

**QUANTIFYING CLOVIS DYNAMICS: CONFRONTING THEORY
WITH MODELS AND DATA ACROSS SCALES**

by

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DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of

**DOCTOR OF PHILOSOPHY
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DEDICATION

I would like to dedicate this dissertation to my wife, Ana Desiree Davidson, and the two halves of my family, the UK Hamilton side and the US Davidson side, for all their love and support. I would also like to dedicate this dissertation to two old friends who were instrumental in getting me interested in archaeology, Briggs Buchanan, and Wayne Warren Kinney, Jr.

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ABSTRACT

This dissertation examines spatial and temporal variation in the Clovis archaeological record across Late Pleistocene North America at multiple scales. This multi-scale approach allows the development of models at a broad continental scale that are then used to inform processes occurring on more localized, regional scales. In particular this dissertation attempts to understand the nature of the Clovis population expansion across the North American continent, and the interplay between this expansion and cultural transmission processes that combine to generate the spatiotemporal structure of the Clovis archaeological record we see today. First, using the spatial distribution of radiocarbon dates across the continent I show that the Clovis expansion was a population expansion originating from the ice-free corridor, most likely sometime after ca. 11.6k ^{14}C yrs BP. Second, I develop a mathematical model of cultural transmission that is designed to explain the generation of variation in the archaeological record. The model predicts that the average size of projectile points should decrease through time at a predictable rate, due to the accumulation of copying errors. When combined with the expansion model, the combined model predicts that Clovis points should get smaller at a predictable

rate, on average, as the population expanded across the continent. Results show that indeed, the mean size of Clovis points reduces through time at the rate predicted. Third, I analyze the Clovis record of the central Rio Grande Valley and adjacent mountains. Results show that the Clovis occupation of the region was relatively long-term, with evidence of the repeated use of the landscape, most notably evidenced at the Mockingbird Gap Clovis site near Socorro, New Mexico. This long-term occupation is consistent with the predictions of the initial expansion model. Moreover, an analysis of Clovis projectile point size in the central Rio Grande Valley meets the predictions of the cultural transmission model, in that the points, while small, are exactly the predicted size given the linear distance of the central Rio Grande Valley from the mouth of the ice-free corridor. When combined, these results demonstrate that the Clovis archaeological record is the archaeological residue of a population expansion, which is evidenced both by the spatial distribution of radiocarbon dates across the continent, and in the spatiotemporal gradient of projectile point sizes. On a broader scale, this dissertation provides an analytic framework for exploring the cultural dynamics of the archaeological record through time and space, highlighting both the development of mathematical models, and the use of statistical metrics to test the predictions of these models.

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CHAPTER 1:

INTRODUCTION

The primary motivations behind this dissertation are twofold. First, I hope to provide a deeper, more objective understanding of the Clovis archaeological record of the North American continent by focusing on statistical tests of Clovis archaeological data sets using hypotheses derived from simple mathematical models. Second, I wish to highlight two fundamental aspects of scientific research that are often overlooked in archaeology: the analysis of dynamics, and the consideration of scale.

TOWARD AN OBJECTIVE APPROACH TO CLOVIS ARCHAEOLOGY

The early Paleoindian archaeology of Late Pleistocene North America draws considerable attention from academics, the public and the media because of the wide diversity of interesting questions the period poses. During the Late Pleistocene, current evidence suggests that the North American continent was colonized by Northeast Asian hunter-gatherers, as part of the broader, world-wide biogeographic expansion of the human species across the planet during the latter stages of the Pleistocene (Anikovich et al., 2007; Dolukhanov et al., 2001; Dolukhanov et al., 2002; Goebel et al., 2008; Kuzmin and Tankersley, 1996; Vasil'ev et al., 2002). North America was colonized sometime after the Last Glacial Maximum, and as the continent warmed from full glacial conditions, the continent underwent wholesale changes in its ecological, environmental, and climatological structure (Lyons, 2003; 2005; Pielou, 1991). During this period of dramatic climatic change and human population expansion, the continent saw the size-

selective extinction of many Late Pleistocene animal species, most notably the megafaunal megamammals, leading to the ongoing, and often spirited debate over the relative role of anthropogenic versus climatic processes in this major extinction event (Grayson and Meltzer, 2002; 2003; 2004; Haynes, 2002; Lyons et al., 2004; Martin, 1967; Mosimann and Martin, 1975; Owen-Smith, 1988; Surovell and Waguespack, In press; Surovell et al., 2005). Archaeologically, it is of considerable importance to understand the broader question of how hunter-gatherer populations adapted technologically and behaviorally to the diverse and dynamic conditions of the North American Late Pleistocene. The human colonization of the North American continent was a natural biogeographic experiment in which a successful and highly adaptive top predator was released into a dynamic natural environment. It is then the job of researchers from multiple disciplines to piece together the archaeological, paleoenvironmental, paleontological and climatological evidence to understand how and why the experiment played out in the way it did.

However, despite the many decades of investigation into this period of prehistory we are no closer to a consensus on the major issues than we were decades ago. On the contrary, we see an ever-increasing diversity of theories proposed to explain different aspects of Late Pleistocene North America, from issues of the origins, routes, and direction of human colonization (Bradley and Stanford, 2004; Dixon, 1999; 2001; Fladmark, 1979; Goebel et al., 2008; Stanford and Bradley, 2002) to the human (Haynes, 2006; Lyons et al., 2004; Surovell and Waguespack, In press; Waguespack and Surovell, 2003), environmental (Grayson and Meltzer, 2002; 2003; 2004), or extraterrestrial demise of the megafauna (Firestone et al., 2007). The increasing diversity of theories is

largely a function of their lack of testability, or falsifiability. As such, theories once proposed often become entrenched positions, to be defended irrespective of their empirical support, rather than subjected to robust, theoretically-driven analyses of data.

Of course, as archaeology is an observational, not experimental science, we have poor control over our data in comparison to most other fields of science, due to the many dimensions of archaeological preservation, recovery, and interpretation. The paucity of archaeological data is particularly true of the Clovis period in which we are often confronted with small sample sizes and low levels of replication. In early Paleoindian archaeology, we are usually limited to the analysis of lithics, or when preservation allows, faunal material, both of which constitute a tiny fragment of what must have been the overall material culture and behavior of Clovis hunter-gatherers. So, statistically we are faced with two options. The first is to bypass quantitative analyses due to the lack of statistical power, and rely solely on the informed judgments of experienced researchers. The second is to analyze statistically the data sets we have available with the understanding that the patterns and trends we may recover are subject to an array of statistical caveats. My approach is the latter, as I believe the quantitative approach is the only scientific way of using the available data to accumulate objective knowledge by revealing replicable statistical patterns in data. These can then be subjected to further analyses as more data become available.

THE IMPORTANCE OF DYNAMICS AND SCALE IN ARCHAEOLOGY

My second motivation behind this dissertation is related to the above points, but stems from perhaps a more philosophical perspective on the goals of scientific research. In

general, science is more interested in dynamics than statics; that is to say scientific research attempts not only to describe phenomena, but to explain how and why phenomena change over time and space. For example, while natural history is the much-needed documentation of living things in the natural world, ecology and evolution are the disciplines that focus on the dynamics of living things, both in terms of their interactions with other organisms and their environments, but also in terms of explaining how those interactions result in biological change over time and in the patterns of biodiversity we see in the world around us.

Because we as archaeologists have very little control over our data, much of our training and research focuses on data recovery (i.e., surveys and excavations), which in turn quite naturally leads to a predominantly cultural historical approach to archaeological research, i.e., the documentation of what happened when and where. As a result, traditionally there has been much less of an emphasis on explanations of cultural change over time, either across cultures or within cultures, from any quantitative, theoretical perspective. Essentially, as archaeologists we are much better at describing things than explaining them.

In this dissertation I have tried to focus on analyzing gradients of change in Clovis archaeology across the North American continent, from the perspective that by doing so we get closer to a mechanistic explanation of the various processes that drive cultural change. A traditional culture historical perspective tends to view prehistory as a sequence of equilibrium conditions punctuated by periods of rapid change in which one culture transforms itself into another through bursts of technological innovations or in response to changing environmental conditions. However, the analysis of gradients of change within

observable time periods lends greater insight into how humans continually adapt to their environments and puts widespread cultural changes within the greater context of human technological, behavioral, and social adaptation to ecological conditions.

A second point I wish to emphasize, which is often over-looked in archaeology, is the importance of scale (i.e., Levin, 1992). Here, by scale I simply mean the scale of analysis at which a research question is addressed and the recognition that the scale of the research question largely determines the level of explanation that can be achieved.

Further, the concept of scale implies a natural hierarchical structuring of data, in which patterns at one scale are necessarily related to patterns at other scales. For example, coarse-grained continent-wide patterns of archaeological variation are structured by the underlying sum of regional patterns, which in turn are structured by local, site level variation, which ultimately, at some level, are the result of fine-grained decision-making processes by groups of individuals. As such, patterns observed at one scale lead directly to hypotheses about patterns that may be observable at higher scales or to mechanistic explanations of patterns at finer scales. In early Paleoindian archaeology, scales of analysis are often conflated and patterns observed at the site level are often presented as indicative of continent-wide adaptations. In this dissertation I have taken a top-down approach by first analyzing coarse-grained patterns of variation in Clovis archaeology across the North American continent, then have used these patterns to explore related finer-grained patterns of variation across the continent, and at regional and site levels.

THE CHAPTERS

All three chapters that constitute the main body of the dissertation are multi-authored, reflecting the various contributions of colleagues to the research, whether through contributing data, aid in data analysis, interpretation, or fieldwork. However, for all three chapters I designed the primary research questions, acquired the data, constructed the mathematical models, performed the data analysis, and wrote the papers.

Chapter 1 is a brief introduction to the primary motivations driving the research presented in the dissertation.

