99-101, 281-294). The complexity of these tools derives in large part from the addition to them of lines, drags, and floats designed to tire a wounded animal and to assist in retrieving it.

Like the Eskimo, the Chumash, a complex maritime hunting and gathering group on the California coast, used harpoons to take sea mammals from boats in open water. However, the Chumash did so under very different conditions than did the Eskimo. The Chumash relied heavily on a very wide range of relatively abundant aquatic resources, including shellfish, and also exploited a wide range of terrestrial foods (Landberg 1965). Given a diverse and productive subsistence base, the cost of losing any one resource, and therefore the risk entailed in attempting to acquire it, must have been lower for the Chumash than for high latitude coastal groups such as the Eskimo. Given weaker selection for success in any one subsistence pursuit, then, the arguments we have made above suggest that Chumash harpoons should be simpler than those used by the Eskimo.

The excellent descriptions of Chumash material culture compiled by Hudson and Blackburn (1982) indicate that, as predicted, Chumash harpoons used in open water are much less complex than those used by the Eskimo, having only seven or eight parts. These descriptions do not suggest, however, that the Chumash relied on a less diverse range of tools than did most high-latitude Eskimo groups, although we have not attempted to quantify this. Similarly, the maximum complexity of any kind of harpoon used by Athapascan groups such as the Ingalik and Tanaina is 11 parts (Oswalt 1976), and these groups inhabited environments that are richer and more diverse in both terrestrial and aquatic resources than those exploited by the Eskimo groups producing more complex tools (although it is difficult to view the Ingalik and Tanaina environments as rich or productive in any absolute sense). Although data on such a small number of societies provide only a partial test of any hypothesis, these examples are clearly consistent with our arguments, suggesting that failure probabilities and failure costs must be considered separately in assessing risk and that technological decisions integrate considerations of both of these.

To briefly summarize, we have made two important points in this section. First, a reanalysis of Oswalt's (1976) data on hunter/gatherer technology provides only partial support for Torrence's (1983, 1989) interpretation of these data. In particular, increasing latitude, which Torrence takes as a proxy measure of increasing subsistence risk due to greater and greater seasonality, seems to relate primarily to toolkit diversity and not to toolkit complexity. Degree of dependence on aquatic resources, which is highly correlated with latitude in Oswalt's data, appears instead to be the major conditioner of technological complexity in this dataset, and also plays an important role in conditioning some aspects of diversity as well. It is therefore not possible to appeal to the correlation between complexity and latitude as evidence supporting the importance to tool design of overall, seasonally-based "risk"; this correlation is largely the spurious result of systematic sampling bias in the available data.

The links between aquatic resources, latitude, and technology might suggest that tool design responds to at least one component of risk, the probability of failure. However, we further pointed out that such a conclusion neglects the other component of risk, failure costs. Focusing on this problem, we were able to show that the available ethnographic data support the importance of failure costs as conditioners of technology. We therefore conclude that Oswalt's data suggest that at least some important aspects of technological design respond to failure costs rather than failure probabilities, as our arguments above predict.

Integrating Technological Costs

However, we noted earlier that a second domain of costs, opportunity costs entailed by choosing to invest in a particular technological strategy, are also likely to be important conditioners of technological behavior: both the full continuum of behavior involved in the production and use of stone tools and the connections between this continuum and other domains of human activity are essential to understanding the overall character of any technological adaptation. Torrence's arguments regarding the data we have just considered deal almost exclusively with the domain of application, and do not consider either procurement or production (as is evident, for example, in such arguments as "when the risk of failure to procure food is high, hunter-gatherers respond by increasing their overall investment in technology and in the diversity of tools" [Torrence 1989: 61]). Our analysis of these data to this point similarly focuses only on the domain of application.

However, an exclusive emphasis on the domain of application requires the assumption that there are no constraints operating in the domains of procurement or production, an assumption that can seriously limit our understanding of the forces that structure technology. Ebert (1992: 35) offers a particularly clear example of such limited understanding, asserting that "Bamforth (1986) argues that it is not the subsistence strategies of a group that determine whether its technology is curated or expedient, asserting that curation is instead a response to raw material shortages. This is tantamount to thinking that someone will not use a pocket knife for cutting if there is a source of steel nearby with which an expedient blade could be fashioned". Unfortunately, the rhetorical panache of this argument masks a failure to grasp some of the most important differences between stone and metal tools, differences that lie particularly in the dramatically higher production costs associated with most metal technology. Many flaked stone tools can be manufactured in an instant, and even the most complex flaked stone tools (for example, fluted points) take a skilled stoneworker no more than an hour to produce; flaked stone tool production also requires very simple tools, most often no more than a hammerstone, an antler billet, and a pressure flaker. It is likely that most stone tool users made most, if not all, of their tools themselves. Manufacturing metal tools, in contrast, virtually always requires substantial investments in production technology, labor specialization, etc., investments that make it effectively impossible for the great majority of metal tool users also to be metal tool producers. Direct comparisons of stone and metal technology that, like Ebert's, fail to take this crucial distinction into account are inevitably misleading (Barton [1991] points out in more detail a range of other important differences between stone and metal tools).

Aspects of Oswalt's data indicate that constraints in the domain of production are extremely important determinants of technology, and considering this issue highlights one specific relationship that is likely to be important in many situations. It is possible to invest substantial amounts of time and/or energy in tool design and construction only when it is possible to take time and/or energy away from other activities without compromising those activities. That is, technological costs as well as failure costs may be high or low. There appear to be two major contexts within which time-intensive (or high cost) technological adaptations are feasible. First, substantial amounts of time may be available to all members of a society when they rely primarily on stored food for some portion of the year, or, at least, when they have some predictable, extended period of "down-time" available. Second, substantial amounts of time may be available to some members of a society if the labor of others is sufficient to generate a surplus of needed goods to support them. Neither of these alternatives is feasible in all circumstances. To illustrate these points, we turn to the technological contrasts evident in Table 1 between the Tanaina and Ingalik, Athapascan groups in western Alaska, and the Caribou Eskimo of the region just west of Hudson's Bay. These groups occupy territories at almost identical latitudes and incorporate similar proportions of aquatic resources in their diets[1], yet the Tanaina and Ingalik show a far more diverse and complex toolkit than do the Caribou Eskimo.

Like any other general technological pattern, this difference probably reflects more than one factor. In part, for example, it is likely that differences in the density and specific character of the aquatic resources on which these groups relied affected the ways in which those resources might be taken. However, it is likely that the much greater diversity and complexity of tools among the Athapascan than the Eskimo groups may also reflect different constraints operating in the domain of production.

