Keeping your Edge: Recent Approaches to the Organisation of Stone Artefact Technology

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BAR International Series 2273
2011

Published by

Archaeopress
Publishers of British Archaeological Reports
Gordon House
276 Banbury Road
Oxford OX2 7ED
England
bar@archaeopress.com
www.archaeopress.com

BAR S2273

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ISBN 978 1 4073 0847 0

Printed in England by 4edge, Hockney

COSTS AND BENEFITS IN TECHNOLOGICAL DECISION MAKING UNDER VARIABLE CONDITIONS: EXAMPLES FROM THE LATE PLEISTOCENE IN SOUTHERN AFRICA

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Abstract: *The issue of technological time costs as applied to the manufacture of flaked stone artefacts is considered. Assuming a positive correlation exists between technological cost and improvements in resource capture, it is shown that the viability of costly technologies is constrained by the abundance of resources in a landscape such that more costly technologies would be likely to be pursued in resource-poor landscapes. This outcome mirrors the results of past assessments of ethnographic data concerning the relationship between subsistence risk and technological complexity. These hypothetical and ethnographic models are then compared to archaeological changes in technological costs at three sites occupied through the late Pleistocene in southern Africa. It is shown that while there is agreement in some respects, there are also times where archaeological outcomes differ dramatically from expectations. The results are taken to suggest that while costly technologies are generally pursued under conditions of increasing global cold, peak cold conditions at the height of Marine Isotope Stages 4 and 2 encouraged a reversion to least-cost technological systems. This may reflect a switch in the focus of optimisation from resource return rates to maximisation of early resource acquisition and/or maximisation of number of subsistence encounters.*

INTRODUCTION

Major changes in the study of stone artefacts in the last half century have stemmed from a shift in emphasis from the description of technological variability to consideration of its underlying causes (Hiscock and Clarkson 2000; Odell 2000). As part of this shift, increased attention has come to be focused on the advantages conveyed by different technological systems under varying conditions. It is assumed that, when confronted with a new set of circumstances, the most beneficial options from the range of available technological alternatives will be preferentially selected (Bamforth and Bleed 1997; Kuhn 1995). Long-term trends in technological variation can thus be explained in terms of the differential persistence of more beneficial over less beneficial systems.

A crucial part of the identification of which technological option is most beneficial is the evaluation of the costs incurred by each option. Though a component of early works in the field (eg., Torrence 1983), the impacts of costs on technological decision making have recently been neglected. While archaeologists tend to consider and speculate on the benefits of different technological systems under different contexts of deployment, they less often consider the relative costs of pursuing one given technological strategy over another. Intuitively such consideration would seem important. It is well documented that certain kinds of artefacts take longer to produce than others (Ugan *et al*. 2003). Furthermore, there are almost certainly costs involved in the acquisition of materials for the manufacture of artefacts, and these will vary depending on the materials selected. Finally, if there were no costs involved in the manufacture of technological items then there would be little incentive to pursue anything other than complex systems, assuming that complexity correlates positively with utility. In reality, however, complex technologies are not ubiquitous in either the archaeological or ethnographic records.

This paper considers the nature of technological costs as they might have applied to stone artefacts. Several avenues of potential cost are explored and modelled, providing general criteria for assessing the cost of a given system. The paper then considers the changing costs of technological systems as they were deployed at three late Pleistocene sites in southern Africa. Changes in costs are considered in relation to changes in coarse climatic indicators. The results of this comparison suggest that there is a general relationship between environment and the technological costs borne by tool-using groups. The identified outcomes are not entirely consistent with predictions from existing models, requiring some consideration of the potential causes of variance.

TECHNOLOGICAL COSTS

Technological strategies featuring stone artefacts involve a complex interplay between costs and benefits (Bamforth 1986, 1991; Bamforth and Bleed 1997; Bleed 1986; Bousman 2005; Clarkson 2007; Hiscock 2006; Kuhn 1994, 1995; Torrence 1983, 1989). Technological costs chiefly arise as a result of three related problems. First, sources of stone suited to artefact manufacture are not ubiquitous in landscapes. Second, sources of stone will not always occur where and when tasks requiring stone artefacts occur. Third, that stone artefacts are rapidly depleted during use and resharpening. In order to maintain a supply of stone artefacts foragers must outlay time on the acquisition and manufacture of stone artefacts and stone artefact-making materials (Kuhn 1995). The benefits derived from stone artefacts relate primarily to the advantages they provide in the successful prosecution of subsistence tasks.

Since the 1980's, numerous researchers have attempted to develop optimality models for the organisation of stone artefact technologies (e.g., Bleed 1986; Clarkson 2007; Kuhn 1995; Marwick 2008; Torrence 1983, 1989 and papers therein). Various currencies have been proposed, including time, energy and risk, but no clear consensus has emerged on which of these is the most useful. Part of the problem may be a perception that different currencies are in conflict (e.g., Nelson 1991: 64). The approach taken here is slightly different, in that time, energy and risk are all incorporated. Time is viewed as a cost relating to the acquisition of stone making material and the manufacture of artefacts. Energy (resources) gain and risk dampening are seen as a benefits resulting from technological investment. The following section begins by considering how time costs are incurred. Subsequently, the relationship between energy, risk and time costs is discussed.

Magnitude costs of material procurement

Acquisition of materials for the manufacture of stone artefacts would have required time outlay. While material for artefact manufacture may occasionally have been abundant, it will more often have been relatively scarce. Furthermore, even when sources of stone were readily available, procurement for the purposes of artefact manufacture would inevitably have involved time costs additional to travel to and from sources, such as cobble testing. Necessarily, such costs would increase as the density of stone resources in the landscape decreased (Bamforth 1986). In material-poor environments, return travel costs alone might conceivably have been in excess of several hours.

Material procurement costs could have been varied in several ways. For example, costs would be maximal where rare and sparsely distributed materials were preferentially sought for artefact manufacture. On the other hand, we might expect that costs would be minimised by people acquiring on-encounter any materials suitable for manufacturing artefacts. Thus, if travel for the purposes of another task led foragers to an encounter with stone, its opportunistic collection would have reduced the need for a dedicated procurement trip in the near future. Embedding such procurement episodes into subsistence tasks would effectively allow the same unit of time to be allocated to both technological and subsistence activities (cf., Binford 1979: 259; Torrence 1983: 12). Brantingham's (2003) neutral model provides a useful way of visualizing the material outcomes of such a minimal cost approach. If we assume that foraging opportunities were randomly distributed across landscapes, that artefacts were consumed at a constant rate, and that consumed artefacts were replaced at exhaustion with whatever material was available, then the material composition of assemblages acquired by minimal time outlay would, when aggregated, come broadly to resemble the frequency of materials as they occur in the landscape.

The downside of such an approach to procurement is that it would, in many cases, result in assemblages dominated by relatively poor-quality materials, where those were most prevalent on the landscape. While such materials may have been suitable to most tasks, they would equally have placed constraints on the efficiency and longer-term utility of the toolkit, possibly increasing the frequency of reprovisioning events (discussed below). In order to increase the proportion of better-quality rock, foragers would almost certainly have had to increase their procurement time outlay by undertaking non-embedded procurement trips.