Chapter 2 addresses spatio-temporal gradients in Clovis-age radiocarbon dates across the North American continent. The main question of interest here is whether there are recognizable trends in Clovis-age dates across the continent, and if there are trends, what they suggest about the timing, location, and origin of the Clovis culture. In particular this chapter uses a simple binning technique (Fort, 2003; Fort and Mendez, 1999a; Pinhasi et al., 2005) to test alternative models of Clovis origins including the ice-free corridor, the west coast, the east coast, and the potential pre-Clovis origins of the Clovis culture. The data show clear evidence of a northwest-southeast gradient in radiocarbon dates across the continent, suggesting that the Clovis archaeological record is the archaeological residue of a population expansion originating from near the supposed mouth of the ice-free corridor. Further, the steepness of the gradient suggests that colonization was extremely rapid, fuelled by a combination of rapid population growth rates, large home ranges, and distinct habitat preferences.

Chapter 3 uses stochastic models of cultural transmission in order to develop a null model of gradients of change in long-lived technologies transmitted through multiple

generations. In particular, we show that information, such as the size and form of a projectile point, is subject to the accumulation of copying errors over time. These copying errors are a significant source of variation in archaeological assemblages as they compound over time and generations. However, most importantly, and non-intuitively, the mathematics of the model show that artifacts subject to this form of cultural transmission and compounding error rates are expected to shrink over time due to the multiplicative nature of the transmission process. Specifically, the model suggests that in the absence of directional selection, copied artifacts, such as projectile points should decrease in absolute size through time at a rate predicted by the Weber fraction, a proportional measure of the lower threshold of human visual perception (Eerkens, 2000). Using the same spatiotemporal gradient model developed in Chapter 1 we show that indeed, Clovis projectile points decrease in size over the North American continent as the population expands through time and space, at exactly the rate predicted by the cultural transmission model. Further, we develop statistics to measure these gradients of change and to estimate the importance of biased transmission rules during the learning process in technological traditions. We show that it is possible to link directly the mathematics of cultural transmission to the shape of frequency distributions of empirical data recovered from the archaeological record. This finding could be a particularly useful development in archaeology because it means that the shape of frequency distributions of archaeological data can, in themselves, generate hypotheses and insights into the underlying generating mechanisms involved.

Chapter 4 takes a more regional, site level perspective of Clovis archaeology by focusing on the Clovis record in the central Rio Grande Valley, New Mexico. In

particular we analyze two Clovis projectile point collections, one from the Mockingbird Gap Clovis site, and the second from Socorro County, New Mexico. In this chapter we show that the Clovis occupation of the central Rio Grande Valley is indicative of a higher-country Clovis adaptation than traditionally assumed in Clovis archaeology. The distribution of artifacts and raw material sources suggests Clovis groups in this area focused on the central Rio Grande Valley, and the mountain country to the west of the Rio Grande, in what seems to have been a large, but relatively well-defined home range. These findings are in qualitative agreement with predictions made in Chapter 2, where we hypothesized that Clovis land use likely incorporated large home ranges centered on particular habitat niches, that may have been used over multiple generations, as opposed to the non-redundant, sweeping model of Clovis land use suggested by Kelly and Todd (1988). Further, we show that the size of Clovis points in the central Rio Grande Valley meets the quantitative prediction of projectile point size from the gradient model developed in Chapter 2. That is to say that Clovis points in the central Rio Grande Valley are almost exactly the size one would predict them to be given the linear distance from the central Rio Grande Valley to the mouth of the ice-free corridor. This finding also suggests that the Clovis occupation of the region probably occurred in the latter stages of the Clovis period, although at this time we have no absolute dating of the Clovis archaeological record in the Rio Grande Valley.

In Chapter 5 I summarize these results and bring them together into a broader picture of the Clovis period in North America as suggested by the analyses conducted in these three chapters. In general, the data and analyses from this dissertation show that the Clovis technocomplex is the archaeological residue of a rapidly expanding population of

hunter-gatherers that most likely entered the continental United States from near the mouth of the ice-free corridor. Colonization proceeded rapidly, most likely in a kin-structured wave of advance, composed at the regional level by a series of home ranges established around preferred foraging niches and habitats, that would increase in number with each generation. This model predicts that Clovis land-use likely focused on regional hotspots of activity, connected by extensive social networks created by familial and genetic ties, and the exchange of goods and information across vast regions. The dissertation concludes with a series of questions posed by these analyses, which will hopefully constitute areas of future research.

CHAPTER 2:

SPATIAL GRADIENTS IN CLOVIS-AGE RADIOCARBON DATES ACROSS NORTH AMERICA
SUGGEST RAPID COLONIZATION FROM THE NORTH.

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ABSTRACT

A key issue in the debate over the initial colonization of North America is whether there are spatial gradients in the distribution of the Clovis-age occupations across the continent. Such gradients would help indicate the timing, speed and direction of the colonization process. In their recent reanalysis of Clovis-age radiocarbon dates, Waters and Stafford [*Science* 315:1122 (2007)] report that they find no spatial patterning. Further, they suggest that the brevity of the Clovis time period indicates that the Clovis culture represents the diffusion of a technology across a pre-existing pre-Clovis population rather than a population expansion. In this paper, we focus on two questions. First, we ask whether there is spatial patterning to the timing of Clovis-age occupations, and second, whether the observed speed of colonization is consistent with demic processes. Using time-delayed wave of advance models we use the radiocarbon record to test several alternative colonization hypotheses. We find clear spatial gradients in the distribution of these dates across North America, which indicate a rapid wave of advance originating from the north. We show that the high velocity of this wave can be accounted for by a combination of demographic processes, habitat preferences, and mobility biases across

complex landscapes. Our results suggest that the Clovis-age archaeological record represents a rapid demic colonization event originating from the north.

INTRODUCTION

In this paper, we consider five alternative hypotheses that have been proposed to account for the initial early Paleoindian occupation of North America. The first hypothesis is the traditional model, which states that Clovis peoples migrated into unglaciated North America from Beringia via an ice-free corridor between the Laurentide and Cordilleran ice sheets (Haynes, 2005). Research suggests an ice-free corridor would have been open and available for human passage by 12,000 years ago, although the habitability of the corridor is still a matter of debate (Mandryk et al., 2001). However, recently there has been renewed interest in alternative hypotheses. A second hypothesis is that Clovis peoples migrated along the coast of Alaska, British Columbia, and Washington State (Dixon, 1999; Mandryk et al., 2001). This model, usually referred to as the Northwest Coast model, suggests that maritime-adapted groups using boats moved along the ice-free western coast and sometime later moved east into the interior of the continent. A third hypothesis, which has been raised recently is that the initial colonists could have rapidly skirted the western coast of North America and established their first substantial occupations in South America (Anderson and Gillam, 2000). In this hypothesis colonists would then have moved north through the Isthmus of Panama colonizing North America from the south. A fourth hypothesis is that North America was colonized by Solutrean people who had traveled along the edge of an “ice bridge” between Europe and North America (Bradley and Stanford, 2004), so that the initial colonization occurred from the

east. This hypothesis is driven by suggested similarities between Clovis and pre-Clovis technology on the one hand and Solutrean technology on the other, which some take to indicate an historical connection (Bradley and Stanford, 2004). A fifth hypothesis, as proposed by Waters and Stafford (Waters and Stafford, 2007), is that Clovis technology may have been a technological innovation that spread via cultural transmission through an established pre-Clovis population, which had colonized North America sometime earlier in the Pleistocene before the Clovis phenomenon.

We test these five models by analyzing the spatial distribution of Clovis and Clovis-aged radiocarbon dates across North America. We include the earliest available Clovis or Clovis-age dates from different regions across North America with the assumption that they reflect meaningful temporal and spatial variation in the initial colonization process. We located the potential origin of a colonizing wave at six locations, four reflecting the external origins of the alternative colonization models (north for the traditional or ice-free corridor model, east for the Solutrean model, south for the Isthmus of Panama, and west for the Northwest Coast model), and two reflecting pre-Clovis origins. For the northern origin, we chose Edmonton, Alberta, following the assumed location of the southern mouth of the ice-free corridor (Martin, 1967; Mosimann and Martin, 1975). For the east we chose Richmond, Virginia, a location roughly halfway down the east coast of North America. For the southern origin we chose Corpus Christi, Texas, reflecting a potential route north through Central America (Anderson and Gillam, 2000), and for the western origin we chose Ventura, California, a location about halfway down the west coast of North America and across from the Channel Islands where late Pleistocene human remains and evidence for a contemporaneous maritime-based

subsistence economy has been recovered (Orr, 1962; Rick et al., 2001). While each wave is centered on a particular location, given the width of the wavefronts used, and the low sample size of available radiocarbon dates, our results are robust to reasonable changes in origin. For the pre-Clovis origin model, we centered the colonizing wave on Meadowcroft Rockshelter (Adovasio et al., 1999), Pennsylvania, and Cactus Hill (McAvoy and McAvoy, 1997a), Virginia, two of the earliest, and most prominent pre-Clovis candidates in North America.

THE TIME-DELAYED WAVE OF ADVANCE MODEL

To model the wave of advance we follow procedures outlined by Fort and colleagues in their recent studies of other human prehistoric expansions (Fort, 2003; Fort et al., 2004a; Fort and Mendez, 1999a; 1999b; Fort et al., 2004b; Pinhasi et al., 2005). The simple wave of advance model combines a logistic population growth term with Fickian diffusion, which describes the spread of the population in two spatial dimensions. The resulting equation is termed the Fisher equation:

$$\partial N / \partial t = \gamma N (1 - N / K) + D \nabla^2 N \quad (1)$$

where γ is the maximum potential growth rate, N is population size or density, K is the carrying capacity of the local environment, D is the diffusion coefficient (in km yr^{-1}), and ∇^2 is the Laplacian operator describing the diffusion of the population, N , in two dimensions.