Both the Tanaina and the Ingalik lived in permanent settlements and supported themselves on stored food for substantial portions of the year (Osgood 1937, 1940, 1958); these groups thus had substantial and predictable periods of down-time during which tools could be made and repaired. In contrast, the Caribou Eskimo followed a relatively unpredictable pattern of seasonal movement, and hunted year-round; although they laid in winter stores, these often were not enough to support family groups until spring (Birket-Smith 1929). Under these conditions, the opportunity to devote large amounts of time and effort to the manufacture of diverse and complex tools is not available, whether or not it might be useful to have such tools, because this time and effort must be taken away from subsistence pursuits.

A few specific examples highlight this pattern. Oswalt (1976) catalogs only two parts for the single type of fish weir constructed by the Caribou Eskimo, but four to eight parts for two different kinds of weirs among the Ingalik. The Caribou Eskimo also produced a single type of fish trap with six parts for use at weirs, while the Ingalik used four different kinds of traps consisting of eight to 12 parts each (mean = 11.0). In procuring land mammals, the Caribou Eskimo relied on four types of untended facilities (pitfalls and cages) made from two to five parts (mean = 3.5), while the Tanaina used six, and the Ingalik eight, such facilities (in both cases, these are snares and deadfalls) made from five to 12 parts (mean = 9.0).

The significance of this pattern is emphasized further by the likelihood that the costs of failure in any given procurement attempt were notably higher for the Caribou Eskimo than for either the Ingalik or the Tanaina. Periodic starvation was relatively common among this group, making all subsistence resources and all efforts to procure these resources important. In contrast, as noted above, both the Ingalik and the Tanaina exploited relatively more diverse and productive environments. That is, these patterns suggest that the Caribou Eskimo inhabited an environment in which high failure costs gave a selective advantage to more complex and diverse toolkits, but which at the same time limited the ability of a human group to bear the high technological costs entailed by producing such toolkits.

There are, of course, other possible expanations for these patterns. For example, we have argued that the higher and more unpredictable mobility of the Caribou Eskimo made it difficult to devote time to the construction of complex tools, but we might also follow Shott (1986) and argue that the simple act of moving from place to place frequently should impact technology by selecting for tools that are compact and easy to transport. However, it is not likely that this explanation accounts for the patterns we have just noted, because the tools that we examined are not used in mobile subsistence activities: fish weirs, traps used at weirs, and untended facilities like deadfall traps are all designed and constructed for use at specific points on the landscape; indeed, in many places, fish weirs are permanent facilities to which human groups return year after year. Better ethnographic data on very specific aspects of tool production, transport, and use would certainly help to sort factors like this out, but the currently available information supports our arguments here.

This example is particularly important because it emphasizes the importance of technological costs as conditioners of technological choices. We have stressed the central importance of failure costs to technology, and a logic much like the one we have followed in arguing this importance underlies most or all archaeological analyses linking technology to overall adaptive patterns. However, the constraints on production evident among the

Caribou Eskimo highlight the potential problems with this logic. Human beings inhabit a world in which demands on time and other resources vary in time and space. Where such demands are limited, humans can choose from a wide range of technological alternatives; where they are not, high-cost alternatives may be impractical regardless of the pressures that might select for them (cf. Maynard Smith [1978] and Pyke [1984] on analogous limits on optimization models in general). We also emphasize the Caribou Eskimo example because it seems likely that the interaction between advantages in the domain of application and constraints on the domain of production is important in many situations, particularly among highly and unpredictably mobile hunter-gatherers and among horticultural groups who rely on plants or animals that require substantial, year-round labor investments and do not produce large surpluses. Whether this is correct or not, though, the Eskimo example highlights the importance of considering risk in more than one domain of behavior: technological organization is not simply determined by the domain of application (also see Bleed & Bleed 1987: 196).

An Archaeological Case: Ditch and Palisade Defenses

The cross-cultural data just discussed thus fit fairly well with the general relations we have outlined here: important aspects of technology can be seen as attempts to reduce failure probabilities in response to high failure costs, with the ability to bear technological costs limiting possible technological options for doing this. A specific archaeological and historical example also provides support for this argument, and emphasizes as well that technology responds to risks in addition to those resulting from uncertainties in the food supply. This example is the construction of ditch and palisade defenses around settled communities along the Missouri River in North and South Dakota from the 1300's through the 1800's.

Warfare among settled horticultural groups along the Missouri River in North and South Dakota (and between these groups and neighboring hunter-gatherers) during the Post- Contact period is well-documented by both archaeology and ethnohistory, and this warfare often resulted in massacres and destruction of entire towns (Lehmer 1971, Owsley et al. 1977, Thwaites 1906). Furthermore, indisputable archaeological evidence indicates that essentially identical patterns of conflict, which sometimes resulted in massacres of the populations of entire towns, existed in the region well before contact, at least as far back as the early 1300's (Bamforth 1994, Willey 1990).

One of the principal technological means of dealing with the risk entailed by this conflict was the construction of extensive defensive works, including the excavation of ditches up to 10 feet deep and 20 feet across which were backed by continuous wooden palisades; many of these defenses included bastions, presumably to allow defenders to set up a cross-fire when necessary. Although towns were often situated on narrow ridges overlooking the Missouri River and defenses were sometimes constructed only across the neck of these ridges, in many cases they completely encircled entire communities. For example, the Arzberger site (Spaulding 1956) was defended by a continuous bastioned defensive perimeter 1.5 miles long, and bastions in a similar perimeter at the Huff site were apparently strengthened by a secondary row of sharpened posts (Wood 1967). The importance of these defenses is indicated at the Crow Creek site, a town whose inhabitants were massacred early in the 1300's: excavations of the fortifications suggest that the site was overwhelmed when its inhabitants had partially dismantled an existing palisade in the course of building a new one (Kivett & Jensen 1971, Willey 1990).

The Post-Contact period saw particularly intense conflict between the settled farming groups (the Mandan, Hidatsa, and Arikara) and the nomadic Lakota, and the frequency of Lakota attacks on farming towns seems to have increased from the 1700's into the 1800's. In the framework outlined here, this implies that the probability of attack (and therefore, presumably, of suffering the consequences of military defeat) was either constant or increasing during this time. Furthermore, contemporary observers and archaeological data show clearly that the costs of defeat in these conflicts (including annihilation of all of the occupants of a community and destruction of their property) were about as high as they could possibly be. However, technological investment in defensive works declined during the Contact period. The elaborate bastioned defenses just noted predate White contact; bastions essentially disappear during the 1700's, and sites dating to the 1800's were often defended only by a palisade without a supporting ditch. The decreasing sophistication of defensive technology in spite of an increasing probability of attack along the Missouri River almost certainly reflects the other major Post-Contact factor that disrupted Indian ways of life there: depopulation resulting from the introduction of epidemic diseases like smallpox. By the 1800's, many settled communities apparently could not field the labor (that is to say, they could not bear the technological cost) required to build elaborate fortifications, and in some cases fortifications were built for Indian groups by Whites (Lehmer [1971: 131-179] discusses the Post-Contact archaeology of the Missouri River valley in detail).