Frequency costs of procurement

Embedding, or neutral procurement, is a way of reducing the magnitude of costs associated with any given episode of material acquisition. Time may also have been saved by increasing the yield from a quantity of procured stone, and thus by reducing the frequency of procurement episodes (cf., Hiscock 1996a: 152; Kuhn 1991). There are a number of ways by which foragers could have increased yields from procured stone. The most obvious is to lower discard thresholds; that is, to lower the size at which an artefact is considered unusable and thus thrown away. Kuhn's (1994) simulation of the effect of optimising multifunctionality and portability on artefact size found that carrying small tools is a solution to the problem of optimising utility/mass ratios. He specifically notes that the optimum utility/mass ratio occurs for artefacts that are three times the minimum possible size. This implies that lowering the lower discard threshold would not necessarily result in pieces at the limits of human physical manipulation, but simply an overall reduction in tool sizes. Archaeologically, the functional 'low-end' artefact size threshold has not been established, however it is clear from some cases that at various times and in various places people were prepared to manufacture and deploy implements that were very small (Orton *et al*. 2005 report complete 8mm backed artefacts from the Northern Cape province of South Africa).With regard to cores, lower discard thresholds are likely to be manifest in a reduction in core sizes and core scar dimensions.

Following Shott (1989) we might think of lower discard thresholds in terms of yield improvements, or an increase in the ratio of realized to potential utility in a transported item. A point to consider in this regard is that not all materials have the same capacity for reduction. Fine grained rocks allow for the production of thinner flakes, resulting in a relatively low mass removed from the core with the production of each flake (Mackay 2008). In a similar vein, materials which fracture predictably allow more blanks to be removed with less chance of catastrophic fracture (Goodyear 1989), while the blanks produced from particularly abrasion-resistant (hard) rocks may be able to do more work for a given quantity of procured material (Braun *et al*. 2009). Thus preferential selection of fine grained, predictably flaking and/or

Table 1: Technological time costs

Outlay	High (3)	Moderate (2)	Low (1)
Magnitude	Largely targeted procurement of specific materials	Largely embedded, some targeted procurement	Entirely embedded
Frequency	High discard thresholds	Moderate discard thresholds	Low discard thresholds
Manufacture	Considerable investment in complex tools	Some complex tools	Largely expedient toolkit

harder rocks may have been an effective means of off-setting increased magnitude of procurement-time outlay with diminished frequency of reprovisioning events.

Manufacturing costs

The other element of time cost in stone toolkits relates to outlay on implement manufacture and repair (Torrence 1983). Though these costs are variable (cf., Hames 1992; Hill *et al*. 1985; Lee 1979; Tanaka 1980; Yellen 1977), they can be considerable. Hill *et al*. (1985), for example, report an average of two hours per day spent by Ache men on the manufacture and repair of tools, chiefly scheduled during down time between or immediately after subsistence tasks. Obviously in the past only a portion of this cost would have been allocated to the manufacture and repair of stone implements, the remainder being allocated to behaviours such as the production of wooden and other organic items, and the hafting of stone implements, all of which can be difficult to detect archaeologically. Nevertheless, direct costs in the manufacture of stone implements might not always have been insubstantial, with the outlay involved increasing with both the complexity and the number of implements manufactured.

Beyond direct costs, there are additional associated costs in the manufacture of complex implements, including high rates of production failure associated with complex reduction strategies (cf., Villa *et al*. 2009), the manufacture of hafts and time spent hafting, as well as time allocated to learning complex crafts during childhood and adolescence. High failure rates in particular may result in greater rates of material waste, introducing positive feedback between manufacture costs and the magnitude or frequency costs of material acquisition.

CHARACTERISTICS OF TIME-COST AGGREGATES

Time costs enter technological strategies at three points; in the magnitude of procurement episodes, in the frequency of procurement episodes, and in the production and maintenance of complex artefacts (the last is taken to include learning and failure-related time). In Table 1, high, moderate, and low costs for each of these parameters are characterized, and assigned the arbitrary column values three, two, and one respectively. Twenty-seven combinations of outcomes are possible of which those with summed values of five to seven account for the bulk (~70%). These also seem generally to characterize most stone artefact technologies as they appear around the world, with minor variations on the themes of some targeted procurement, moderate discard thresholds and some production of complex implements. This approach is more useful, however, in characterising what we might think of as technological time-cost extremes, or 'least cost' and 'highest cost' technologies. Least-cost toolkits (summed value of three) would be expected to feature materials in roughly the same proportions as they occur in the immediate landscape, reflecting minimum magnitude of outlay. Minimising frequency of procurement episodes would necessitate maximizing the yield acquired from procured material, and we would thus expect low discard thresholds. These could be expressed either in the exhaustion of implements or cores prior to discard, though the latter seems more likely, given that the former implies at least some investment in the manufacture of complex implements. In a least-cost solution we seem more likely to encounter maximally-reduced cores with no outlay on complex and time-consuming tool manufacture.

In highest cost technologies (summed value of nine), all of these trends are reversed. Thus, we might expect targeted procurement of rare or infrequently encountered materials, the manufacture of elaborate implements, and relatively high discard thresholds. Consideration of the literature suggests that this combination of characteristics is rarely observed among hunter-gatherers. The few clear examples all appear to come from food-producing societies, featuring the production of prestige items by craft specialists (for example, Danish flint knives (cf. Apel 2008; Stafford 2003) or Mayan eccentrics (cf., Shafer and Hester 1991)). Examples of relatively high cost technologies (technologies with a summed value of eight), however, are more easily identified. Numerous hunter-gatherer technological systems feature targeted procurement of specific materials, the manufacture of complex implements, and relatively moderate discard thresholds (eg. Torrence 1983; Gould 1980; Sillitoe 1982).

MODELLING VARIABILITY IN TECHNOLOGICAL TIME-COSTS

Torrence (1983) considered the issue of technological time costs in relation to general time-budgeting. The concept hinges on the idea that hunter-gatherers have a limited time budget available to allocate to the various tasks of which life is comprised (including social, subsistence and technological tasks). While social and subsistence, and social and technological tasks may at times have been undertaken simultaneously, it seems likely that subsistence and technological tasks were often temporally exclusive; it is difficult to knap and stalk simultaneously. That is, time spent in the manufacture of a toolkit was probably time not spent actively engaged in subsistence. Consequently, technological time costs might be thought of as lost subsistence opportunities, or opportunity costs (cf., Hames 1992). Complicating the relationship between technological time costs and subsistence opportunity costs is the observation that increased outlay on more complex and/or more predictably performing implements may result in more efficient prosecution of subsistence tasks (cf., Bright *et al.* 2002; Ugan *et al.* 2003). Thus, the greater time invested in technology may be offset by increases in the efficiency of resource acquisition during those periods allocated to subsistence tasks. These trade-offs can be modelled as a modified marginal value problem (cf., Charnov 1976).

In his original description, Charnov used the marginal value theorem to model the optimal time for a foraging animal to spend acquiring resources in a patch, given that return rates would diminish as duration of occupation increased, and taking into account travel time between patches. The modified version presented here is concerned with optimising the time to acquire a minimum quantity of food or non-stone resources in a patch given diminishing returns and variability of resource capture rates brought about by differential investment in technology.

For the purposes of the model, total time outlay (T_{max}) is taken to include subsistence and technological time elements. Total time outlay is finite – thus, increases in technological time (T_{tech}) come at the cost of reduced subsistence time (T_{sub}). Foraging outcomes are assumed to be concerned with capturing a minimum quantity of resources (R_{min}), reflecting the viable subsistence threshold, within T_{max}. The model also assumes that there is a finite quantity of resources to be harvested (R_{max}) within the patch.

The curve incorporates an encounter rate, E (number of resources encountered per unit time) and a capture rate, C (number of resources acquired per encounter), which combined provide a success rate, S. Thus, for example, if five resources are encountered per unit time and the capture rate is set at 20% (or 0.2), the success rate is 5 x 0.2, or one resource per unit time. Because R_{max} is finite, however, each capture reduces the resource base, and thus the rate at which subsequent encounters occur. In the present modelling, R_{max} is arbitrarily set at 100 for simplicity. After the first unit time, where one resource is taken, 99 resource units remain available. The subsequent rate of encounter is reduced to 5 x 0.99, where 0.99 represents the fraction of the original resources that are available to the individual. Similarly, success in the second unit of time is (5 x 0.99) x 0.2, or 0.99. In the third unit of time rate of encounter is reduced to 5 x 0.9801, and in the fourth 5 x 0.970299, etc. T_{max} is set at 1000, though in reality this would rarely be reached – we would expect the foraging patch to be abandoned at some time between S_{min} and the point where return rates fall below the environmental average (Charnov 1976).