The diffusion coefficient measures the lifetime dispersal of an individual, measured by the average distance between location of birth and first reproduction. This

measure, the mean squared displacement of an individual, is then adjusted by random dispersal in two dimensions, and generation time T , giving the diffusion coefficient $D = \lambda^2 / 4T$, where λ^2 is the mean square displacement. The well-known solution to equation 1 produces traveling waves of colonists, radiating out in concentric circles from an initial point of origin. The velocity, v , of this wavefront of colonists is given by

$$v = 2\sqrt{\gamma D}. \quad (2)$$

Note that the velocity is simply a function of the population growth rate, γ , and the diffusion rate, D , and independent of population size, N , or carrying capacity, K . Although widely used in the analysis of spatial movement, the Fisher equation incorporates some biologically and anthropologically unrealistic assumptions (Fort and Mendez, 2002) perhaps most importantly that individual dispersal begins at birth, and so dispersal is continuous through life. However, human dispersal is best modeled discretely as there is generally a time delay between birth and dispersal, related to rates of human growth and development. This time delay reflects the situation that as a hunter-gatherer residential group establishes a new home range during the process of colonization, there is a time delay before the next generation expands into the adjacent landscape. Fort and colleagues (Fort and Mendez, 1999a; 1999b; 2002) derived a model to account for such generational time-delays in the diffusion process. They show the velocity of the time-delayed traveling wave is then

$$v = \frac{2\sqrt{\gamma D}}{1 + \frac{\gamma T}{2}}. \quad (3)$$

The velocity of the wavefront is thus reduced as a function of the generational time delay, T . Note that in cases where there is no time delay ($T = 0$), equation 3 reduces to equation 2. The expected velocity of a hunter-gatherer population expansion can then be estimated by parameterizing equation 3 with ethnographic data on maximum population growth rates, γ , mean generation times, T , and measures of individual lifetime dispersal, D .

Parameter estimation

We estimate these parameters using published data from refs (Walker et al., 2006) and (MacDonald and Hewlett, 1999). For natural fertility populations, age at first birth, a common measure of mean generation time, T , is approximately 20 years, and maximum annual population growth rates, $\gamma \approx 0.04$ (Walker et al., 2006). Measures of lifetime dispersal in modern hunter-gatherers are more difficult to quantify. Using hunter-gatherer mating distance data (MacDonald and Hewlett, 1999), mean individual dispersal within populations can be conservatively estimated to be up to 3000 km² per generation, though the upper range for a recorded marriage distance gives a mean squared distance of near 21,000 km². While these data are not ideal measures of dispersal, where the data is available marriage distance has been shown to correlate both strongly and positively with generational dispersal (Hewlett et al., 1982). Therefore, we use 3000 km² as a conservative measure of lifetime dispersal, giving $D = 37.5$ km². These demographic measures are conservative as these data originate from societies near demographic

equilibrium, with neighboring populations, a situation far from representative of a rapidly growing, late Pleistocene hunter-gatherer population expanding into an open landscape. Combining these parameters with equation 3, the expected velocity of this wave is then about $v = 1.77$ km per year.

Data

We used radiocarbon dates or averaged dates from 23 sites (see Figure 2.1, Table 2.1 and Methods). Seventeen of the dates are those identified by Waters and Stafford (Waters and Stafford, 2007) as either reliable Clovis or Clovis-aged dates. The other six are dates from other Clovis or Clovis-age sites that occur in similar contexts but were not considered in their analyses (see Methods for details). Five of these sites (Debert, Vail, Casper, Hiscock, and Big Eddy) can be considered Clovis sites due to the presence of Clovis-like fluted points. Hedden lacks fluted points, but has a subsurface assemblage dating to the same period as other regional Clovis-age sites (Table 2.1). The majority of the additional dates ($n = 5$) are from early Paleoindian sites located in eastern North America, which are widely considered to represent the earliest dated late Pleistocene occupations of the east (Haynes et al., 1984). This sample size is admittedly extremely small, but we are limited by the rarity of well-dated Clovis-age sites (Waters and Stafford, 2007). All radiocarbon dates used in our analyses (Table 2.1) were calibrated using the Intcal04.14 curve (Reimer et al.) in Calib 5.0.

Statistical approach

To represent the expanding waves for each analysis we measured the distance of each site from the wave's point of origin using great circle arcs (in km). To establish the earliest

occupations per region the earliest observations per bin were regressed against the dependent variable. Following methods outlined by Fort and colleagues, concentric bins were set at a consistent width (450 km) radiating out from each wave origin, and the earliest dated site within each bin was regressed by its distance from origin (see Methods for details). To evaluate the best-fit model, we calculated the correlation coefficient (r) for each test. The origin with the highest correlation coefficient is therefore the most likely point of origin (Fort and Mendez, 1999a; 1999b; Pinhasi et al., 2005). Similar methods have been used successfully in understanding colonization processes in other regions throughout prehistory (Fort, 2003; Fort and Mendez, 1999a; 1999b; Fort et al., 2004b; Pinhasi et al., 2005). Here we do not attempt to differentiate between demic and cultural diffusion models directly, as both types of model can be constructed to predict the same trajectories through time (Ammerman and Cavalli-Sforza, 1973). Rather, similar to other researchers, we suggest that if a model can predict a demic diffusion, given realistic demographic and ethnographic parameters, then the hypothesis of demic diffusion has not been falsified until a cultural diffusion model could be shown to yield similar, or more accurate results (Ammerman and Cavalli-Sforza, 1973; Fort et al., 2004a; Fort and Mendez, 1999a; 1999b; Pinhasi et al., 2005).

Following Fort's methods, we estimate the velocity, v , of the wavefront as the inverse of slope of the linear regression of time (calibrated dates) by distance (km from origin). Because there is likely much more error in the measurement of time than in the measurement of distance, time is placed along the y -axis and distance along the x -axis. We also estimate the slope of distance by time due to possible errors in the measurement of distance. Simulations show that Fort's inverse regression method tends to over-

estimate the slope when dealing with small sample sizes (data not shown) so we use randomization methods (10,000 iterations) to estimate the slope and significance of the second regression method. Further, we suggest that randomization statistics are appropriate here, as we are interested in testing both whether the pattern is significantly different from random rather than from an a priori distribution, which may or may not be normal, and whether the slope and correlations are negative, not simply statistically significant. We report the results of both methods.

RESULTS

Best-fit model

Our data show clear spatial gradients in the distribution of earliest Paleoindian occupation dates (Figure 2.2). Not only was the northern origin model the model with the highest correlation coefficient ($r = -0.73$), but it was also the only statistically significant model ($p = 0.008$). Importantly, the only other wave near statistical significance was the western origin model (Figure 2.2). It is interesting that in Figure 2, each plot clearly reflects a general west to east trend in radiocarbon dates as shown by the dashed lines (linear regressions of the entire data sets), consistent with recent findings based on the cladistic analysis of Clovis projectile point morphometrics (Buchanan and Collard, 2008). The plot of all dates used in the analysis by distance from the northern origin is also highly significant ($r = -0.59$, $p = 0.001$, $n = 23$), suggesting that the spatial gradients of earliest occupation dates we report here are also evident in the average timing of the Clovis occupation across the continent.

The consistency of the west to east gradient in the ages of radiocarbon dates suggests that despite the small sample size, these results are robust. In other words, there would need to be a consistent and fundamental change to the dating of early Clovis-age occupations both in the south and east to alter the findings we present here. Further, while the significance of the slope of the northern origin model is influenced by the relatively young date of the furthest bin (black circle to the furthest right in Figure 2.1, upper left panel), excluding this data point does not change our results, as the slope remains significant ($p = 0.034$).

Slope

The estimated velocity of the wavefront using Fort's inverse regression technique was $v = 7.56$ km per year, and with the resampling method was $v = 5.13$ km per year (1.89-14.14, 95% confidence limits (CLs)). The confidence limits are too wide to provide much further constraints on the velocity. A possible reason for their width, aside from the small sample size, is that the wave velocity shown in the upper right panel of Figure 2.2 begins very rapidly and decreases dramatically as the continent fills. Indeed, the correlation coefficient is improved by fitting the northern origin model with a quadratic model ($r = -0.82$) reflecting this trend. We discuss this pattern further below.

Intercept

The intercept of the regression equation predicts that Clovis colonists arrived at the mouth of the ice-free corridor about 13,378 cal BP (12,896-13,867, 95% CLs), or using the uncalibrated data, 11,342 ^{14}C BP (11,114-11,607, 95% CLs).

DISCUSSION

Our results provide clear, quantitative evidence of a colonizing wavefront of early Paleoindians originating from the north. This wavefront moved rapidly to the south and east, traveling considerably faster than predicted from ethnographic data, and faster than other recorded hunter-gatherer expansions into previously unoccupied land masses (Barton et al., 2004; Fort et al., 2004b; Macaulay et al., 2005), though at a speed which is not, in itself, unprecedented (Fiedel, 2000; 2004). While this result does not discount the possible presence of a pre-Clovis population within North America, the speed of the wavefront suggests that any pre-existing human populations offered little demographic, ecological, or territorial competition to the advancing front of colonists, and the available data suggest these populations were not the source of the subsequent Clovis culture.

Both the rapidity with which the Clovis culture appeared over the continent, and the general trajectory of the colonization process has been noted several times before. In their classic model, Kelly and Todd (Kelly and Todd, 1988) suggested that the speed of colonization was driven by high rates of residential mobility, due to the large foraging areas required of a primarily carnivorous diet (Haskell et al., 2002). Reasoning from optimal foraging theory they suggested that colonizing hunter-gatherers, with a northern latitude pre-adaptation (Barton et al., 2004), would have maximized return rates by focusing on widely available, predictable, high-return resources, in particular, mammalian megafauna. As these prey species likely occurred at low densities, local prey would have been depleted quickly, causing foragers to expand into adjacent open regions. Due to their specialized foraging niche, home ranges would have been both very large

and have had very low effective carrying capacities, resulting in a fast moving, shallow wavefront (Hazelwood and Steele, 2004).

This model receives support from recent theoretical and empirical ecological research (Raposo et al., 2003; Santos et al., 2004), which shows that across species optimal search strategies, hence patch residence times are influenced heavily not only by environmental productivity, but also by the regeneration rates of key prey species. In patches where prey regeneration rates are fast, foragers can reuse habitats regularly due to the rapid restocking of prey, whereas in patches where prey regeneration rates are long to infinite (i.e., where foraging causes local extirpation of prey) optimal search strategies become linear (Raposo et al., 2003; Santos et al., 2004) leading to high levels of mobility and the utilization of large foraging areas. Another, though not necessarily mutually exclusive hypothesis, suggests that colonizing populations followed least-cost pathways into the lower continent, where movement occurred rapidly either through favorable corridors, such as river drainages, or across areas of relatively homogenous topography (Anderson and Gillam, 2000; Barton et al., 2004). These models predict that colonization would have by-passed, or traveled quickly across landscapes that were unfavorable, either due to topography and/or ecological productivity.