Construction of ditch and palisade defenses along the Missouri River thus appears to fit well with our arguments here: these defenses clearly represented technological mechanisms for reducing risk by minimizing failure probabilities, but constructing them even in situations where they were strongly selected for apparently depended on the ability to bear substantial technological costs. This example also highlights the important point that subsistence is not the only domain of human activity in which we face risks and that technology can be important in other domains as well.

RISK AND FLAKED STONE TECHNOLOGY

Our goal for the remainder of this paper is to sketch an outline of how risk as we have defined it can be considered in the specific context of flaked stone technology. At the outset of this discussion, it is important to reiterate two points. The first is that the risk entailed by any overall technological adaptation results from interactions among the probabilities and external costs of failure and the technological costs entailed by activities in the domains of procurement, manufacture, and application. Any technological adaptation represents a balance of all of these, with the interaction between the domains of production and application perhaps being particularly important. Second, the technological options available to human beings do not all involve tool design and production: as we noted in the first section of this paper, technology includes knowledge about how to apply tools, and a single toolkit can often be used in many different ways to perform a single activity (also see Schiffer & Skibo 1987). Bamforth (1988) has argued, for example, that variation in the ways in which human beings organized themselves on the Great Plains for communal bison hunts was an adaptive response to the environmental conditions under which those hunts were conducted, but follows Fawcett (1986) in noting that essentially the same kinds of tools appear to have been used in this activity throughout the Plains for at least 10,000 years. Not all technological options, then, involve choices about what kinds of tools to make or how to make them, and archaeology needs to develop analytic means of recognizing such options.

Costs of Failure in Procurement, Production, and Application

It is possible to derive a simple heuristic model of the failure costs to which technology responds by conceiving them as dichotomous variables operating within each of the three domains of technological behavior: failure costs can be high or low in raw material procurement, in tool production, or in tool application, producing a total of eight possible combinations (see Figure 7.1). Reality is obviously more complex than the model depicted in Figure 7.1–costs should ideally be measured on a continuous rather than a dichotomous scale, for example (Winterhalder 1986: 385-386) and Figure 7.1 does not incorporate technological opportunity costs–and we present this illustration only as a tool to help think about the issues we have raised here.

If technology helps to minimize risk, we can predict that high cost situations should select for solutions that minimize the probability of technological failure. Predicting technological responses to low-cost situations, though, is somewhat less straightforward. Durham (1976) has pointed out that, although medium- and high-cost behavior is very likely to be constrained by adaptive considerations, low-cost behavior is not, and may vary considerably for idiosyncratic ideological or other reasons. That is, if technological failure just does not create any substantial problems, we may not be able to predict many aspects of technological choices very accurately. Considered in the framework outlined here, this problem may also arise if failure probabilities are extremely low. Durham further points out that the cost of any behavior depends on the "budget" of the organism(s) engaged in that behavior, and this may vary from society to society or from individual to individual or season to season within a single society: the same pattern of behavior may thus be costly in one context and not in another.

This ambiguity can perhaps be reduced, although not eliminated, by considering the costs of investing in a given technological option. As discussed earlier, when an option's costs are unacceptably high, that option should be avoided whether it would reduce risk or not. This suggests that the circumstances that are most likely to be ambiguous from the perspective of the general conceptual framework we have presented here are those in which some aspect of a particular way of life makes it possible to invest heavily in technology even though such investments are not required to reduce failure probabilities in response to high failure costs: for example, group that spend a substantial portion of the year in one place and live off of food stores that can be acquired easily and reliably with simple tools may be able to produce elaborate tools even though they are not "necessary" in the utilitarian sense we emphasize here. Such production might instead grow out of regional patterns of economic specialization or internal social and political processes. However, as failure costs and probabilities rise, risk should play an increasingly important role in structuring technological choices, within the limits set by a society's ability to bear technological costs.

Bearing in mind these probable limits on the conditions under which risk is likely to be a key determi-

		Procurement Costs			
		high		low	
		Production costs		Production Costs	
		high	low	high	low
Application Costs	high	A proc high prod high appl high	B proc high prod low appl high	C proc low prod high appl high	D proc low prod low appl high
	low	E proc high prod high appl low	F prod high prod low appl low	G proc low prod high appl low	H proc low prod low appl low

Figure 7.1 A heuristic model of failure costs in the domains of procurement, production, and application.

nant of technological strategies, it is useful to consider how failures in flaked stone tool procurement, manufacture, and application inflict costs on human beings. The most obvious cost of failure in procurement derives from the absence of the material needed to produce tools. If suitable stone is not available when needed, scheduled production may be impossible, special trips may be required to procure it, and tools may not be available when they are needed, resulting in failure in some other activity. The degree to which a failure to have stone available is risky, of course, depends on the costs of the activities disrupted and of making special efforts to obtain additional material. This latter problem clearly depends on the abundance and distribution of material within a region relative to the locations of human settlement and on a society's ability to take time from other activities and devote it to procuring raw material. Archaeologists studying hunters and gatherers have often minimized this problem by appealing to Binford's (1979) observation that the Nunamiut Eskimo "embed" lithic procurement in other activities, a habit that is often asserted to eliminate or, at least, minimize procurement costs while simultaneously ensuring access to raw material. However, the modern Nunamiut virtually never actually use the stone that they procure this way: the Nunamiut depend on metal tools and use stone tools, on those rare occasions when they use them at all, as an emergency backup. Whether a stone-dependent group could supply itself without periodically making special efforts to obtain raw material is at least open to question, and Gould (1978) has discussed the substantial efforts that stone tool-dependent Australian groups made to obtain raw material.

If tools fail during production, additional time must be invested in producing more, and, if failure rates are too high, tools may not be available when they are needed. High failure rates also require access to substantial amounts of raw material, often requiring greater efforts in procurement. Reliance on tools that are particularly difficult to make may also require at least part-time support for specialist producers and substantial investments of time in training these individuals. Less directly, time spent manufacturing tools is time that cannot be spent in other activities, and spending substantial amounts of time in tool production may impose severe limits on the other things people can do, as we note above. In addition, under conditions where tools are needed continuously or unpredictably, or where long periods of time cannot be set aside for single purposes, it may be difficult to allocate sufficient time to produce some kinds of tools. Finally, failure in application, which may result from tool breakage, poor tool design, or the lack of the needed tools (as well as from other factors, including deficits in the skill or knowledge of the tool user), can mean that the opportunity to obtain a resource or to carry out some other activity that cannot be scheduled at will is lost, or may require additional investments of time and effort attempting the application again; when failure results in the loss of essential resources like food, human groups may face starvation.