Setting R_{max} to 100 allows it to function as a percentage, rather than an absolute value. Thus at T_0 there are 100% of resources available. After T_1 here are 99% available, etc. The advantage of doing so is that the absolute value of acquired resources can be shifted without changing other parameters. Thus, one resource unit might be worth 30 calories, or it might be worth 130 calories. Consequently R_{max} might be 3000 calories or it might be 13000 calories. As it is also a proportional value, R_{min} shifts in accordance with R_{max}. Thus, if the value of one resource unit is raised to 40 calories, R_{max} is 4000 calories and R_{min} might be placed at around 60-70%. If the value of one resource unit is raised to 60 calories, R_{min} would be reduced to around 50%.

The resulting curve from this model can be described by a von Bertalanffy growth function. This function was originally introduced to predict the lengths of sharks as a function of its age and is now widely used to study the growth of individuals belonging to several types of animal populations (Román-Román *et al.* 2010). Von Bertalanffy is better known to archaeologists as the source of General Systems Theory (Salmon 1978). Here we draw on his work in empirical and theoretical biology which has had limited application in archaeology. The von Bertalanffy growth function is an adaptation of the simpler S-shaped Verhulst logistic growth function which states that a growth rate is proportional to the population and limited by a function describing carrying capacity.

The von Bertalanffy function extends the simple logistic function by assuming a maximal value of the growth variable (which might eventually be attained), and by considering the growth rate as proportional to the difference between maximal and current value (Román-Román *et al.* 2010).It is these extensions that make it especially suitable for modelling hunter-gatherer costs when an individual is active in a patch. In the case of the growth of fish and other animals, the function assumes that the rate of growth of an organism declines with size so that the rate of change in length decreases with increasing size. For hunter-gatherers, the function reflects how the success or return rate in a patch will gradually decrease as the patch is increasingly exploited and resources are depleted over time. The maximum resources available from the patch are explicitly expressed in the model as a limiting factor relative to the time the individual has been in the patch.

Although there are several different parameterizations of the function in use, we prefer the simplest form (Cailliet *et al.* 2006):

$$S(t) = S_{inf} - (S_{inf} - S_0)e^{-kt}$$

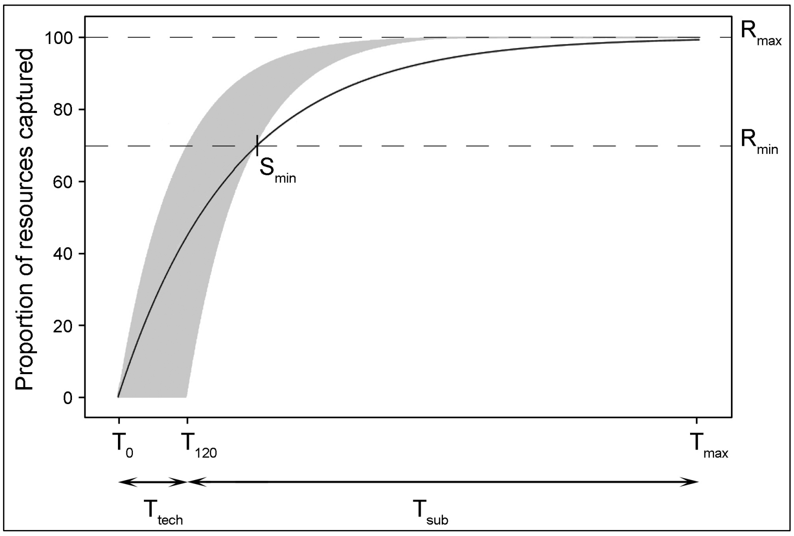

Figure 1: Resource capture curves for E = 5 where R_{min} = 70 and where no technological investment results in a capture rate of 0.1 (black line), and the range of viable costs where capture rate = 0.2 (grey shaded area)

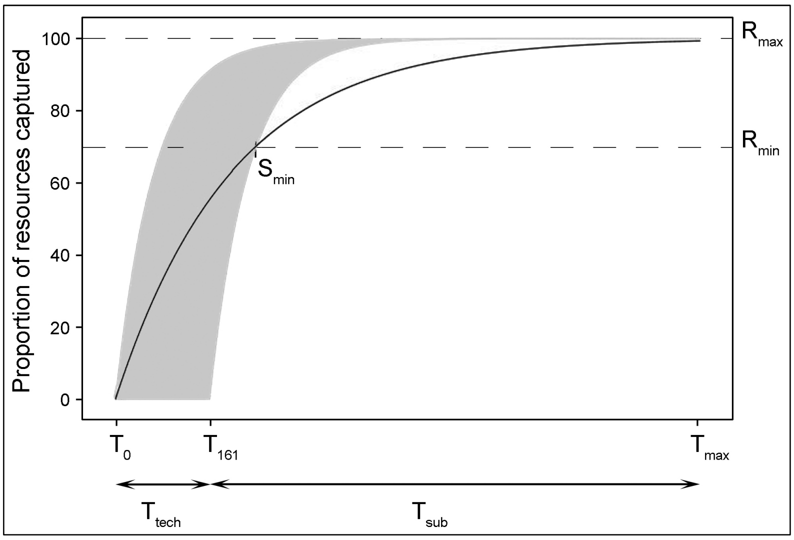

Figure 2: Resource capture curves for E = 5 where R_{min} = 70 and where no technological investment results in a capture rate of 0.1 (black line), and the range of viable costs where capture rate = 0.3 (grey shaded area)

Where S(t) is success as a function of time (t), S_{inf} is the theoretical asymptotic success rate (equal to R_{max}), S_0 is the success rate at time zero (in this case arbitrarily set at -1), and k is the rate constant. We can further expand k to represent our encounter and capture variables as k = (E x C)/100.

The model and its function is of course a simplification of complex and stochastic real-world processes. What makes this model useful is that it draws attention to specific mechanisms (or activities) that hunter-gatherers engage in, such as encountering and capturing resources, and allows us to manipulate variables describing these mechanisms. This manipulability property is a test for distinguishing causally relevant from causally irrelevant factors in the model (Glennan 2010).

Resource returns for E = 5, C = 0.1 with no initial outlay on technology (T_{tech} = 0) are modelled in Figure 1 (black line). It is assumed that foragers will cease acquiring subsistence resources at or soon after passing R_{min} – thus at the intercept S_{min} (subsistence minimum). In Figure 1, R_{min} is arbitrarily set at 70, or 70% of the available resources (R_{max}). The time taken to S_{min} using this curve is 240 time units, or 24% of the available time budget.