These models have obvious implications for regional variation in late Pleistocene foraging strategies. On the Plains and in the Southwest, where the archaeological record shows Clovis foragers targeted mammalian megafauna, diffusion rates would have been fast. In these regions initial foraging return rates would have been high as regeneration rates of megafaunal prey would have been very slow (perhaps infinite (Martin, 1967; Mosimann and Martin, 1975; Surovell et al., 2005)) due to low reproductive rates,

leading to large home ranges and the rapid geographic expansion of human populations (sensu Kelly and Todd, 1988). Similarly, Clovis colonists would have moved rapidly through large river systems (Anderson and Gillam, 2000), such as the Missouri and Mississippi drainages, leading to an initially rapid rate of colonization through the mid-continent, which would have then slowed dramatically as diet-breadths broadened with the increased biodiversity of the eastern forests (Barton et al., 2004; Steele et al., 1998), and as prey size, abundance, and availability changed (Meltzer, 1988).

We suggest that these ideas are consistent with recent developments in understanding the movement of colonizing wavefronts across heterogeneous landscapes. Campos, Mendez, and Fort analyzed the effects of diffusion across complex surfaces (Campos et al., 2004) in order to understand the rapid rate of expansion (>13 km per year) of European populations across North America in the 17th - 19th centuries (Campos et al., 2006) where colonization was known to be biased toward key landscape features, particularly river valleys. They derived an analytical expression for the velocity of a traveling wave moving across complex, or fractal, surfaces:

$$v(t) = \left(\frac{1}{d_{\min}} \right) \left(\frac{\mu}{d_w} \right)^{1/\mu} (4\gamma D)^{1/\mu} t^{1/d_{\min}-1} \quad (4)$$

which, combined with the time-delay adjustment in equation 3 gives

$$v(t) = \left(\frac{1}{d_{\min}} \right) \left(\frac{\mu}{d_w} \right)^{1/\mu} \frac{(4\gamma D)^{1/\mu}}{1 + \frac{\gamma T}{2}} t^{1/d_{\min}-1} \quad (5)$$

where d_{min} is the minimum dimension of the landscape, d_w is the basic dimension of movement (2 dimensions in this case), and $\mu = d_{min}d_w / (d_{min} + d_w)$. The important parameter here to note is μ , which essentially measures the extent to which the population saturates the area behind the advancing wavefront (Bertuzzo et al., 2007). When $\mu = 2$, the expanding population saturates 100% of the landscape behind the wavefront, or occupies proportion $P = 1$ of the landscape, where $P = \mu / d_w$, which would be the case if the colonizing population had no specific niche preferences and utilized all landscapes with equal probability.

However, as outlined above, an expanding, colonizing population of hunter-gatherers would have favored certain habitat types based on behavioral and technological adaptations, preferred foraging niches, prey types, and the mobility costs of different landscapes (Anderson and Gillam, 2000; Barton et al., 2004). Thus, it is more than likely that for the Clovis colonists $\mu < 2$, meaning that the population uses less than the full 2 dimensions of the landscape, with $1 - P$ proportion of the landscape unoccupied, causing the wavefront to advance at an increased velocity (see Figure 3). Solving for μ when $v \approx 5 - 8$ (the observed velocity) gives $\mu \approx 1.3 - 1.6$, suggesting that Clovis colonists need to have utilized only about 2/3 to 3/4 of the available landscape in order for the colonizing wave to have traveled at the velocity we observe in our data (Figure 3, upper panel). This finding is in qualitative agreement with the early Paleoindian archaeological record, which suggests that Clovis-age sites are found commonly in high productivity areas, such as river basins as well as prime hunting areas (Barton et al., 2004). In addition, recent research shows that, indeed, ethnographic hunter-gatherers utilize

landscapes in complex ways, which are reflected in nonlinearities in space use (Hamilton et al., 2007a), residential mobility (Brown et al., 2007), and social network structure (Hamilton et al., 2007b).

The model we have proposed in this paper to account for the velocity and trajectory of the colonization process emphasizes the interplay of population growth rates, hunter-gatherer adaptations, and the ecological and topographic complexity of landscapes. In particular, our model predicts that; 1) the majority of Clovis-age sites should be associated with the types of ecological and topographic landscapes favorable to colonization, as outlined above (i.e., major river drainages and areas of high foraging return rates); 2) the Clovis-age archaeological record should reflect the repeated use of regional landscapes due to the generational time-delays of the colonization process; 3) regional variation in the size of home ranges should be influenced by both ecological productivity and, perhaps more importantly, the potential regeneration rates of high ranked prey (i.e., home range size should co-vary with high-ranked prey body size); and 4) the earliest Clovis dates on the continent should occur on the far northern Plains, and the youngest Clovis dates for the initial occupation of a region should occur in Central America.

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METHODS

Wavefront/bin width

We used wavefront bins of 450 km, though our results do not change quantitatively with reasonable adjustments in bin widths. A sensitivity analysis showed that our results are robust to bin widths of between about 300 to 600 km wide (all $p < 0.05$). Below 300 km bins are too narrow to capture variance in the sparse radiocarbon record, and above 600 km there are not enough bins across the continent to make meaningful comparisons. We used widths of 450 km to provide enough bins across the continent for meaningful statistics, but at the same time ensuring that sites in the analysis were far enough apart so we could be confident of seeing an underlying trend. A bin width of 450 km also helps us meet the first of two criteria laid out by Hazelwood and Steele (Hazelwood and Steele, 2004) for archaeological diffusion modeling: 1) Due to modeling error, or errors in the width of the wavefront, the distance between two sites, Δx , must be greater than the width of the wavefront, $L = 8(\sqrt{D/\gamma}) = 245$ km. In our northern wave (the wave of interest) we note $\langle \Delta x \rangle > L$, therefore meeting the first condition; and 2) due to errors in radiocarbon dates, the difference in time between two sites, Δt , must be greater than the combined error rates of the two sites plus the modeling error, $\theta = |\varepsilon_A + \varepsilon_B| + 8/\gamma$, where ε_x is the radiocarbon error at site x , and so $\Delta t > \theta$. Again, working with averages, our average change in time between bins, $\Delta t = 149$, is significantly less than the modeling error, $\theta \approx 335$, meaning that we do not meet the second condition. Therefore, while we can be confident that our sample tracks the distance between traveling wavefronts over

time, we must express caution in interpreting the dates here as the earliest dates within each wavefront bin. However, as the time it took for the colonization process to occur (~11,200-10,600 = 600 radiocarbon years) is greater than the modeling error, we feel confident that our analysis accurately tracks the general trend in the early occupation history of the continent, if not the exact timing.

Radiocarbon evidence

In addition to the 17 radiocarbon assays reported as reliable by Waters and Stafford (8), we include six radiocarbon dates in our analyses that they do not evaluate (Table 1). In situations in which multiple dates were available, averages were calculated using Calib 5.0. *Casper*. Recently dated camel bone from the Casper site in Wyoming suggests that a Clovis occupation underlies the Hell Gap kill at the site (Frison, 2000). A single Clovis projectile point was recovered from the site and several of the camel bones exhibited evidence of human breakage. *Big Eddy*. Big Eddy is a well-stratified, multicomponent site in Missouri (Ray et al., 1998). A number of radiocarbon dates bracket the stratum containing the Clovis-aged assemblage, which yielded dated charcoal samples from the same lithological and cultural stratum 2 cm and 16 cm below a fluted projectile point. *Debert*. Haynes (Haynes et al., 1984) evaluated Macdonald's (MacDonald, 1968) 13 radiocarbon dates and averaged them for the age estimate of the early Paleoindian occupation at Debert.. *Hedden*. Two radiocarbon dates were taken from excavated charcoal samples (pine and spruce) associated with a buried, single component early Paleoindian occupation (Spiess and Mosher, 1994; Spiess et al., 1995). *Hiscock*. An early Paleoindian lithic assemblage, along with fluted projectile points were recovered along

with numerous bones of caribou and mastodon (Laub, 2003). Three culturally-modified bones yielded the three radiocarbon ages that were averaged for use in this study. *Vail*. We use Barton et al's (Barton et al., 2004 and personal communication) average of dates from charcoal samples recovered at Vail. The charcoal samples were recovered by Gramly (Gramly, 1982) from the habitation area of the Vail site within cultural features 1 and 2.

FIGURES

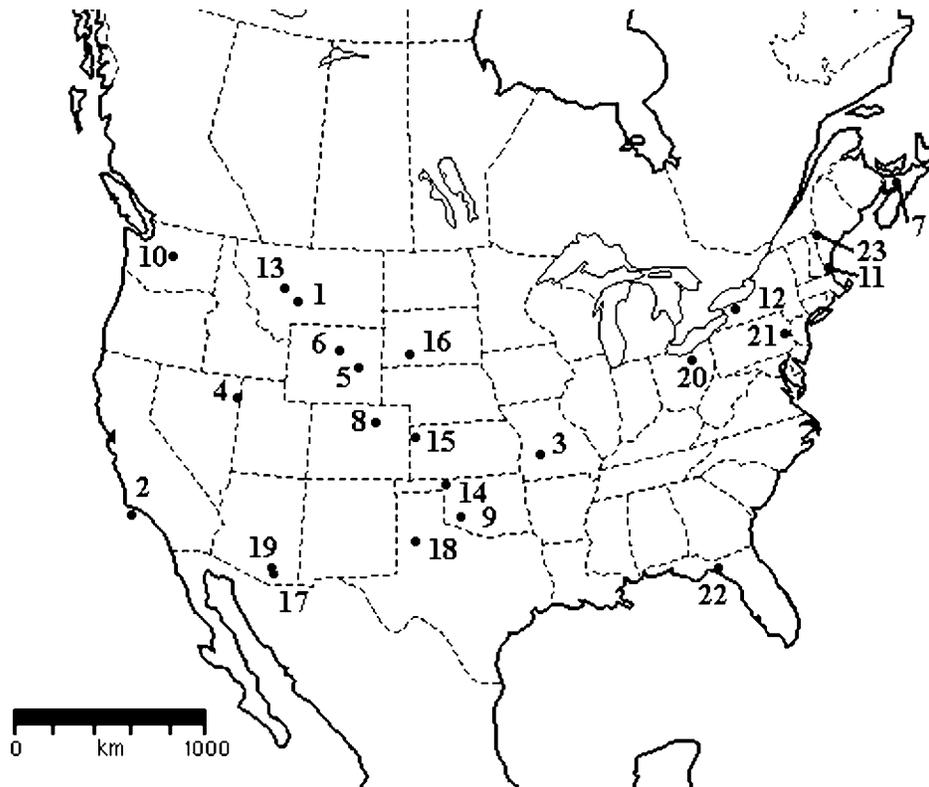


Figure 2.1. Map showing the location of Early Paleoindian sites mentioned in text.