Problems like these arise in different ways and to differing degrees in the varying contexts in which humans need and use technology, and technological solutions to these problems are also affected by the varying opportunities and constraints such contexts offer. Recognizing this, archaeologists have identified a wide array of such solutions which appear to be effective under different conditions of (for example) raw material availability, movement across the landscape, etc. Table 7.3 summarizes many of these strategies (also see Nelson 1991), grouped into those that potentially reduce the probability of failure in each of the three domains of technology we recognize here. These options represent our interpretation of the topics that have been discussed in the archaeological literature, as well as our own assessment of possible courses of behavior. Although we do not claim that Table 7.3 presents every course of action that might possibly reduce the risks associated with a reliance on stone tools, it does present the major options that archaeologists have recognized and have not rejected. Ideally, it would be possible to bring together the selective conditions presented in Figure 7.1 with the technological options summarized in Table 7.3 to derive a series of reasonably specific predictions regarding the ways in which stone tool users should have adapted their behavior. In the real world, though, there are serious difficulties in doing this.

These difficulties result most obviously from the paucity of more than impressionistic data regarding the failure probabilities and technological costs of the options in Table 7.3. Data on failures reflected in the archaeological record are rarely presented in systematic form, in part because there have been few methods for organizing and analyzing such information (Bleed 1991). Furthermore, the implications of failure are hard to estimate because there has been little experimental or ethnoarchaeological investigation of this topic. Certainly, estimating failure costs is not a simple matter. Broken preforms or nearly finished points with series of deep step fractures can be interpreted as production failures, and high frequencies of such items may sometimes allow us to infer high failure costs. However, the concept of production failure in our sense here refers not to failure rates for individual items, but to the inability to produce adequate numbers of tools. Even high rates of preform breakage, then, may not result in high failure probabilities if knappers have enough time and raw material to reach their production goals. Analogous points can be made for the domains of procurement and application.

Table 7.3 Potential technological options for reducing failure probabilities in the domains of procurement, production, and application.

Procurement:
- storage of stone
- strategic caching of stone
- economizing raw material use:
  - designing long use-life tools*
  - designing multi-function tools*
  - tool recycling
  - tool resharpening
- exploit many different raw materials sources
- use of durable stone
- permanent residence near a quarry or cache
- transport of large amounts of stone

Production:
- stockpile/cache partially finished tools
- advance production of tools/production during "down" time
- production at a quarry
- production by specialists
- reliance on technologically simple tools*
- use of easily workable stone
- heat alteration

Application:
- careful design for specific purposes*
- overdesign to prevent breakage*
- design for easy repair*
- transport of extra tools
- tool use by specialists/experts
- cooperative group organization of tool use

* option involving artifact design

In addition, it is essential to recognize the distinction between "tools" as archaeologists use the term and "tools" as actual functioning implements in the past. We reject the common equation drawn between "tools" and "retouched pieces", on the grounds that systematic microwear analyses universally show that unmodified flakes were a central component of every prehistoric technological adaptation known (also see Barton 1991, Gero 1990). In this context, we also note that archaeologists are often not very good at identifying used flakes, a serious problem in any lithic analysis (Young & Bamforth 1990). In addition, the presence of retouch on a piece of flakeable stone in no way guarantees that that piece was actually used to carry out a task.

However, a deeper problem in dealing with failure or technological costs is the equation of the flaked stone objects that archaeologists recover with the tools that prehistoric people used. In the case of unhafted, handheld implements, such an equation is reasonable, but it is not in the case of hafted tools. In general, the stone blade of a hafted tool is the "cheapest" part of that tool; manufacturing the haft often takes much more time than manufacturing the disposable blades that are set into it (Keeley 1982). Although the investment of time and energy represented by the haft is made only once over the useful life of the tool as a whole, using a blade in a haft alters the conditions under which a worn or broken edge can be replaced, because replacing a well-hafted blade takes time and, often, such special facilities and materials as fire, sinew or other material for wrapping, and/or some form of glue. The common association of hearth areas in residential sites with spent stone blades (such as projectile point bases) from hafted tools (Keeley 1982) illustrates this clearly. The notion of "production costs" for hafted tools therefore refers not only to the costs of making the stone portions of those tools, the component of such implements with which archaeologists are most familiar, but also to the the costs of manufacturing hafts and of replacing worn or broken blades in those hafts.

In at least some cases, techniques like "event tree analysis " (Bleed 1991) can be used to reconstruct failure probabilities for at least some categories of stone tools. From such calculations and adequate data on the behavioral contexts within which technological failure occurred, acceptable assessments, perhaps even quantitative assessments, of failure and technological costs for flaked stone technology might be approachable; the final section of this paper presents an attempt to do this. However, consideration of the ideas presented here need not wait for these developments. There are serious limits on our ability to rigorously test the ideas we have presented here against most archaeological data. However, if we take the cross-cultural and archaeological data discussed above as provisional evidence that these ideas are useful, it is possible to consider how they illuminate archaeological cases and guide analysis towards interesting questions; to paraphrase Winterhalder (1987: 313, 315), we can treat these ideas as the basis for a form of "structured inquiry" and see whether or not they are "good to think" in specific archaeological contexts. We thus turn to summarize and compare two examples to show that it is possible for archaeologists to address variables like the probabilities and costs of failure in stone age technologies and to suggest that understanding thse variables illuminates interesting aspects of the ways of life that relied on those technologies.

TWO PATTERNS OF PROJECTILE POINT PRODUCTION

The cases we consider are production of microblades during the Late Paleolithic at the Araya site in Niigata, Japan (Bleed 1996, Sutoh et al 1990) and of fluted points during the Folsom period on the North American Great Plains (Akerman & Fagan 1986, Crabtree 1968, Flenniken 1978, Frison & Bradley 1981, Sollberger 1985, Tunnell 1977, Winfrey 1990). We begin by contrasting rates of production failure in these two technologies and then turn to consider the implications of such failure rates.

As reconstructed in several studies (Kobayashi 1970, Yoshizaki 1959), production of microblades in Japan and elsewhere (Andrefsky 1987, Morlan 1970) entailed a number of routinized steps, carried out in precise sequence, with great skill. Based on artifacts found in their hafts in Siberian sites (Kajiwara 1989), it is inferred that microblades were used as replaceable barbs and edges of hunting projectile points. It is also assumed that the small blades were important to their makers, because they are very common in the sites that yield them. However, beyond that, little is known about the operation of the cultures that made the microblades.

To address failure and cost rates in the Araya microblade technology, this example uses "event tree analysis," an operations research technique developed by engineers to model the operation of technical systems (Bleed 1991, 1996; Winfrey 1990). Event trees describe activities in terms of "events," or steps that contribute to completion of the system, making it easy for them to accommodate failed and rejected production residues which are, of course, direct and accurate reflections of the failures associated with a technology.

Essentially all of the flaked tools at Araya were made from a fine-grained hard shale that was brought to the site in the form of bifaces that were used both as cores and as chopping tools. Bifaces were also the starting point for production of microblade cores. Six distinct events were involved in this process. As shown in a graphic model (Figure 7.2), each event is reflected by distinctive residues that can be considered here in two ways. First, they can be counted to calculate the total number of cores that were worked at the site. Secondly, since failed residues are direct reflections of production failures, they can be used to determine failure rates for individual events and for the sequence of events as a whole (Bleed [1996] discusses these data in detail).