Also included in Figure 1 is the curve representing outcomes where outlay in technology results in doubling of the capture rate (eg., C = 0.2). The curve is shown as a grey shaded area, reflecting the range of starting time costs for which a capture rate of 0.2 reduces time to S_{min}. The curve suggests that an outlay in technology which doubles capture rates is only viable if the technological

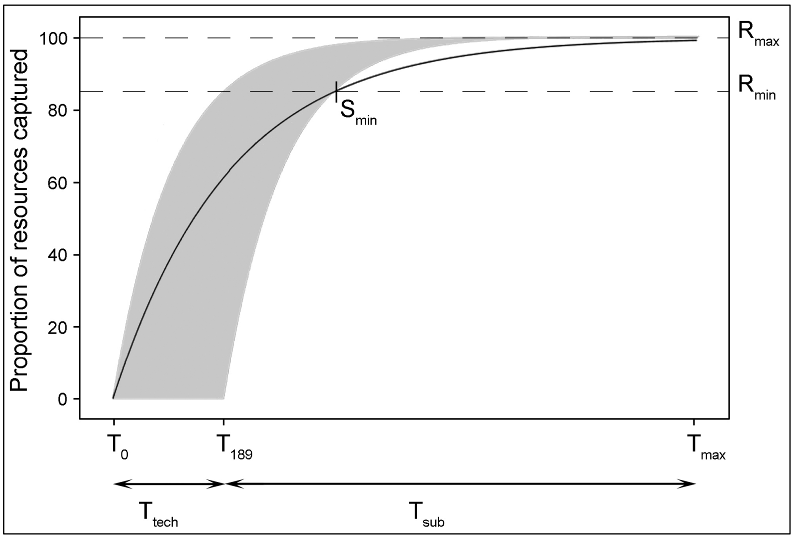

Figure 3: Resource capture curves for E = 5 where R_{min} = 85 and where no technological investment results in a capture rate of 0.1 (black line), and the range of viable costs where capture rate = 0.2 (grey shaded area)

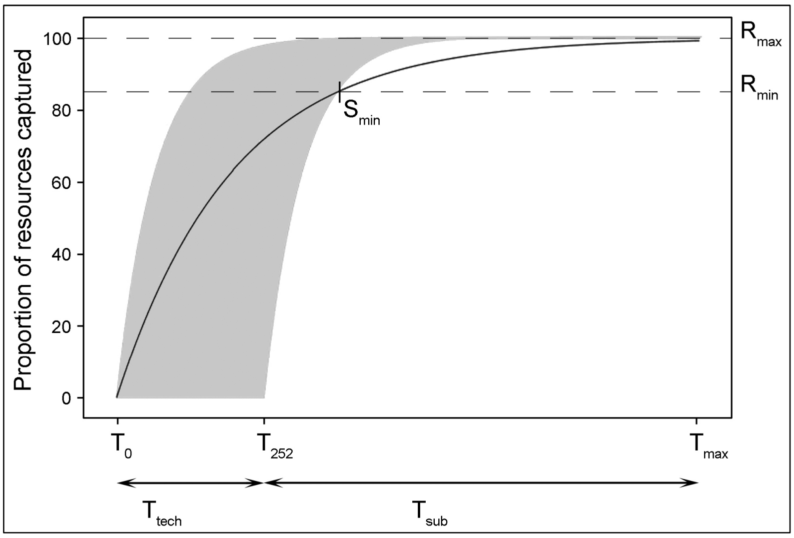

Figure 4: Resource capture curves for E = 5 where R_{min} = 85 and where no technological investment results in a capture rate of 0.1 (black line), and the range of viable costs where capture rate = 0.3 (grey shaded area)

time costs (T_{tech}) are less than 120 units, or 12% of the time available (T_{max}). If the technological time costs exceed 12% of the time available then the time to S_{min} will exceed the time under conditions of no technological cost and a lower capture rate. Figure 2 presents the range of outcomes against the same starting curve (black line) where outlay in technology results in a capture rate of 0.3 – triple the basic value. Under these circumstances time to S_{min} is reduced only where T_{tech} is < 161, or 16.1% of T_{max}.

In Figures 3 and 4 all parameters remain the same with the exception that R_{min} is now set to 85%. In effect the value of one resource unit has been lowered, such that foragers are now required to gain more resource units from the patch in order to make a living. This might be understood as reflecting a lower quality subsistence environment. Time to S_{min} using the basic model of E = 5, C = 0.1 is now 379 units, or 38% of the subsistence time budget.

While reducing the R_{min} value simulates a lower quality subsistence environment, a less dense subsistence environment can be simulated by reducing the value of E and keeping C constant. This has the simple effect of flattening the curve and increasing the time until the R_{min} value is obtained. With these simple manipulations, increasing R_{min} or reducing E, we can simulate a wide spectrum of situations that hunter-gatherers were likely to be in.

The effect of the poorer subsistence environment modelled in Figures 3 and 4 is equivalent to a less dense environment, that is they both make viable a greater range of technological time costs. Investment in technology that results in doubling of the resource capture rate is viable even if up to 189 time units, or 19% of the time budget, is used. Technologies which triple capture rates are viable at time costs of up to 252, or 25% of the time budget.

Implications of the model

The modelling presented above has two substantial implications for understanding costs and benefits of technological investment. First, the amount of time that can advantageously be invested in technology is limited. The major limiting factors are the difference in success rates that the increased investment provides and the abundance of resources in the environment. Technological systems which provide greatly improved success rates can be viable with very high time costs, though even these are constrained. For example, for the return curve E = 5, C = 0.1, where R_{min} is set to 70%, time to S_{min} is 240 units. Under such circumstances, no technology that required more than 240 time units to produce could be advantageous. Even technological systems with perfect capture rates (i.e., C = 1) would only be advantageous for time costs of less than 216 units.

Second, subsistence environments with poorer resources also allow greater technological time costs to be sustained. If R_{min} is raised to 95% of total, capture rates of 0.2 are viable up to 299 time units (~30%) and capture rates of 0.3 are viable up to 399 time units (~40%). Systems with perfect capture rates are viable up to 539 time units (~54%).

If we assume that technological time costs and resource capture rates are positively correlated then we would expect to see more costly technologies appearing under conditions of greater environmental duress. Alternatively, in resource-rich environments the benefits of pursuing costly technologies become more marginal – short times to S_{min} limit the marginal value of substantial initial outlay in technology. These hypothetical outcomes agree with the results of ethnographic studies of the causes of variance in technological complexity (eg., Bousman 1993; Collard *et al*. 2005; Read 2008; Torrence 1983, 1989). Using a variety of proxies these studies suggest that as subsistence resources become poorer, technological complexity tends to increase. Explanations for this relationship are phrased in terms of risk. Risk has many definitions in anthropological literature, including simply 'unpredictable variation' (Winterhalder *et al*. 1999: 302) as well as the probability and magnitude of loss (Bamforth and Bleed 1997: 112-113). In resource-poor environments the consequences of failing to acquire resources at a given point of opportunity may be significant, potentially even threatening overall subsistence viability. Thus at such times people may invest more in technology such that the probability of failure at any given opportunity is reduced. Though phrased for risk this is little different from suggesting that people would invest more in technology to improve capture rates – that is, to improve the quantity of resources acquired from a given number of encounters. We believe that while risk is a useful general heuristic, models such as those presented above offer opportunities to refine our understanding of how the effect of specific variation can be reflected in technological choices evident in the archaeological record.

For example incorporation of time costs helps to explain why the ethnographic data take the form they do. Without accounting for time costs there is no reason why people in a resource-rich environment would not invest heavily in technologies – if these investments provide improvements in capture rates with no attendant cost then they will be advantageous under all circumstances. However, if more complex technologies take more time to produce then their benefits are constrained by resource abundance and the general ease of subsistence. The poorer the environment, the more time can viably be invested in technology, and the more complex technologies might be.