Numbers correspond to those found in Table 2.1.

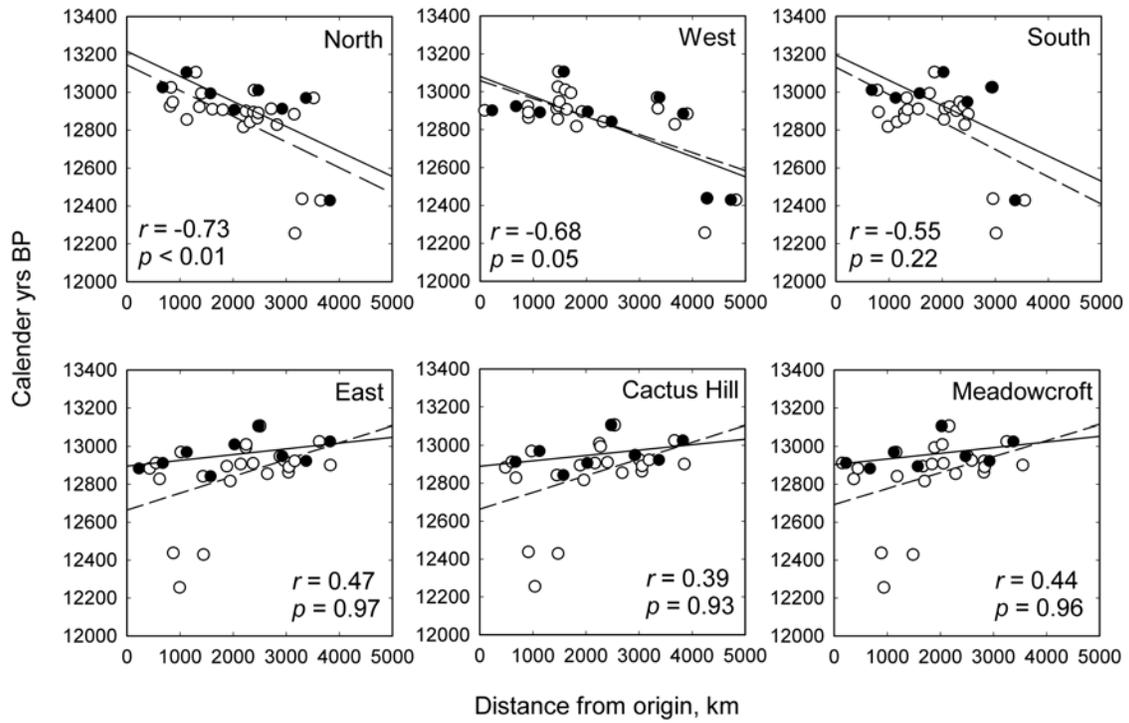


Figure 2.2. Bivariate plots of the wave of advance analysis for each of the six potential origins. Black circles are the earliest dates per 450 km bin. White circles are the raw data (all 23 dates). Solid lines are regressions through the binned data, and dashed lines are regressions through the raw data. The correlation coefficients and p -values refer to the solid lines.

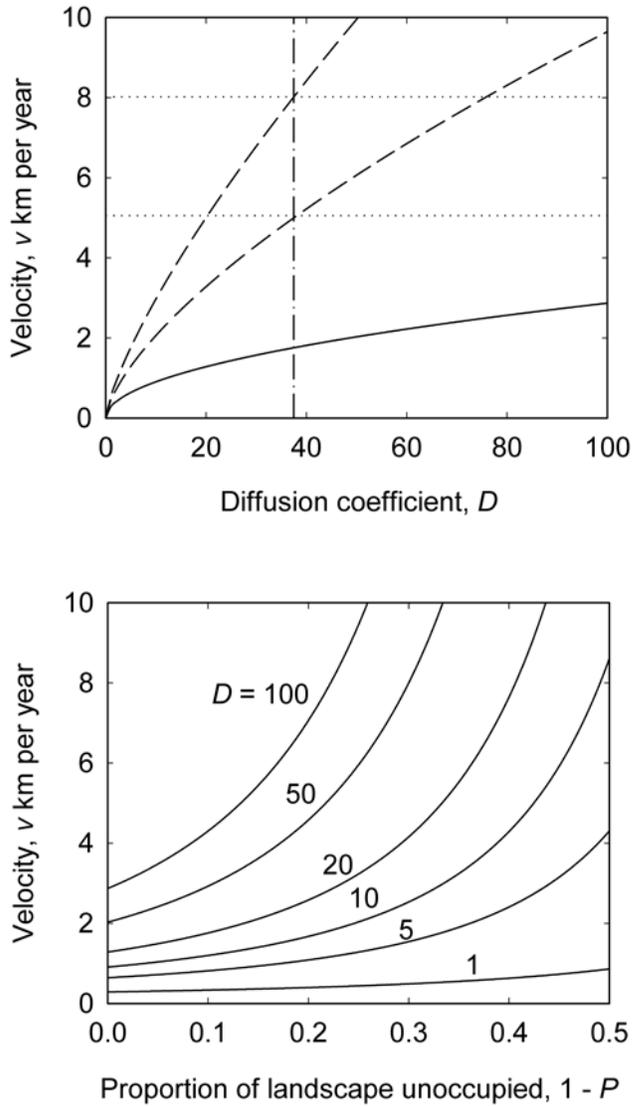


Figure 2.3. Upper figure. Wave velocity, v , as a function of the diffusion coefficient, D , for data used in the analysis. The horizontal dotted lines indicate the approximate upper and lower bounds for the observed velocity of the Clovis wavefront. The vertical dot-dash-dot line gives the approximate diffusion coefficient based on ethnographic data. The expected velocity from the simple time-delayed model (solid line) falls considerably short of the archaeologically observed velocity. The upper and lower curves based on

equation 5 (dashed lines) show that the archaeologically observed velocities are easily accounted for by movement across complex landscapes. Lower figure. Wave velocity expressed as a function of both the proportion of the landscape occupied, P , and the diffusion coefficient, D (from equation 5).

Table 2.1. Radiocarbon and calibrated dates used in the paper (see Figure 2.1).

No.	Site	Date, ¹⁴ C yrs BP	Error (+/- 1 sig)	Calibrated date BP	Source
1	Anzick	11040	35	12948	(Waters and Stafford, 2007)
2	Arlington Springs	10960	80	12901.5	(Waters and Stafford, 2007)
3	Big Eddy	10832	58	12842.5	(Ray et al., 1998)
4	Bonneville Estates	11010	40	12922.5	(Waters and Stafford, 2007)
5	Casper	11190	50	13106	(Frison, 2000)
6	Colby	10870	20	12855.5	(Waters and Stafford, 2007)
7	Debert	10590	50	12429	(Levine, 1990)
8	Dent	10990	25	12910.5	(Waters and Stafford, 2007)
9	Domebo	10960	30	12895	(Waters and Stafford, 2007)
10	East Wenatchee	11125	130	13025	(Waters and Stafford, 2007)
11	Hedden	10550	43	12437.5	(Spiess and Mosher, 1994; Spiess et al., 1995)
12	Hiscock	10795	39	12828.5	(Laub, 2003)
13	Indian Creek	10980	110	12925	(Waters and Stafford, 2007)
14	Jake Bluff	10765	25	12817.5	(Waters and Stafford, 2007)
15	Kanorado	10980	40	12906.5	(Waters and Stafford, 2007)
16	Lange-Ferguson	11080	40	12994	(Waters and Stafford, 2007)
17	Lehner	10950	40	12891	(Waters and Stafford, 2007)
18	Lubbock Lake	11100	60	13010	(Waters and Stafford, 2007)
19	Murray Springs	10885	50	12862.5	(Waters and Stafford, 2007)
20	Paleo Crossing	10980	75	12912.5	(Waters and Stafford, 2007)
21	Shawnee-Minisink	10935	15	12883	(Waters and Stafford, 2007)
22	Sloth Hole	11050	50	12969	(Waters and

23	Vail	10530	103	12255	Stafford, 2007) (Levine, 1990)
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CHAPTER 3:

THE ACCUMULATION OF STOCHASTIC COPYING ERRORS CAUSES DRIFT IN CULTURALLY TRANSMITTED TECHNOLOGIES.

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ABSTRACT

The archaeological record is the empirical record of human cultural evolution. By measuring rates of change in archaeological data through time and space it is possible to estimate both the various evolutionary mechanisms that contribute to the generation of archaeological variation, and the social learning rules involved in the transmission of cultural information. Here we show that the recently proposed accumulated copying error model (Eerkens and Lipo, 2005) provides a rich, quantitative framework with which to model the cultural transmission of quantitative data. Using analytical arguments, we find that the accumulated copying error model predicts negative drift in quantitative data due to the proportional nature of compounded copying errors (i.e., neutral mutations), and the multiplicative process of cultural transmission. Further, we find that the theoretically predicted rate of drift in long-lived technologies is remarkably close to the observed reduction of Clovis projectile point size through time and space across North America.

INTRODUCTION

One of the major transitions in evolutionary history was the evolution of pathways that allowed the transmission of fitness-related, non-genetic information between individuals (Maynard-Smith and Szathmary, 1998). These transmission pathways and the social networks they form have been central to both human cultural and biological evolutionary history (Boyd and Richerson, 1985; Henrich and McElreath, 2003). Because the archaeological record documents changes in material culture over time and space, it is the only empirical record of past human cultural evolution. A primary goal of archaeology must be then to develop quantitative mechanistic theories derived from fundamental principles that explain the rates of change we observe in empirical data. In this paper we move toward this goal by developing stochastic models that describe the cultural transmission of complex technologies, and show how the key parameters can be measured statistically from archaeological data.