Taking refitted pieces into account, archaeological evidence thus indicates that 37 separate cores were made or modified at the Araya site. If we consider the failed pieces shown on the event tree to be concrete evidence of

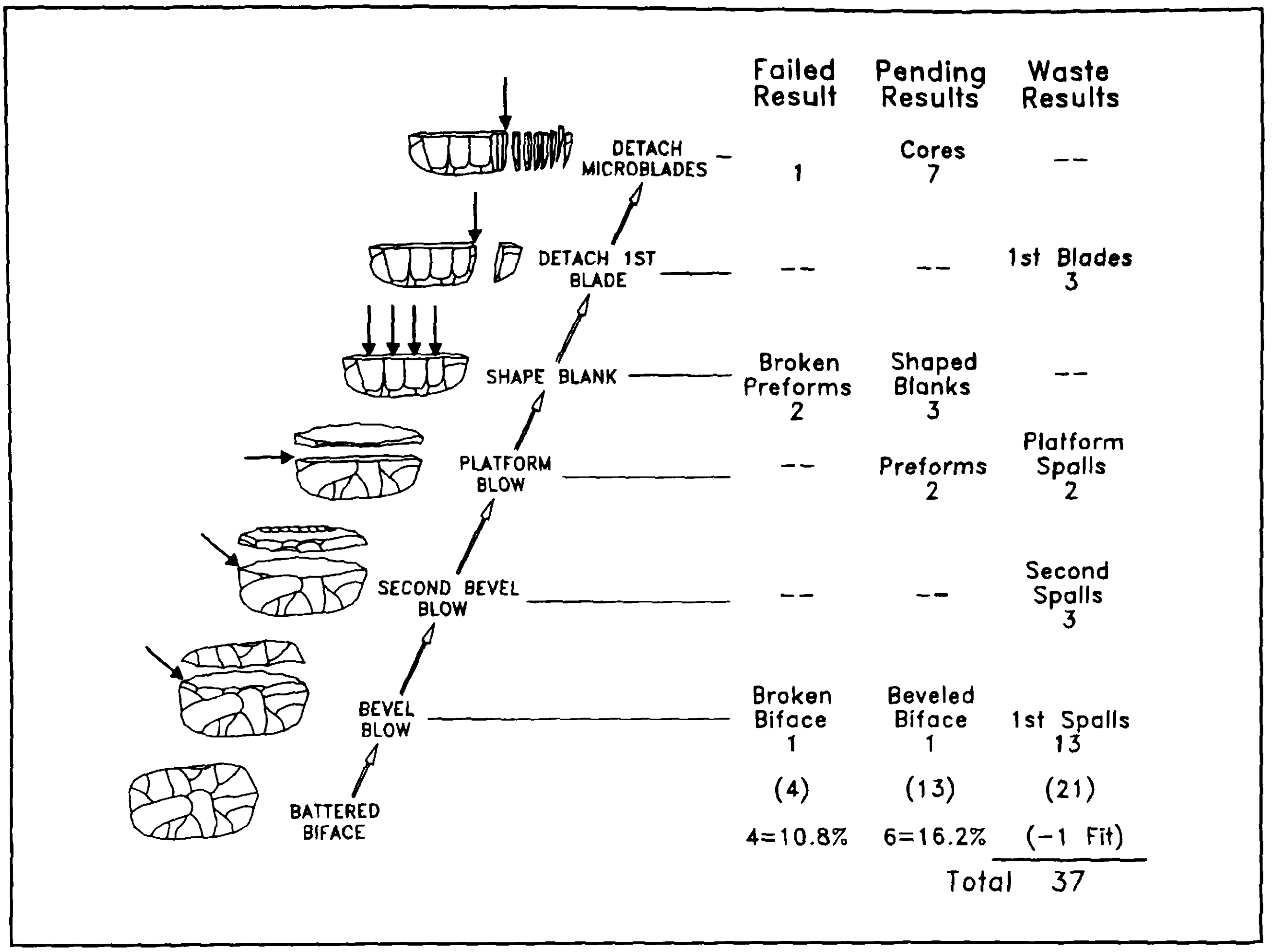

Figure 7.2 Event tree model of Araya microblade production (from Bleed 1996).

the actual failure rates involved in microblade production, the four broken cores in the assemblage suggest that the overall production failure rate for Araya microblade cores was only 10.8 percent. It is hard to interpret that rate, since there is little comparative information available on failure rates in other stone tool technologies. As the next example shows, however, reconstruction of Folsom point failure rates is much higher, which suggests that the 10 percent production failure rate reconstructed for the Araya cores is quite low. Furthermore, the point in reduction where failure occurred is interesting: cores left at Araya failed in all steps *except* during microblade removal. Clearly, then, failure added little to the production cost of the microblades. Some thick and irregular microblades in the assemblage indicate that microblade removal may not always have made perfectly "efficient" use of the core, but it appears never to have caused total failure of the cores. The ability to detach microblades so predictably must have entailed great skill. This degree of skill suggests that microblade production may have been an activity carried out by practiced experts, if not by "specialists." It also seems likely that microblades were detached in "batches" and that this further reduced failure probabilities. Batch processing reduces "set-up" costs and makes it possible to schedule production during times that do not conflict with other opportunities.

As is true for Araya microblade production, fluted point manufacture clearly involves a complex and technically difficult sequence of stages. Although a variety of forms can provide an initial blank (see Callahan 1979: 41-66), the sequence of reduction from this blank to a finished point involved bifacial flaking to shape the overall preform, more refined flaking to carefully contour the surface to be fluted, preparation of the platform from which to drive the flute, and removal of the flute itself; once one face of the preform was fluted successfully, this sequence was repeated on the other face. Finally, the fluted preform was pressure-flaked into its finished form and its edges were ground for hafting. Taking this sequence of steps as outlined by Frison and Bradley (1981) and arraying frequencies at the Hanson and Agate Basin sites of production failures at each step in an event tree, Winfrey (1990) estimates an overall failure rate in Folsom point production of approximately 50 percent. Unsurprisingly, Winfrey's analysis indicates that most