CASES STUDY: THREE LATE PLEISTOCENE SEQUENCES IN THE WESTERN CAPE OF SOUTH AFRICA

The case study for this paper relates to three rockshelter sites in the Western Cape province of South Africa – Diepkloof Rock Shelter (DRS), Klein Kliphuis rock shelter (KKH) and Elands Bay Cave (EBC) (Figure 5). The sites all fall within the present southern African Winter Rainfall Zone, and lie within 70 km of one another. All were occupied at times during the late Pleistocene. The southern African late Pleistocene is of interest because of conspicuous, time-structured changes in flaked stone artefacts, including brief periods in which various complex implement forms were relatively common (Jacobs *et al.* 2008). There are also periods in the late Pleistocene where implements appear not to have been made regularly. Coincident with some of these shifts are marked changes in material procurement patterns (Mackay 2006, 2008; Minichillo 2006; Volman 1984) and also in core size at discard (Mackay 2009). Finally, the late Pleistocene witnessed significant changes in environments both globally and in the Western Cape specifically, including two periods of glacial cold

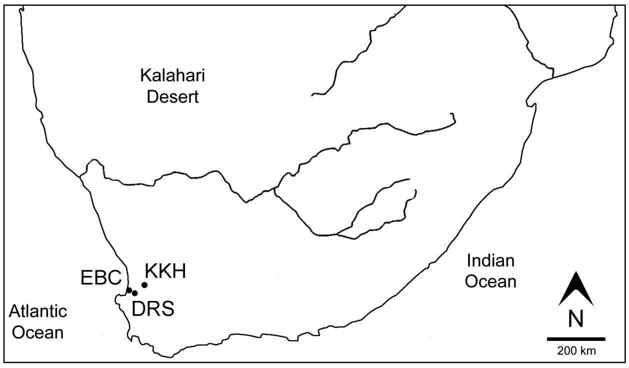

Figure 5: Location of study area and sites used

(Marine Isotope Stages (MIS) 2 and 4), and two warmer interglacials (MIS 3 and 5).

Diepkloof (DRS)

Diepkloof is a large north west-facing rock shelter perched high on a stone outcrop approximately 19 km from the present day coastline. The site was first excavated in 1969, and is currently the subject of excavations by teams from the Universities of Cape Town and Bordeaux. As it presently stands, the DRS sequence includes a minor late Holocene component underlain by a suite of culture-historic units identified as post-Howiesons Poort, Howiesons Poort and Still Bay (cf., Rigaud *et al*. 2006). There are two further unknown or unnamed units, one of which lies between the Howiesons Poort and Still Bay, and the other of which underlies the Still Bay (Mackay 2009).

Dating of the DRS sequence has been undertaken using both Optically Stimulated Luminescence (OSL) (Jacobs *et al.* 2008) and Thermo-Luminescence (TL) (Tribolo *et al.* 2008). Unfortunately the sets of ages returned by these two methods are strongly divergent, particularly in the older parts of the sequence. For the purposes of this paper, the ages presented by Jacobs *et al.* (2008) are preferred, largely because they are in accordance with ages from similar assemblages in other sites. The Jacobs *et al.* ages place the Howiesons Poort layers at the site between ~60 ka and ~65 ka, and thus in the context of warming during late MIS 4. Post-Howiesons Poort is bracketed by the upper Howiesons Poort age of ~60 ka and by an AMS age of >55 ka (Parkington *et al*. 2005). The Still Bay is dated to early MIS 4 between ~70 ka and ~74 ka. The older of the two unnamed units thus antedates 74 ka, while the younger lies between 65 ka and 70 ka.

Klein Kliphuis (KKH)

Klein Kliphuis is a north east facing rock shelter site located approximately 50 km north west of DRS and 4 km east of the large Olifants River. The site was first excavated in 1984 by a team from the South African Museum (now part of Iziko Museums of Cape Town). That excavation revealed a late Holocene component immediately overlying MSA-assigned materials (van Rijssen 1992). The pre-Holocene component of the site was removed in four coarse spits, varying in thickness from 105 mm to 250 mm. Subsequent analysis of this assemblages (cf., Mackay 2006) revealed a basal Howiesons Poort component, overlain by post-Howiesons Poort and possibly a final Middle Stone Age (MSA) unit.

Renewed excavations in 2006 refined the sequence, adding a terminal Pleistocene component, and providing a suite of ages (Jacobs *et al.* 2008; Mackay 2010). Those ages place the Howiesons Poort at the site between ~60 ka and ~66 ka, the post-Howiesons Poort between ~55 ka and ~60 ka, and the terminal Pleistocene to around 22 ka. The final MSA is bracketed by ages of ~55 ka and >40 ka.

Elands Bay Cave (EBC)

Elands Bay Cave is located at the present day coastline, 15 km north west of DRS. The site was first excavated in 1970, revealing a sequence of near-modern occupation underlain by a discontinuous sequence of Holocene, terminal Pleistocene and late Pleistocene deposits. The late Pleistocene units are presently represented only by radiocarbon ages with large errors. Of interest here are the terminal Pleistocene units with ages centring on ~16 ka and ~25 ka respectively; there is an apparent occupational hiatus during the peak of MIS 2 (see Mackay 2009 for discussion).

MATERIAL CONSTRAINTS

Three materials dominate the assemblages at DRS, KKH and EBC; quartz, quartzite and silcrete. Between them these rock types account for more than 90% of artefacts in most sequence components of all sites. These materials have different qualities and different patterns of distribution (Table 2). Silcrete is the finest-grained material of the three and is also the least often flawed. However, silcrete is usually only encountered in isolated and uncommon primary contexts within the study area. Surveys of river cobbles in the large Olifants River valley, where silcrete is known to outcrop, failed to reveal any substantial quantities of water-borne silcrete clasts.

In contrast to silcrete, both quartzite and quartz are widely distributed. Both occur within the dominant geological group in the study area – Table Mountains Sandstone (TMS) – though quartzite occurs in primary and secondary forms, while quartz occurs as pebbles eroding out of TMS conglomerates. The pebble form of quartz generally limits the size of clasts available for knapping to < 80 mm.

Quartzite and quartz also have quite different qualities with respect to flaking. Quartzite is comparatively coarse-grained, though generally flakes in a predictable way. Quartz, on the other hand, might be considered to be very fine-grained, but pieces are often badly flawed. Another potentially important difference between the two materials is that quartzite does not sustain bipolar reduction very well, making it difficult to reduce cores heavily. Of 66 quartzite cores studied, only 3 (4.5%) had sustained bipolar reduction, with a minimum core mass of 1.7 g. Comparable values for silcrete were 18.4% (n=60) and 0.6 g; and for quartz 45.9% (n=177) and 0.1 g. Limits are also evident in the minimum thickness of quartzite flakes. Among 1044 complete quartzite flakes with lengths >15 mm studied by Mackay (2008), the lower quartile for thickness was 6.36 mm. Comparable values for silcrete and quartz were 3.69 mm and 4.61 mm respectively. Minimum values for the three materials were: silcrete = 1.45 mm, quartz = 1.5 mm, and quartzite = 2.28 mm. These data show that silcrete and quartz were more frequently reduced to a greater extent that quartzite, suggesting that silcrete and quartz offered better

Table 2: Availability and quality of key materials in the study area

Material	Prevalence	Distribution	Size limits	Reduction potential
Quartzite	Common	Wide	None	Low
Quartz	Common	Wide	80 mm	High
Silcrete	Rare	Isolated	None	High

Table 3: Temperature changes in Epica Dome C relative to analytic time units

Time unit (ka)	MIS	Mean temp.	S.D.	Expected tech. costs
16-25	2	-9.06	0.94	highest
35-55	late 3	-7.15	1.04	high
55-60	early 3	-6.34	0.89	moderate
60-65	late 4	-7.95	0.96	high
65-70	mid 4	-8.76	0.71	highest
70-74	early 4	-6.72	0.89	moderate
>74	5	-3.69	2.70	low

reduction potential than quartzite (note also Mackay 2008).