While many cultural, behavioral, and biological mechanisms combine to shape the archaeological record, in general, all mechanisms can be classified either as deterministic or stochastic. Deterministic mechanisms are the selective processes that shape variation in material culture via the rules of social learning, whereas stochastic mechanisms are the inherent, random statistical effects of probability that generate variation. Selective processes reflect the human cognitive ability to evaluate the economics of alternative strategies, such as the ability to evaluate the differential performance of tools at particular tasks, or the likely cost-benefit structure of employing different learning strategies in different environmental conditions. These selective processes are best described by biased transmission rules, where the term “bias” refers to

a type of social learning that is constrained to some subset of the overall variation within a population (Boyd and Richerson, 1985). Stochastic mechanisms, on the other hand, include both variation generated by the probabilistic nature of naturally-occurring processes, and the random processes of recovery, preservation, and taphonomy that influence sampling from the archaeological record (i.e., Brantingham et al., 2007; Surovell and Brantingham, 2007). One important evolutionary consequence of sampling variation is drift, which is caused by population fluctuations and subsequent founder effects (Lipo et al., 1997; Shennan, 2000; 2001). A second source of drift is the accumulation of neutral, unbiased, but proportional copying errors through time (see Eerkens and Lipo, 2005), a mechanism we explore in detail below.

The archaeology of cultural transmission: Quantitative data and lognormality

Archaeological applications of cultural transmission theory focus either on discrete, categorical forms of variation such as changes in the diversity of pottery styles or tool types over time or space (e.g., Bettinger and Eerkens, 1999; Brantingham, 2007; Henrich, 2004; Neiman, 1995) or quantitative, continuous variation in archaeological data, which focus on rates of change within particular artifact types (Buchanan, 2006; Buchanan and Collard, 2007; Buchanan and Hamilton, submitted; Lycett, 2007; Lycett and von Cramon-Taubadel, 2008; Lycett et al., 2006). Recently, Eerkens and Lipo (2005) outlined a general yet powerful Markovian approach to modeling quantitative variation in archaeological data. Using a simple mathematical framework they showed that Markov models can be used to capture the essential elements of transmission rules that shape the transfer of quantitative information between individuals, which can then be used to

inform the mechanisms that drive variation in archaeological data. Their model, which we term the accumulated copying error (ACE) model, describes how imperceptible copying errors during transmission events accumulate over time to become a significant source of variation in the archaeological record. Here we extend their model to show that this general framework leads to a surprisingly rich body of quantitative theory and some non-intuitive insights into cultural change.

When considering quantitative data we move from analyzing changes in the frequencies of discrete, categorical classes of data within or across populations to considering distributions of continuous variation, and the changes in the shapes of those distributions through time and space as measured by their statistical moments. In particular we are interested in measuring rates of change in the first four moments; the mean, variance, skewness and kurtosis.

Quantitative data, particularly measurement data, often will be right skewed. This skew occurs because measurements are ratio level data where zero is an absolute lower bound. The lower bound means that by definition measurements must be greater than zero, so the lower tail of the distribution is bounded while the upper tail is unbounded. While the upper tail is unbounded, in general large measurements occur with exponentially decreasing frequency such that the distribution becomes skewed to the right, as smaller variants are more common than larger variants. This skew is expected to be especially relevant to archaeological assemblages if variation is the result of an inherently reductive technology, such as stone tool manufacture. Specifically, right-skewed distributions will be lognormal when the underlying generative mechanism is multiplicative (Limpert et al., 2001), due to the mechanics of random walks and the laws

of logarithms. The stable probability distribution of a simple random walk over time is a normal distribution (Allen, 2003; Taylor and Karlin, 1998). Because a lognormally distributed variable is normally distributed on the logarithmic scale it follows from the laws of logarithms that an arithmetic process on the log scale is a multiplicative process on the linear scale. So, while arithmetic random walks (i.e., simple Brownian motion) produce normal distributions of outcomes over time, multiplicative random walks (i.e., geometric Brownian motion) result in lognormal distributions. Indeed, lognormal frequency distributions are common in nature as growth processes are inherently multiplicative (Limpert et al., 2001). We see this mechanism in anthropological data where hunter-gatherer group sizes at multiple levels of social organization are lognormally distributed (Hamilton et al., 2007b) due to the multiplicative process of reproduction and population growth.

Recognizing that different generating mechanisms lead to different kinds of frequency distributions has important implications for understanding the mechanisms that generate variation in archaeological data. All archaeological frequency distributions consist of artifacts that were manufactured, used, and discarded over some period of time (from days to centuries) and over some measure of space (from sites to continents). Essentially, frequency distributions of artifacts can be thought of as the solutions of multiple mechanistic functions integrated through time and space. By decomposing these frequency distributions it is then possible to measure rates of change by analyzing changes in the statistical parameters of the distributions. Therefore, by building mathematical models based on the mechanisms of interest we can then understand the generative mechanisms behind empirically observed frequency distributions and develop

statistical methods of estimating the key parameters from empirical data. Using this approach it becomes not only possible to measure rates of change in empirical data, but also to deconstruct the various mechanistic processes that contribute to the variances observed in the empirical frequency distributions.

ACCUMULATED COPYING ERROR MODEL UNDER VERTICAL AND BIASED TRANSMISSION

The power of the accumulated copying error (ACE) model lies in its simplicity. In most traditional craft technologies social learning of complex tasks usually occurs as a series of transmission events between an apprentice and a master, where a master attempts to teach an apprentice the skills required to replicate a certain artifact. In this paper we use the example of the social learning of knowledge required to manufacture a projectile point within a hunter-gatherer society, though the model is generally applicable to the cultural transmission of complex tasks in a variety of socio-economies. If the apprentice is a novice, each copying attempt is likely to vary widely from the master's example, especially given the complexity of the knowledge and skills required in manufacturing a functional projectile point. However, even as the skills of the apprentice progress to the point of expertise, copying attempts will never produce perfect replicas of the master's example, though such copies might be fully functional, easily falling within the acceptable performance criteria for projectile points. These functional points will then be used, and at some point during their use-life will enter the archaeological record.

This inevitable copying error occurs as a result of the lower threshold of human perception (Eerkens, 2000; Eerkens and Lipo, 2005). Experimental research on human subjects shows that in the absence of measuring devices where subjects were asked to

replicate tasks such as drawing simple objects, typical deviations of a copy from its target example are around 3-5% (Eerkens, 2000). This phenomenon is well recognized in the social sciences, and is termed the Weber Fraction. Thus, over multiple transmission events, the Weber fraction compounds to become a significant source of variation (Eerkens, 2000; Eerkens and Lipo, 2005). For example, continuing with our projectile point example, as points are manufactured over time, some proportion of the overall variance in size will be due to accumulated copying errors, while other sources of variation may include length of use life, and the quality and size of raw material from which the projectile point was manufactured. In the following sections we examine the implications of the ACE model under both unbiased and biased transmission. We have three objectives in our examination of the ACE model. First, we model the long-term implications of the ACE model by examining the expected statistical distributions of projectile point sizes through time. Next, we look at the implications of the ACE model under biased transmission rules, and develop a biased accumulation of copying error (BACE) model. Lastly, we explore how the different components of the model can be estimated statistically from empirical data, and use these estimates to examine spatiotemporal changes in Clovis projectile point size across late Pleistocene North America.

Unbiased transmission: The ACE model

Following Eerkens and Lipo (2005), we outline the ACE model under the basic assumptions of unbiased vertical transmission (transmission from parent to offspring), where an artifact manufactured in one generation is copied from the previous generation

within the same lineage. For the models we outline below, we interpret the Weber fraction as the standard deviation of the copying error rate. This is because, all else being equal, the deviation of any copy x_i from its expected value $E[x] = \bar{x}$ is given by

$\Delta x = x_i - \bar{x}$. We can write this deviation in terms of the copying error rate $\varepsilon(t)$ thus,

$E[x] = x_i + \varepsilon(t)$, so $\Delta x = \varepsilon(t) = |x_i - \bar{x}|$. The variance in the copying error rate is then a

function of x giving $\sigma_\varepsilon^2 = 1/N \sum_{i=1}^N (x_i - \langle x \rangle)^2$, and so the average accuracy of a copy

from its target (i.e., the Weber fraction) within a population is given by the standard

deviation $\sigma_\varepsilon = \sqrt{1/N \sum_{i=1}^N (x_i - \langle x \rangle)^2}$.

Eerkens and Lipo (2005) described the accumulated copying error rate model as a simple Markov process where a single sample path is given by:

$$Y(t+1) = Y(t) + Y(t) \cdot c \cdot N(0,1) \quad (1)$$

where Y is the attribute of interest, t is time, c is half the error rate, and $N(0,1)$ is a standard normal distribution. Because the error term is normally distributed, equation 1 is a discrete-time continuous-state Markov process that describes the evolution of Y over time t . It is important to note here that equation 1 is a multiplicative process, as opposed to an arithmetic process, and so describes a geometric Brownian motion rather than a simple Brownian motion. The multiplicative nature of equation 1 arises because of the structure of the error term, the second term on the right hand side of the equation. Here,

the error term, $cN(0,1)$, is proportional to the attribute of interest, $Y(t)$, and so the error is multiplicative. We redefine terms and rewrite equation 1 equivalently as

$$s_i(t+1) = s_i(t)[1 + \varepsilon(t)] \quad (2)$$

where $s_i(t)$ is the attribute of interest time t , and $\varepsilon(t)$ is a normally distributed copying error rate with mean zero, and variance, σ_ε^2 ; that is $\varepsilon(t) = N(0, \sigma_\varepsilon^2)$. Note that the error term, $\varepsilon(t)$, models the effect of a neutral mutation occurring during the transmission event. Because random walks are more straightforwardly analyzed on the linear scale we linearize equation 2 by taking the natural logarithm of both sides giving

$$S_i(t+1) = S_i(t) + \ln[1 + \varepsilon(t)]. \quad (3)$$

where $S = \ln s$. In addition to copying error there is also variation in $S_i(t)$ due to other random factors, such as variation in the size of raw material nodules, the quality of different raw materials, and the use-life of the tool. Eerkens and Lipo (2005) term these other sources of error structural error. We include structural error in the model by introducing a second stochastic term, $\kappa(t)$, which is a normally distributed random variable with mean 0 and variance σ_κ^2 , yielding

$$S_i(t+1) = S_i(t) + \ln[1 + \varepsilon(t)] + \kappa(t). \quad (4)$$

Note that $\kappa(t)$ is independent of $S_i(t)$. Equation 4 describes the sample path of an attribute $S_i(t+1)$ as a function of the artifact in the previous generation plus two sources of stochastic error, the proportional copying error rate, $\ln[1 + \varepsilon(t)]$, and structural error, $\kappa(t)$. To examine the long-term behavior of equation 4 we expand it in a Taylor series around $\varepsilon(t)$, yielding

$$S_i(t+1) = S_i(t) + \kappa(t) + \left[\mu_\varepsilon - \frac{1}{2} \sigma_\varepsilon^2 \right] (t). \quad (5)$$