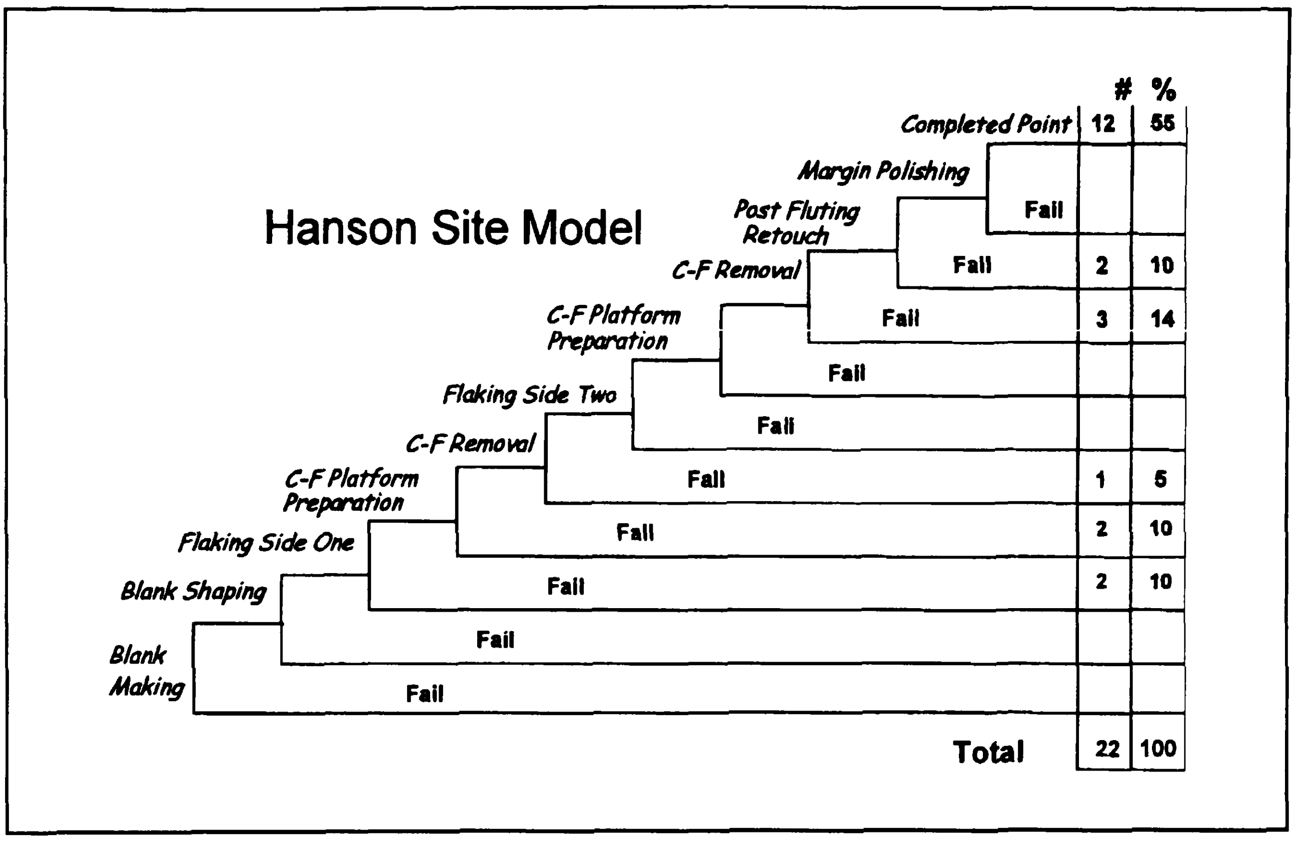

Figure 7.3 Event tree model of Folsom point production at the Hanson site (from Winfrey 1990). "C-F" is an abbreviation for "channel flake".

failures-roughly half of the total-occurred during removal of the flutes, particularly the second flute (Figures 7.3 and 7.4).

The substantial difference between failure rates in the Araya and Folsom examples is particularly interesting because both patterns of production appear to have required high levels of knapping skill: as we have noted, consistent removal of microblades is difficult, and it is clear that it takes many years of practice to flute points consistently. To return to an earlier issue, though, consistent reliance on these patterns of production over relatively long periods of time and large areas implies that both patterns consistently produced adequate supplies of tools despite the need for highly skilled artisans in both cases, and particularly despite the great waste of raw material and production time in the Folsom case. Considering Araya and Folsom production in terms of our general sequence of procurement, production, and use helps to see how this was accomplished.

The procurement cost of the cores used for Araya microblade production was very low since they all appear to have be made out of bifaces that had already had long use histories: reduction to a microblade core appears to have been a step taken only after a biface had been much used and become too small to be useful as a core or a beveled chopping tool. Placing microblade production at the end of the recycling system kept procurement costs low and meant that other operations of the stone tool technology resulted in raw material suitable for use as microblade cores. There was, then, a low probability of failing to have raw material suitable for microblades.

Archaeologists have made similar arguments in the Folsom case, reconstructing a pattern in which large bifacial cores were transported, initially used as sources of flake blanks for other tools, and finally transformed into fluted point preforms (Hofman 1992, Ingbar 1992, Kelly & Todd 1988); Hofman (1992) further suggests that Folsom knappers produced unfluted points (which make up a substantial proportion of the total points dated to the Folsom period [Bamforth 1991b]) when replacement material was scarce. However, such a pattern clearly imposes higher procurement costs than the Araya case. First, a 50 percent failure rate implies that Folsom groups would have had to transport two preforms for every fluted point they expected to produce, which adds weight and bulk to a mobile toolkit rather rapidly. Second, the importance of carefully contouring the surface to be fluted places important limits on a knapper's ability to strike large flakes from a bifacial core. Relative to the Araya case, then, Folsom point production imposed high procurement and raw material transport costs.