ENVIRONMENTAL VARIATION IN THE STUDY PERIOD

Environmental change in the Western Cape through the late Pleistocene is complex (Chase 2010). Unlike many other areas of Africa, the Western Cape likely responded to cooler Pleistocene conditions with increased rainfall, and considerable variation in floral and faunal communities (Chase and Meadows 2007). Unfortunately, terrestrial archives of environmental change in the area are presently few, coarsely resolved and not easily understood directly in terms of changing subsistence opportunities. Though unsatisfying, recourse to coarse global proxies of climate change, specifically those in global temperature, is practical in three respects. First, high-resolution records are available which cover the study period. Second, there is a demonstrable relationship between temperature and primary productivity, albeit that this is strongly conditioned by water availability (Kelly 1995). Third, studies of the relationship between risk and technological complexity are generally phrased in broad terms relating to global temperature patterns. For example, Collard *et al.* (2005) found that effective temperatures as a proxy for risk was a significant predictor variable in modelling technological variation across twenty hunter-gatherer groups.

Temperature data for the present study are taken from the Epica Dome C ice core, derived from Antarctica (Jouzel *et al*. 2007). This record is presumed to be of more relevance to southern hemisphere changes than northern hemisphere records (though note Chase 2010 who suggests northern hemisphere forcing has dominated southwest African climates at 10^3yr timescales in the last 12 kyr). Temperature changes in the Epica Dome C record are summarised in Table 3. The temporal divisions used in table 3 derive from the ages of culture historic units as discussed above (eg., Howiesons Poort, ~60-65 ka, Still Bay ~70-74 ka etc). The data suggest that the two coolest periods occur during MIS 2 between 25 ka – 16 ka and in the middle of MIS 4 between 65 ka – 70 ka.. The warmest period is that ante-dating the onset of MIS 4 – thus before 74 ka.

EXPECTATIONS FROM EXISTING MODELS

Cooler temperatures are likely to be associated with increased risk for hunter-gatherers because of reduced available biomass on the landscape and reduced opportunities for encountering and capturing resources. Furthermore, periods of increased risk resulting from lowered resource quality and/or density are likely to be associated with more costly technologies as our model above suggests. Given these conditions, highest costs are likely to have been borne during MIS 2 and mid MIS 4, as people responded to the increased risk arising from peak cold temperatures. Such costs are expected to have been reflected in the manufacture of complex implements and potentially also in an emphasis on high quality materials for artefact manufacture. Thus we might expect to see high proportions of silcrete in assemblages. Conversely, we might expect that during the warm conditions of MIS 5 people invested relatively little in complex implements and acquired material largely on-encounter, with procurement embedded in their other routines. Resulting assemblages might thus contain greater proportions of quartzite and quartz and less silcrete. In between these extremes, the cool conditions of later MIS 4 and possibly also late MIS 3 might have favoured reasonably high-cost technologies, while earlier MIS 4 and earlier MIS 3 might have favoured reasonably low-cost systems. These predictions are summarised in Table 3.

Table 4: Changes in implement discard rates (shaded cells highlight highest values)
* Artefact numbers for this time unit at KKH are arbitrarily doubled to account for a reduced excavation area

Site	Time unit (ka)	Time elapsed (approx)	Dominant implement type	Number of cases		Discard rate (imps / kyr)	
				dom.*	all	dom.*	all
DRS	55-60	5	Unifacial point	4	6	0.8	1.2
	60-65	5	Backed artefact	29	37	4.8	7.4
	65-70	5	Backed artefact	7	14	1.4	2.8
	70-74	4	Bifacial point	15	31	3.8	7.8
KKH	35-55†	20	Scraper	6	6	0.3	0.3
	55-60	5	Unifacial point	9	36	1.8	7.2
	60-65	5	Backed artefact	86	145	17.2	29.0

Table 5: Changes in material selection (shaded cells highlight highest values)

Site	Material	Age unit (ka)						
		16-25	35-55	55-60	60-65	65-70	70-74	>74
DRS	*Quartzite*			10.0	10.1	38.6	54.1	74.1
	Quartz			18.6	34.0	41.8	19.4	22.7
	Silcrete			71.5	55.1	19.7	26.5	3.2
KKH	*Quartzite*	37.5	37.6	28.6	14.3			
	Quartz	60.7	50.5	8.7	9.9			
	Silcrete	1.8	11.8	62.7	75.8			
EBC	*Quartzite*	1.0						
	Quartz	88.9						
	Silcrete	10.1						

RESULTS: LATE PLEISTOCENE TECHNOLOGICAL CHANGES IN THE CASE STUDY

Three facets of technological change, derived from the discussion of costs above, are investigated here. Those are changes in the prevalence of complex implements, changes in the selection of high quality materials, and changes in discard thresholds.

Changes in complex implements

There are marked changes in the nature and prevalence of implements through the study period. No implements are common in the oldest unit, while bifaces and bifacial points are restricted in time to the 70-74 ka unit at DRS. Backed artefacts occur from 70 ka through to 60 ka and thereafter are replaced by unifacial points as the dominant form at both DRS and KKH. From 55 ka onwards at KKH there are few implements generally, with scrapers the most common form. Backed artefacts occur in the 16-25 ka units at KKH and EBC, though the numbers are small.

Table 4 summarises changes in discard rates for the dominant implements in each unit at each site. Note that though the samples at both DRS and KKH derive from a single 1 m square, they should not be compared with one another. The sizes of the sites are very different and thus 1m^2 represents a different proportional sample in each case. The variance is best considered between units within sites. No data are presented for the MIS 5 unit at DRS, or for the MIS 2 unit at KKH and EBC as the duration of these units not been established sufficiently by bracketing ages. Nevertheless, as noted above, neither appears to be characterised by a profusion of implements.

At DRS implement discard rates peak in the 60-65 ka unit, with almost six implements discarded per 1000 years within the sampled area. High discard rates also occur in the 70-74 ka unit. On the other hand, discard rates are generally low during the 65-70 ka and 55-60 ka units. At KKH, as at DRS, peak rates of implement discard occur in the 60-65 ka unit, with more than 17 implements discarded per 1000 years within the sampled area. Subsequent implement discard rates are very low.

Changes in material selection

Changes in material selection at the three sites are presented in Table 5. At DRS, the earliest unit contains a preponderance of quartzite and quartz with small

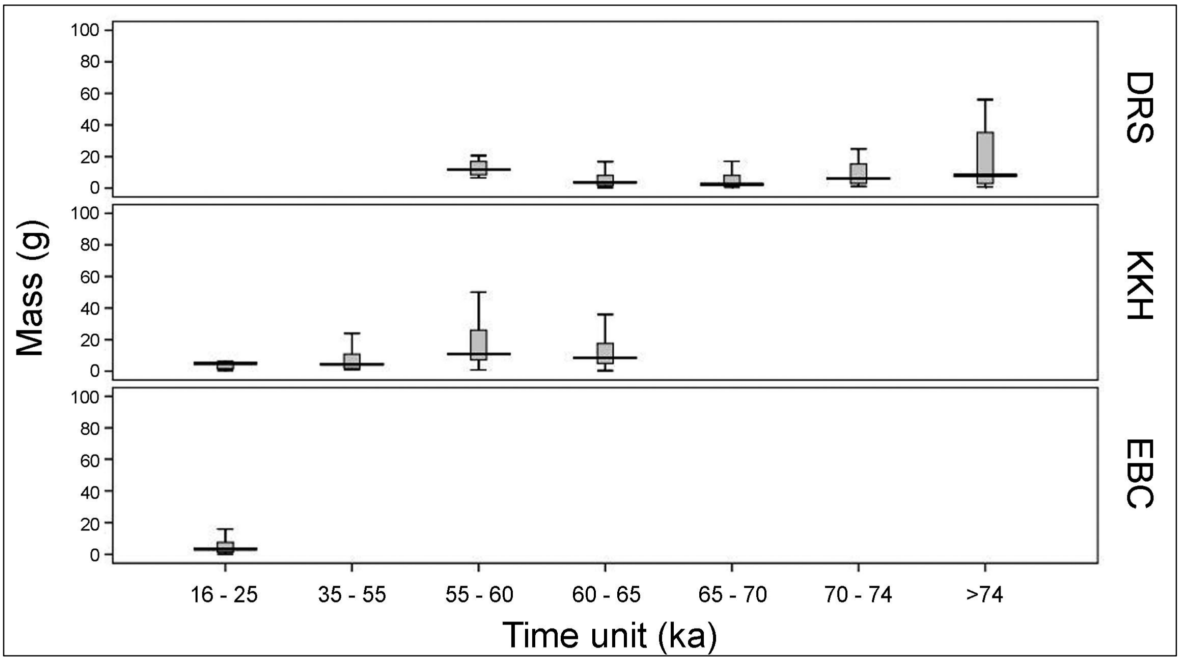

Figure 6: Changes in core weight through the time units used

contributions from silcrete. Quartzite continues to be dominant in the 70-74 ka unit, though with silcrete having replaced quartz as the second most common material. From 65-70 ka quartz becomes the dominant material, followed by quartzite. Through the remainder of the DRS sequence, silcrete is the most common material.