The expected value of S at time t is found by averaging over equation 5, yielding

$$E[S(t)] = \bar{S}(t) = S_0 - \frac{1}{2} \sigma_\varepsilon^2 t. \quad (6)$$

Note that the expected value is equivalent to the mean value of $S_i(t)$ over a sample of N random walkers. Because the error rate $\varepsilon(t)$ is normally distributed, the distribution of all values of $S(t)$ at time t will also be normally distributed, and so the higher moments of the distribution are simply the parameters of a normal distribution

$$Var[S(t)] = V_S(t) = (\sigma_\varepsilon^2 + \sigma_\kappa^2) t = \sigma_\phi^2 t, \quad (7)$$

$$Skew[S(t)] = 0, \quad (8)$$

$$Kurtosis[S(t)] = 3\sigma_\phi^4. \quad (9)$$

These moments show that the variance of the distribution of $S_i(t)$ increases linearly with time, whereas the skewness is zero as normal distributions are symmetrical by definition, and the kurtosis of the distribution is a constant function of σ_ϕ . However, we are interested not only in characterizing the distribution of $S_i(t)$, but also in measuring the rate of change in this distribution over time. The rate of change in these parameters over time (their time derivatives) are given by their infinitesimal moments (Karlin and Taylor, 1981):

$$\lim_{\Delta S, \Delta t \rightarrow 0} \frac{1}{\Delta t} E[\Delta S] = \alpha = -\frac{1}{2}\sigma_\varepsilon^2, \quad (10)$$

$$\lim_{\Delta S, \Delta t \rightarrow 0} \frac{1}{\Delta t} E[\Delta S]^2 = \beta = \sigma_\phi^2, \quad (11)$$

$$\lim_{\Delta S, \Delta t \rightarrow 0} \frac{1}{\Delta t} E[\Delta S]^\theta = 0, \quad \theta > 2, \quad (12)$$

where $\Delta S = S(t + \Delta t) - S(t)$. Equation 10 gives the rate of change in the mean, termed the drift constant, and equation 11 gives the rate of change in the variance, termed the diffusion constant, whereas all higher infinitesimal moments are zero as they remain

unchanged through time. We can then rewrite equation 4 more straightforwardly in terms of the above diffusion parameters thus,

$$S(t+1) = S(t) + \alpha + \sqrt{\beta}\Phi(t), \quad (13)$$

where $\Phi(t)$ is a standard normal distribution. Simulations of equation 13 are shown in figure 1. By taking the continuous time limit of equation 13, we can describe the evolution of S over time t under the conditions of the ACE model with the stochastic differential equation

$$dS = -\alpha dt + \sigma dz, \quad (14)$$

which has the solution,

$$\phi_{ACE}(S|\alpha, \beta, t) = \frac{S_0}{\sqrt{2\pi\beta t}} \exp\left(-\frac{(S - S_0 - \alpha t)^2}{2\beta t}\right), \quad (15)$$

which is a normal distribution with mean $S_0 - \alpha t$ and variance βt (Figure 1). In other words, at all times traits subject to transmission described by the ACE model will be normally distributed (on the log scale), but as $\alpha < 0$ the distribution will drift deterministically to the left, as the variance increases linearly with time at a rate βt . This can be seen clearly in the simulations shown in Figure 3.1.

The mean value of the distribution drifts negatively over time due to the accumulation of copying errors, errors which are proportional to mean value in the previous generation. Thus, the accumulation of unbiased copying errors (i.e., neutral mutations) over multiple transmission events causes drift in the mean over time as those copying errors are proportional to the object being copied even though the probability of creating a copying error is unbiased. While somewhat non-intuitive, this result has a clear empirical interpretation. Because the variance of the distribution governing the copying error is proportional to the object being copied, variants produced in the present generation that are smaller than the mean of the previous generation will be copied with absolutely less error in the subsequent transmission event, and so will remain small over time. Similarly, variants larger than the mean will be copied with more error in the subsequent transmission event, which increases the probability that eventually they will produce smaller variants over time. So, small variants stay small, and large variants have an increasing probability of eventually producing small variants, with the result that the overall mean of the distribution drifts to the left over time at a rate proportional to the accumulation of copying errors.

Biased transmission: The BACE model

We now build on the simple unbiased vertical transmission model by considering sources of bias in the transmission process and how these processes affect the resulting distributions of traits through time. We are particularly interested in how biasing processes in social learning constrain variance. As above, we start by building a discrete-time, continuous-space Markov model and then use diffusion approximations to describe

the long-term statistical properties of the model. We term the model the biased accumulated copying error (BACE) model.

Across human societies a ubiquitous form of bias is conformism where individual social learning is frequency-dependent (Boyd and Richerson, 1985; Henrich and Boyd, 1998), a process akin to stabilizing cultural selection (Cavalli-Sforza and Feldman, 1981). Another common form of bias in human societies is prestige bias, where prestigious individuals influence social learning (Boyd and Richerson, 1985; Henrich and Gil-White, 2001). For this paper we model these two forms of bias identically. We make this simplifying assumption for the following reason. Under conformist bias, each individual within a population chooses either to copy the most frequent variant, often given by the population mean, $\bar{X}(t)$, of the previous generation with probability λ , or to follow the rules of vertical transmission with probability $1-\lambda$. Similarly, under prestige bias each individual within a population chooses either to copy a prestigious individual, $X_p(t)$, from the previous generation with probability λ , or to follow the rules of vertical transmission with probability $1-\lambda$. The two models are the same analytically because the population mean $\bar{X}(t)$ is also the expectation of $X(t)$, that is $E[X(t)] = \bar{X}(t)$, so the expected value of any individual chosen at random, such as the prestigious individual, $X_p(t)$, is also given by the population mean, that is $E[X_p(t)] = \bar{X}(t)$. Therefore, if we assume that prestigious individuals produce projectile points of an average size, though perhaps simply of better quality, then mathematically, both conformist and prestige bias are equivalent. However, the model below can be altered straightforwardly to incorporate any biasing scenario.

We think this argument is particularly relevant to the cultural transmission of lithic technology in hunter-gatherer societies. With tasks as complex as projectile point manufacture individual flint knappers are likely to vary in their skill-level. Given the presumed importance of projectile point function to hunting success, highly skilled flintknappers were likely prestigious individuals within any given group. Other prestigious individuals may have been successful hunters. In either case it is reasonable to assume such individuals would bias learning strategies as novice flint knappers may choose to learn from such experts, rather than learn solely from their parents. However, there is no a priori reason that prestigious flint knappers would produce either particularly small or large projectile points, but likely would produce projectile points of an expected, or average size, presumably with less variance, and of higher overall quality than less skilled flintknappers. As such, we assume that prestigious individuals produce projectile points that are similar in size to the mean, but are copied with greater frequency because they were produced by a master flintknappers, or another type of prestigious individual.

If λ is the strength of bias (i.e., the probability of conforming or copying a prestigious individual during a transmission event), building on the above ACE model, we include the probabilities of bias and non-bias into equation 5, thus

$$S_i(t+1) = \left[\lambda \bar{S}(t) + (1-\lambda) S_i(t) \right] + \kappa(t) + \ln[1 + \varepsilon(t)]. \quad (16)$$

We can then rewrite equation 16 in terms of the diffusion parameters given above,

$$S_i(t+1) = S_i(t) + \lambda \left[\bar{S}(t) - S_i(t) \right] + \kappa(t) + \alpha + \sqrt{\beta} \varepsilon(t), \quad (17)$$

simulations of which are shown in Figure 3.2. The rate of change in S over time $t \rightarrow t+1$ is then

$$\Delta S = \lambda [\bar{S}(t) - S_i(t)] + \kappa(t) + \alpha + \sqrt{\beta} \varepsilon(t), \quad (18)$$

and taking the continuous time limit, we can describe the evolution of S over time t under bias transmission with the following stochastic differential equation

$$dS = \lambda [\bar{S}(t) - S_i(t)] dt + \sigma dz. \quad (19)$$

When the strength of bias is greater than zero ($\lambda > 0$), equations 16-18 describe an Ornstein-Uhlenbeck mean-reversion process (Dixit and Pindyck, 1994; Karlin and Taylor, 1981; Taylor and Karlin, 1998), which reduces to equation 14 when $\lambda = 0$. As before, the mean value of $S(t)$ is given by the expectation

$$\mathbb{E}[S(t)] = \bar{S}(t) = S_0 - \frac{\sigma_\varepsilon^2}{2} t = S_0 - \alpha t, \quad (20)$$

and the variance

$$\text{var}[S(t)] = \sigma_s^2(t) = \frac{\beta}{2\lambda} (1 - e^{-2\lambda t}). \quad (21)$$

So, while the behavior of the mean is the same as under both bias and non-bias conditions as the biasing process simply restricts the variance of the distribution, the variance approaches equilibrium at $\beta / 2\lambda$, at a rate $1 - \exp(-2\lambda t)$. Therefore, under biased transmission the long-term population variance is bounded by the strength of bias, λ , unlike the unbiased vertical transmission model, where the variance increases linearly with time (Figure 3.3). The variance reaches equilibrium because the inverse of the strength of bias is the frequency at which individuals choose to follow biased learning strategies, that is $\lambda = 1 / f$, so if $\lambda = 0.2$, then about 1 in every 5 transmission events an apprentice will choose to conform rather than learn from their parents. If the strength of bias is greater than zero ($\lambda > 0$) the amount of variation that can accumulate within the population is limited, such that the total amount of variation that can occur at any one time is bounded by the frequency with which individuals choose to conform or copy prestigious individuals. In terms of the infinitesimal moments of the BACE model, the drift coefficient remains the same as the ACE model

$$\lim_{\Delta S, \Delta t \rightarrow 0} \frac{1}{\Delta t} E[\Delta S] = \alpha = -\frac{1}{2} \sigma_\varepsilon^2 \quad (22)$$

whereas the diffusion coefficient is

$$\lim_{\Delta S, \Delta t \rightarrow 0} \frac{1}{\Delta t} E[\Delta S^2] = \beta = 0 \quad (23)$$

for large t , as the variance is constant with respect to time once it reaches equilibrium.