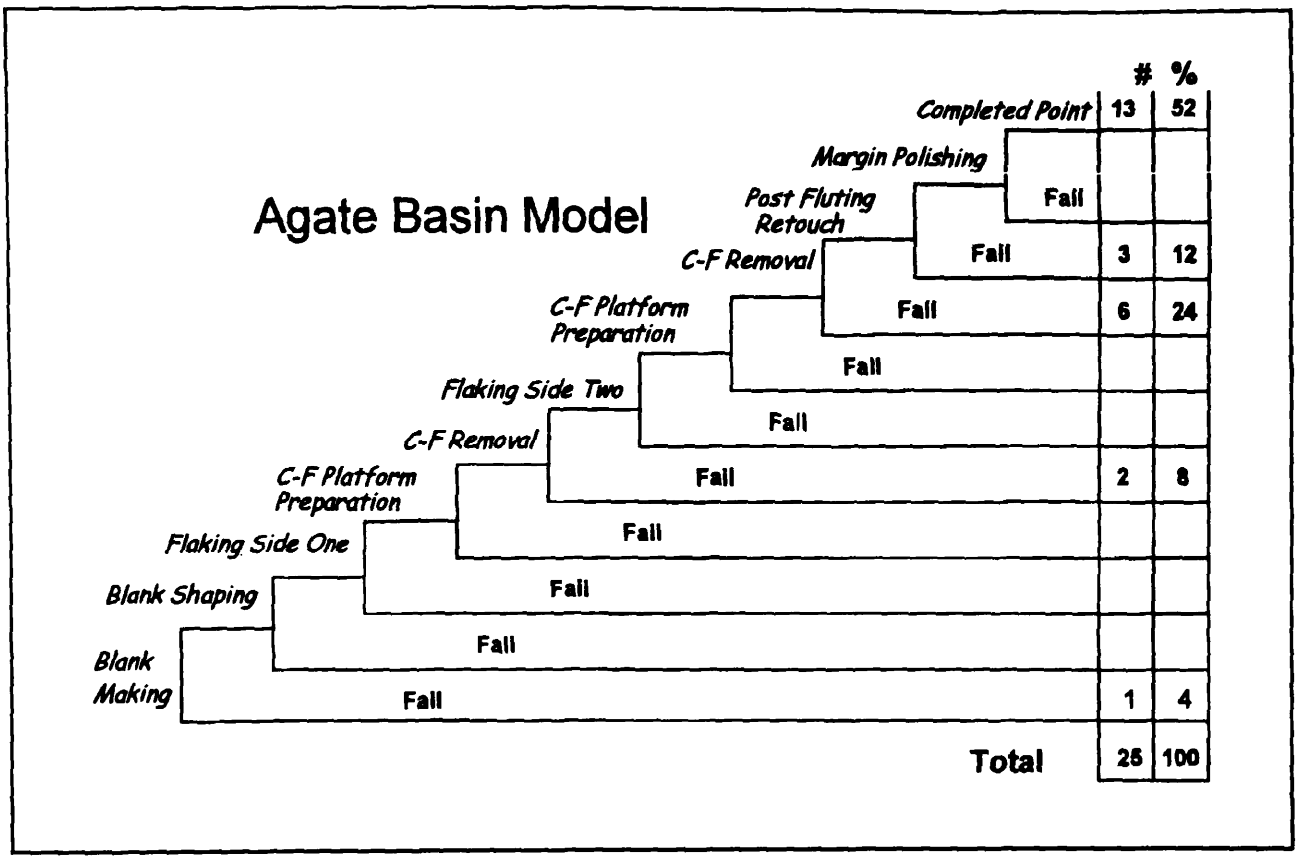

Figure 7.4 Event tree model of Folsom point production at the Agate Basin site (from Winfrey 1990). "C-F" is an abbreviation for "channel flake".

Araya and Folsom production share some important costs in the context of production, particularly in their apparent reliance on high levels of knapping skill. Skillful execution like that observed in the removal of microblades or Folsom flutes is easiest to achieve when repetition results in a positive "practice effect"; in combination with the likelihood that a reliance on batch processing helps to reduce failure rates, these examples must have required Araya and Folsom society to support lengthy periods of training and predictable periods of uninterrupted work time. It is likely that it takes longer to produce a single fluted point than to produce a series of microblades, but we note again that making a stone blade for a hafted tool is only part of the cost of producing that tool: projectile points are useless without shafts, and fixing more than one stone blade in the haft to produce a single useful projectile certainly increased Araya production time over that needed for at least some alternative weapons. Lacking estimates of production time, we infer tentatively that there is no reason to reconstruct substantial differences in overall production costs for the Folsom and Araya cases, although it is clear that Folsom and Araya toolmakers incurred these costs in different ways.

Finally, because microblades appear to have been used as barbs and edge blades in composite projectiles and because Folsom points were clearly used to tip projectiles, failure in application could carry serious costs: without stone blades, these projectiles would not have been functional. It is likely, however, that use of microblades as tips and barbs in compound projectile helped to minimize the probability of such failure. First, multi-barb projectiles are "over-designed" weapons in which individual blades served as redundant elements (Bleed 1986). Failure to have a microblade, therefore, or inadequately fastening or breaking one of several microblades in its haft, would not cause the projectile to fail completely. Second, production of microblades in batches meant that microblades could be produced in groups that could cover periods of anticipated need. Thus, batch processing would contribute to a low probability of no blades whatsoever being available at times of need.

Interestingly, it is difficult to make comparable arguments for the practical benefits of Folsom points in the context of use. Although several archaeologists have suggested that the fluting process played an important ceremonial or other non-utilitarian role in Folsom society (Frison & Bradley 1982), there is no evidence that fluting increased the killing power or accuracy of the weapons to which fluted points were attached; certainly, Plains Indian hunters (including, as we noted earlier, at least some Folsom period hunters) slaughtered bison with great success for millenia without using fluted points and it is difficult to see how the details of the stone tip of a projectile would greatly influence the effectiveness of that projectile, so long as that tip is sufficiently sharp to penetrate its target (but see Nelson 1996). For example, Parks (ms.) shows that points of the size used on both arrows and darts in prehistoric North America have no influence on the flight of either type of projectile. Alternatively, M. Peterson (personal communication) has suggested that fluted Folsom points may be less breakable in use than unfluted points because the material of the haft, which presumably extended along the flutes on both face, may have provided more support for the stone blade on impact than hafts that are confined the base of a point. However, lower rates of use-damaged points probably have more significance in reducing replacement rates (that is, production costs) than in reducing rates of application failure. Folsom points were sometimes resharpened (Hofman 1991), thereby extending their use-lives, but there is similarly no evidence that fluting made this easier to do: later Paleoindian groups on the Plains also resharpened their non-fluted points (i.e., Wheat 1977). We thus see nothing specific to fluted points which reduces failure probabilities in the context of use.

In our terms, the Araya case thus seems to represent an investment in the domain of production which helps to minimize failure probabilities in the domains of procurement and application. In contrast, Folsom point production has relatively high procurement costs (although these may have been somewhat reduced by using bifaces as both cores and preforms), and also imposes high production costs, but seems not to compensate for either of these by reducing failure in application. Following our arguments above, we might interpret the Araya pattern as evidence for a way of life in which (1) access to raw material was not assured and raw material conservation was extremely important, (2) it was important to maximize the chances of hunting success, and (3) it was possible to invest time and effort in production to deal with these problems. The Araya case might then fall into cell B in Figure 7.1, although the paucity of supporting evidence on Araya lifeways leaves no way to test these possibilities at present.

In contrast, there appears to be no reason to suppose that the increased procurement and production costs associated with fluted points were compensated by practical benefits at other steps of the Folsom technological continuum. Appealing again to our earlier discussion, we suspect that Folsom hunters may have found themselves either in an adaptive context in which both technological (opportunity) costs and failure costs were low or one in which technological costs were low and failure probabilities were reduced by means other than tool design. Archaeological data suggest that the costs of failure in application were probably high in Folsom times: fluted and unfluted points were used to hunt bison and probably other prey on which Folsom hunters depended for their survival, and fluted points appear to be disproportionately common in large bison kills (Bamforth 1991b). Instead of designing a tool which reduced failure in application through its design, we suspect that Folsom groups reduced failure probabilities in this activity through the organization of hunting behavior, probably by relying (perhaps seasonally) on relatively large-scale cooperative bison hunting.