As with DRS, material selection at KKH appears strongly to have favoured silcrete in the period from 55-65 ka. The later part of MIS 3 (35-55 ka) and the MIS 2 unit both demonstrate a preponderance of quartz. The MIS 2 pattern is replicated at EBC, though it should be noted that while the material prevalence data for DRS and KKH derive from all artefact types in the assemblage, the EBC data are based on material prevalence among cores and retouched flakes only (the remainder of the assemblage has not been studied by Mackay). At DRS, the site located closest to and in the more similar stone procurement context to EBC, quartz is over-represented cores by around 17% and under-represented in retouched flakes by around 1.5%. Using these figures to adjust the EBC data results in a quartz proportion between ~72% and ~90%. Thus, even allowing for maximum scaling down (eg., using the core-based correction only), it seems likely that at EBC quartz was comfortably the most common of the three materials considered.

Reduction changes at DRS, KKH and EBC

Discard thresholds are approximated here using core mass at discard. Changes over time are presented in Figure 6. Clear patterns are evident at both DRS and KKH. At DRS core masses are at their largest in the MIS 5 unit (>74 ka), with initial reductions in mass following the onset of MIS 4. In the 65-70 ka unit, during the coldest period of MIS 4, cores are at their smallest, with subsequent increases in size apparently tracking warming out of MIS 4 and into MIS 3. At KKH cores are small during late MIS 4, increasing in size into early MIS 3, and then decreasing again through late MIS 3 into MIS 2. Cores are also very small in the MIS 2 unit at EBC, with masses comparable to those at KKH.

DISCUSSION: ASSESSMENT OF RESULTS RELATIVE TO EXPECTATIONS

In Table 6, results for the three variables considered above are assigned ranked scores from one to three, allowing a coarse assessment of overall 'technological costs' for the assemblages in each time unit. Also in Table 6 are the expected outcomes for each unit. The results reveal some interesting patterns.

First, expectations of high costs are met only once – during late MIS 4. The period identified as having the lowest overall risk was the MIS 5 unit, and this indeed appears to be represented by low cost technologies. Aside from these two matches, the predictions of the model are not satisfied by the data in the other five time units. Apparently high cost systems pertained during periods identified as of moderate risk with respect to global temperatures, for example in early MIS 3 and early MIS 4.

At first glance, such a poor match between the model and the data might indicate that the model has no value. However the failure of model can be just an informative as its success as it can help to define and isolate problems (Winterhalder 2002). Equally interesting to the instances of agreement between expectations and outcomes are those of divergence. Most notably, the two periods identified as having the highest temperature-related risk, during the peak cold of MIS 2 and MIS 4, exhibited low

Table 6: Summary of results vs expectations

Time unit (ka)	MIS	Observed costs			Summary	Expected cost
		Magnitude (material selection)	Frequency (discard threshold)	Complexity (implement frequency)		
16-25	2	low (1)	low (1)	low (1)	lowest (3)	highest
35-55	late 3	low (1)	low (1)	low (1)	lowest (3)	high
55-60	early 3	high (3)	moderate (2)	moderate (2)	high (7)	moderate
60-65	late 4	high (3)	low (1)	high (3)	high (7)	high
65-70	mid 4	moderate (2)	low (1)	low (1)	low (4)	highest
70-74	early 4	moderate (2)	moderate (2)	high (3)	high (7)	moderate
>74	5	low (1)	high (3)	low (1)	mod-low (5)	low

cost, rather than high cost technologies. Similarly the high costs anticipated for late MIS 3 were in contrast to the observed outcomes.

There are several potential confounding factors that might have induced failures of correspondence between the model and the case study results. The first and most obvious is that southern hemisphere temperature is simply not a good proxy for risk. At the very least, and as noted earlier, the effect of temperature on primary productivity is moderated by moisture, and moisture was clearly variable in the Western Cape through the late Pleistocene. That said, evidence for moist conditions have been particularly well-remarked for MIS 4 – thus from ~60 ka to ~74 ka (cf., Chase 2010). Indeed, increased moisture has been implicated in the appearance of the Still Bay and Howiesons Poort culture historic units, which cohere in this study with the time units 70-74 ka and 60-65 ka respectively. Yet increased moisture would hypothetically have decreased risk at this time; in contrast, early and late MIS 4 are periods where technological costs would imply elevated risk. A further complication is that in the middle of MIS 4, when temperatures are at their nadir, technologies appear to become low cost. Unless this period was dramatically wetter than the earlier or later parts of the Stage then moisture-driven improvements in primary productivity are unlikely to be responsible for the observed variance. Perhaps more important is the fact moisture is not accounted for in models such as that put forward by Collard *et al.* (2005), which nevertheless demonstrate an inverse relationship between temperature and technological complexity.

A second possible complication arises from variation in population. Several authors have recently suggested that increases in technological complexity in early and late MIS 4 may have been driven, or at least underpinned, by increases in population (Powell *et al*. 2009). Specifically it has been suggested that adaptively beneficial technological variants might only be sustained among larger populations (Kline and Boyd 2010), and thus the viability of complex responses such as those witnessed in the Still Bay and Howiesons Poort might have been predicated on population increase during MIS 4. Again, mid MIS 4 provides a complicating factor. In order for population to have played a direct role in the appearance of technological complexity we would require population increases in early MIS 4, followed by decreases in mid MIS 4, with increases again occurring in late MIS 4 and being sustained into MIS 3. While not impossible, such an explanation would require at the very least some substantiation external to the predictions of the model itself – eg., some other, independent measure of population size demonstrating that such a complex suite of changes actually took place. This evidence is currently unavailable and as it stands we consider this explanation to be inelegant.

The final potential confounding factor is that the modelling used here for time costs is limited in its predictive power by assumptions that do not closely correspond to the real world. This seems reasonable on two fronts. First, the proposed interaction between magnitude and frequency costs of procurement, though having some intuitive merit, currently lacks an evidential basis. It is not clear how much time would be spent on the acquisition of stone, what proportion of a daily time budget this might be, and how effectively high magnitude costs could be offset by reduced discard thresholds. Second, the 1-3 point ranking system used may be inaccurate in providing equal weight to the costs of acquiring tool-stone, discarding large cobbles, and manufacturing large numbers of complex implements. It is not hard to imagine that lowering the discard threshold might have a lower cost than increasing travel time to acquire desirable stone and so perhaps the weightings should be different in the matrix in table 6.

Further consideration of the details of major failures of fit may also be informative. Specifically, it can be noted that higher cost technologies tended to occur, as predicted, during cooler conditions. This is most obvious in early and late MIS 4 and in early MIS 3. Furthermore, the warm period MIS 5 lacked costly technologies, again as expected. Where the predictions largely fall apart is under conditions of extreme cold, eg., MIS 2 and mid MIS 4. At this point we might return to the model discussed earlier.