At minimum, it seems clear that something about the Folsom way of life ensured that Folsom stoneworkers would have substantial amounts of time to devote to their craft as well as adequate supplies of raw material. In this regard, it is particularly interesting that failed preforms are discarded so regularly in Folsom sites (i.e., Ingbar 1992, Wilmsen & Roberts 1979), often apparently without being reused for other purposes. This implies, arguably, that raw material was not at a great premium in the contexts in which most Folsom points were manufactured. Such a pattern of behavior is difficult to reconcile with a way of life in which residences are always moved unpredictably or with great frequency, which has obvious implications for reconstructions of Folsom mobility patterns. Depending on our view of Folsom raw material procurement, the Folsom case might thus fall into either cell H or cell F in Figure 7.1.

Investigating these, or other, possibilities for either the Araya or the Folsom case is beyond the scope of this paper, and is almost certainly probably beyond the present capacity of the Araya data base. Since the purpose of these illustrations is to show that archaeologists can address risk in various technological domains, exploring all of the implications of these data is beyond the scope of this discussion. However, these cases do illustrate ways in which our perspective helps to predict and explore linkages between technology and the adaptive context in which it operated.

SUMMARY AND CONCLUSIONS

To summarize, we have argued, following Torrence (1989), that risk is an important determinant of technological adaptations. However, we believe that it is essential to recognize two distinct components of the risk concept–probability and costs of failure–and we view technology as attempts to reduce failure probabilities in the face of high failure costs. Our analysis of ethnographic data on hunter-gatherer technology supports this assertion, but also indicates that choosing any technological option also imposes costs that may themselves be unacceptable in certain contexts: the fact that a particular option may be advantageous in a given situation does not ensure that it will develop–to be chosen, options must feasible as well as effective. We further considered the special problems of examining these issues in the context of flaked stone technology, and concluded that the absence of reasonable estimates of failure probabilities and failure and technological costs in prehistoric contexts seriously limits our ability to test these ideas archaeologically. Despite these limits, this conceptual framework has the potential to provide important insights for archaeologists, and we demonstrated this potential by examining construction of ditch and palisade defenses along the Missouri River and comparing the production of microblades during the Japanese Paleolithic and of Folsom fluted projectile points on the North American Great Plains.

Our arguments here clearly derive from the optimization perspective that underlies much of the recent theoretical research in lithic analysis (i.e., Bousman 1993; Nelson 1991, 1996; Torrence 1989). However, the emphasis here on the full continuum of technological decision making from raw material acquisition to tool discard, the recognition that the ability to bear high technological costs may constrain technological choices, and the possibility that the combination of low failure and low technological costs may produce technological choices that reflect idiosyncratic cultural rather than utilitarian factors all combine to lead our arguments towards new conclusions. In particular, this perspective allows us to begin to analyze the diversity of technological responses to superfically similar needs, as exemplified in the contrasts between Eskimo and Chumash harpoons and between the complexity of Caribou Eskimo and Athabascan tools and facilities discussed earlier. Such diversity is difficult to accomodate within most existing arguments, which often rely on relatively vaguely defined descriptions of technology, particularly Binford's (1979) notions of curated and expedient technological strategies, and empirically unsupported assertions about the links between these descriptions and selected aspects of hunter-gatherer mobility patterns (see Bamforth 1986, 1990). Design differences among functionally similar items have thus often been attributed solely to such factors as ethnic preferences (i.e., Lemmonier 1986, Sackett 1982), and the framework we have presented here suggests that this is a serious oversimplification.

Finally, by helping to identify more clearly the forces which structure technological choices, our perspective helps to make technological change understandable within a selectionist perspective, although, again, it is not clear that it helps to identify truly Darwinian processes of change. The example of Folsom points above shows this particularly clearly. As we noted, despite a common archaeological emphasis on fluted Folsom points, many points dated to the Folsom period are unfluted. Fluted points disappear from North America after Folsom times, and later Paleoindian points, although still manifesting great stoneworking skill, are finished by pressure flaking, a shift which can easily be seen as selection for unfluted points at the expense of fluted points. Our discussion above suggests that the basis for this selection is likely to be the high procurement and production costs of fluting. For example, the size of large bison kills appears to increase after Folsom times (Judge n.d.), and it may be that slaughtering larger herds required so many projectile points that a 50 percent failure rate simply required more stone than Paleoindian groups could transport. Alternatively, changing social and/or environmental patterns may have made it more difficult to rely on only the most skilled stoneworkers to produce important tools (Bamforth 1988: 188, 1991).

Assessing possibilities like these requires data and arguments which go well beyond the scope of this paper. However, we think that the ability of our perspective to help to raise them is a measure of its usefulness. Although the ideas we have presented here are useful to archaeologists in their current form, there is no doubt that they will require refinement and elaboration. One one hand, a number of authors have identified aspects of "risk" beyond those we have discussed here (for example, its frequency and seasonal pattern–Cashdan 1992, Rescher 1983), and different kinds of risks will certainly entail different kinds of responses; the existing literature, as well as most of our discussion here, emphasizes subsistence risks, and other domains of risk may entail very different kinds of analyses. It is also likely that many of the changes that will be needed to "fine tune" this perspective will result from deeper insights into the ways in which non-technological factors affect technological choices and from a better understanding of the range of technological choices that do not involve tool design. Like all other aspects of human ways of life, technology is embedded in, and conditioned by, many other aspects of culture, and the interactions among these various conditioners are likely to be complex. However, the basic framework we have presented here provides, at least, a way of structuring our thought about these issues and thereby helping to integrate a wide-ranging and exciting, but theoretically dispersed and sometimes contradictory, body of literature.

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NOTES

1. Murdock's estimate of the proportion of fish in the Caribou Eskimo diet derives from the work of Birket-Smith (1929), the same work which provided Oswalt's (1976) data on tool form and construction. Recent research by Burch (1986, 1988) indicates that Birket-Smith's travels among the Caribou Eskimo occurred towards the end of an extended period of extreme deprivation, during which caribou were scarce and human population was reduced by as much as half by starvation. Murdock's figure is therefore probably not an accurate estimate of the role of fish in the Caribou Eskimo diet over the long term. However, this observation has few or no implications for our analysis. First, the conditions under which Birket-Smith observed the Caribou Eskimo had existed for some time and, to survive under these conditions, this group must have had to alter many aspects of its behavior, including its diet and the frequency of use of the tools needed to support that diet. The tools in use during Birket-Smith's visit must therefore have been those required to survive under the conditions which Birket-Smith observed. If key resources, particularly caribou, were scarce at this time, and normally less important resources, particularly fish, were therefore essential to suvival, we might expect that conditions should have favored the construction of the tools required to maximise success in procuring these other resources. The persistent differences between Caribou Eskimo and Ingalik/Tanaina technology under these conditions emphasize rather than damage our arguments.

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