One facet of a diminishing returns model of resource acquisition is that return rates are at their highest at the

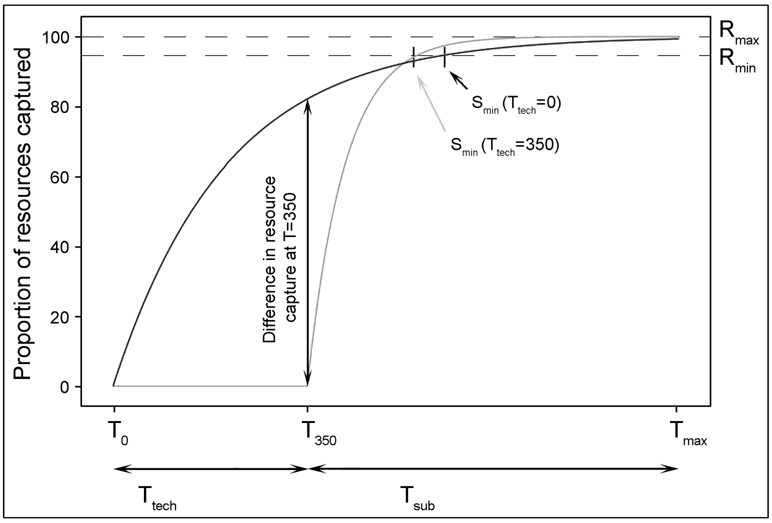

Figure 7: Differences in initial return where T_{tech}=350 and C = 0.3

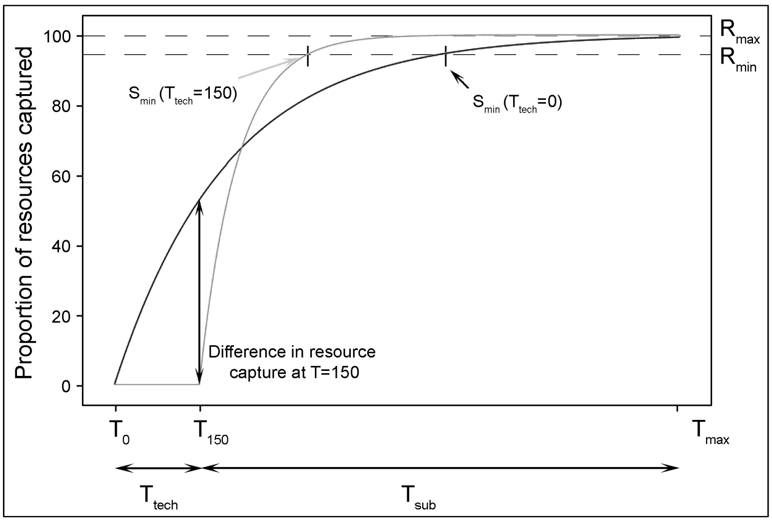

Figure 8: Differences in initial return where T_{tech}=150 and C = 0.3

start of foraging and decrease thereafter. Where time costs are factored in as a prelude to subsistence, initial foraging opportunities are foregone. Modelling results for two foragers taking different strategies into a poor environment (R_{min} = 95) shows the importance of this observation (Figure 7). The black line represents returns for a forager who invests the minimum in technological costs. Encounter rates are set at 5, and capture rates at 0.1. The grey line represents returns for a forager who invests 350 time units of their foraging time (T_{tech} = 350) in technology for a capture rate of 0.3, three times the rate of other forager.

The forager who invests heavily in technology (grey line) has a lower time to S_{min}, and would thus be expected to be pursuing the favoured strategy if reduction of time to S_{min} was the factor under selection. As the discrepancy between the return lines shows, however, there are also advantages to pursuing the low or least-cost strategy. Specifically, because return rates are highest at the start of foraging, the least-cost forager has already secured 78% of R_{min} by the time the high-cost forager has begun acquiring resources. Even if we reduce the time cost for a technology with a capture rate of 0.3 to T_{tech} = 150 – which would result in a reduction of time to S_{min} by 25% (348 time units vs. 598 time units) – the least-cost forager would still have acquired 50% of their resource requirements before the high-cost forager had begun foraging (Figure 8)[1]. A second point that might be made

[1] This idea becomes particularly interesting where the two foragers in question compete, rather than co-operate for the same limited set of resources. Allow that the high-cost forager prepares his/her equipment for the first hour of the day while the low-cost forager simply begins foraging with first light. By the time the high-cost forager enters the field, a proportion of the available resources – probably those most easily acquired – have already been taken. The resource base from which the high-cost forager begins to harvest is thus smaller than the starting resource base of the low-cost forager. In effect then, the actions of the low-cost forager suppress the return rates of the high cost forager. If the total quantity of resources in the patch is insufficient to support all of the foragers present, it is conceivable that something of a negative arms-race might ensue where time spent in the preparation and maintenance of gear was minimised in favour of time spent in subsistence.

is that so long as investment in technology does not increase the rate of encounter but only the rate of capture, the forager who invests less in technology will have more encounters within the available time. Effectively, the least-cost forager is trading off capture rates against number of encounters.

These observations may be relevant for understanding the mismatch between the model's predictions and the data for MIS 2 and mid MIS 4. Under these conditions of extreme cold, foragers appear to have switched from optimising time to S_{min} to optimising their number of encounters. It may be the case that there is a threshold value such that as the temperature gets lower, for example from late MIS 4 to mid MIS 4, increasing technology costs are no longer worth the benefit of a quicker time to $S_{min.}$

The modelling discussed earlier in this paper was predicated on foragers optimising for reductions in time to S_{min}. The archaeological data suggest, however, that at times foragers may have optimised for other currencies, potentially including number of encounters or maximisation of early returns. There may be some correlation between these inferences and what Hames (1992) refers to as a resource maximisation strategy. As Hames (1992: 209) notes, for a resource maximiser, "alternative activities […] are less fitness enhancing than foraging". Under conditions of extreme subsistence duress maximising the time spent engaged in subsistence, even if it is undertaken inefficiently, may be more advantageous than spending less time foraging efficiently (Bousman 2005).

CONCLUSIONS

Understanding technological decision-making requires an understanding of the costs and benefits of different technological systems. Studies of available ethnographic data suggest that complex technologies are likely to be favoured in high risk environments, with the inference that such technologies provide advantages in terms of improved rates of resource capture. Consideration of time costs helps explain why complex technologies are not also pursued in low risk environments. Where return rates are already high improvements arising from the pursuit of costly technologies are likely to be marginal. The archaeological data from late Pleistocene southern Africa seem generally to support the idea of a relationship between risk, resource abundance and technological cost, but also allude to greater complexity in that relationship than either the ethnographic data or models that optimise for time to S_{min} would suggest. Specifically at times of extreme cold, and by inference of subsistence duress, foragers appear to have minimised their technological time costs, presumably in favour of maximising the amount of time spent in subsistence. While this is not presented here as a thorough explanation of technological decision making under variable conditions, it suggests at least that the quality of modelling can be improved when hypothetical, ethnographic and archaeological data are considered together.

Acknowledgements

This paper stems from doctoral and post-doctoral research undertaken by AM while at ANU. Funding for that research has come from the ANU (PhD fieldwork grant), the Palaeoanthropology Scientific Trust (PAST), the South African Archaeological Society Kent Bequest and an Australian Research Council discovery grant (DP#1092445). AM would also like to thank John Parkington and Ced Poggenpoel for allowing access to the DRS material, and Will Archer for robust and enlightening discussions on the subject matter covered herein. BM was supported by a Luce/ACLS postdoctoral fellowship (B9471 01 180401 7301).

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