Therefore, over time $S_i(t)$ converges on a stable distribution

$$\phi_{BACE}(S|\alpha, \beta, t) = \frac{S_0}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(S - S_0 - \alpha t)^2}{2\sigma_s^2}\right) \quad (24)$$

which is, again, a normal distribution with mean $S_0 - \alpha t$, but with variance σ_s^2 that reaches equilibrium at $\beta / 2\lambda$. So, the mean of the distribution drifts negatively at a rate $S_0 - \alpha t$ as in the unbiased case, but the distribution ceases to expand once the variance reaches equilibrium at $\beta / 2\lambda$ (Figure 2). This equilibrium has important consequences for measuring the presence and magnitude of transmission bias in archaeological data.

Model summary

The equations above show that regardless of bias in the transmission process, continuous traits passed down via cultural transmission will drift deterministically over time due to the multiplicative nature of the accumulation of copying errors. Indeed, the above analysis demonstrates that biased cultural transmission is best modeled as an Ornstein-Uhlenbeck mean-reversion process, which reduces to geometric Brownian motion (i.e., Brownian motion with drift on the log scale) in the special case when the strength of bias is equal to zero, $\lambda = 0$. This is a particularly important theoretical finding for archaeology because it suggests the relevant null model of cultural transmission, under biased or non-biased processes is negative drift, due to the accumulation of copying errors. In our projectile point example, this model predicts that mean artifact size

will decrease steadily through time at a rate of half the variance of the copying error rate. It follows that this trend should be most noticeable in long-lived technologies that are transmitted through multiple generations.

Further, our analysis shows that biased transmission results in bounded variance, such that the amount of variance within a population should stabilize through time at a level determined by the strength of bias, λ . Because biasing processes are ubiquitous in human social learning (Boyd and Richerson, 1985; Henrich and McElreath, 2003), the null model predicts that population variance in long-lived technologies should be statistically constant through time.

PARAMETER ESTIMATES OF THE CULTURAL TRANSMISSION PROCESS

We concentrated on defining four sets of parameters: 1) The drift and diffusion constants (and higher infinite moments); 2) the Weber Fraction, or the standard deviation of the copying error rate, σ_e ; 3) the amount of structural error, κ ; and 4) the strength of transmission bias, λ . These four parameters allow for a relatively complete description of the mechanisms and sources of variation in archaeological assemblages. As such, we now turn to consider how these parameters can be estimated statistically from empirical data.

Founder effects

As mentioned in the Introduction, one of the key sources of drift is founder effect. All biological populations fluctuate in size through time and space due to naturally occurring variation in reproductive rates caused by a combination of a population's demographic

profile (demographic stochasticity) and changes in local environmental and ecological conditions (environmental stochasticity) (Lande et al., 2003). These fluctuations cause the distribution of biological and cultural variation within a population to vary (Henrich, 2004; Shennan, 2000; 2001). Over time, these fluctuations result in sampling bias that has the effect of reducing the overall amount of variation within a population by reducing the (biological and/or cultural) effective population size. Therefore, successive founder effects in human populations are predicted to reduce the within-assemblage variation in archaeological assemblages through time (see Lycett and von Cramon-Taubadel, 2008).

We can use an ordinary least squares regression of the form $V_A = \beta_0 + \beta_1 t + \varepsilon$ to explore intra-assemblage variation, V_A as a function of time, t . If $\beta_1 < 0$, intra-assemblage variation decreases with time, consistent with the hypothesis of drift caused by founder effects. If $\beta_1 > 0$, then intra-assemblage variation increases with time, perhaps due to increased innovation rates within populations. If $\beta_1 = 0$, then intra-assemblage variation does not vary significantly with time suggesting a relative degree of demographic and cultural stability.

ESTIMATES OF STATISTICAL MOMENTS AND COPYING ERROR

Infinitesimal moments and copying error

We estimate the first four infinitesimal moments using OLS regression. In particular, we use the model $E[S(t)^\theta] = \beta_0 + \beta_1 t + \varepsilon$, where $E[S(t)^\theta]$ is θ th moment at time t . As $\beta_1 = dE[S(t)^\theta]/dt$, this is an estimate of the infinitesimal moment. For example, to estimate the drift constant α we use the linear model $\bar{S}(t) = \alpha t + S_0 + \varepsilon$,

where the slope of the model is the drift constant, $\alpha = -\sigma_\varepsilon^2 / 2$. The copying error rate is then found by rearranging the equation for the drift constant thus, $\sigma_\varepsilon = \sqrt{2\alpha}$.

Transmission bias and structural error

The transmission bias model equation 17 can be written as the first order autoregressive model $S(t+1) = \beta_0 + \beta_1 S(t) + \phi$, with the parameters $\beta_0 = \lambda \bar{S}$, $\beta_1 = 1 - \lambda$, and

$\sigma_\phi = \sigma_R \sqrt{1/2\lambda}$, where σ_R is the standard deviation of the residuals. Rearranging these parameters, the transmission bias parameter is then estimated by $\lambda = 1 - \beta_1$, the long-term mean is $\bar{S} = \beta_0 / \lambda$ and the structural error term is $\sigma_\kappa = \sigma_\phi - \sigma_\varepsilon = \sigma_R \sqrt{1/2\lambda} - \sqrt{2\alpha}$. It then follows that the proportion of the total error explained by copying error is approximately $\sigma_\varepsilon / \sigma_\phi = \sigma_R^{-1} \sqrt{4\alpha\lambda}$.

CASE STUDY: SPATIOTEMPORAL GRADIENTS IN CLOVIS PROJECTILE POINT SIZE

To illustrate the efficacy of the above model we examine the archaeological example of spatiotemporal gradients in the size of Clovis projectile points across late Pleistocene North America.

The Clovis archaeological record represents the population expansion of the first successful human colonization of North America (Hamilton and Buchanan, 2007; Meltzer, 2004). The initial size of the founder population was likely very small (see Hey, 2005 and references therein), and therefore would have exhibited limited biological and cultural diversity. However, by the end of the Clovis period, a period of no more than a few hundred years (Haynes et al., 1984; Haynes, 2002; Waters and Stafford, 2007),

hunter-gatherer populations occurred throughout the North American continent, as well as much of the rest of the Americas (Haynes, 2002). During this period of expansion, Clovis colonists would have encountered novel environments, ecosystems and prey species that varied widely both in space and time as the continent underwent widespread post-glacial ecological changes (Lyons, 2003; 2005; Lyons et al., 2004; Webb et al., 1993; Wright, 1987; 1991). Under these dynamic conditions, the suite of selective pressures on lithic technology would have been complex. On the one hand, in an expanding population undergoing changing ecological conditions, cultural evolutionary theory would predict that there would be both strong frequency-dependent selection and biased social learning toward prestigious individuals (Boyd and Richerson, 1985; Henrich and Boyd, 1998), such as successful hunters or master flintknappers. However, at the same time, population expansion across an heterogeneous landscape would have promoted technological diversification if regional populations adapted to specific local environmental conditions, and became increasingly geographically isolated. Furthermore, the most demographically unstable populations would have been those entering novel environments at the leading edge of the colonizing wave, due to small population sizes and the consequent increased stochasticity in growth rates, as well as increased effects of environmental variance caused by the novel ecological conditions.

The effects of cultural evolutionary processes on projectile points are particularly interesting as projectile points played a primary role in hunting technology. Because of their importance it is likely that projectile points, and other aspects of technology, were subject to dynamic, subtle selective pressures as populations expanded into novel ecological niches (see Buchanan and Hamilton, submitted). The statistical expectations

derived from the ACE/BACE models can be used to quantify rates of change in Clovis projectile point size over time and space and to determine the rules of social learning that characterized Clovis cultural transmission. Clovis projectile points are an ideal case study as they are: 1) technologically complex tools that require significant expertise and investment in learning to reach the generally high level of quality we see in the archaeological record; and 2) because they were manufactured over a period of a few hundred years and therefore were transmitted across several successive generations (Haynes, 2002; Haynes et al., 2007; Meltzer, 1995; Waters and Stafford, 2007).

To examine changes in Clovis projectile point sizes across the Clovis time period we combine expectations of the ACE/BACE model with the spatiotemporal gradient model developed in Hamilton and Buchanan (2007). In Hamilton and Buchanan (2007) paper we showed that spatial gradients in Clovis-age radiocarbon dates from archaeological sites indicate that the most likely origin of the Clovis colonization of North America was the ice-free corridor, when tested against multiple alternative hypotheses. Our analyses showed that the date of the earliest Clovis occupation across the continent decreased linearly with distance from Edmonton, Alberta, traditionally taken to represent the approximate location of the southern exit of the ice-free corridor (i.e., Martin, 1967; Mosimann and Martin, 1975). Thus spatial gradients in Clovis occupations across the continent also reflect temporal gradients. So, by combining these spatiotemporal gradients with the predictions of the ACE model we derive four null hypotheses relating to variation in Clovis projectile point size:

Hypothesis 1: The overall distribution of point sizes should be lognormal.

Hypothesis 2: The mean size of projectile points should decrease linearly with distance from Edmonton, Alberta.

Hypothesis 3: The expected rate of size decrease over time due to stochastic cultural transmission is predicted by the Weber Fraction, ~5%. That is to say the drift constant, α , should be negative, and approximately

$$\sigma_{\epsilon}^2 / 2 = 0.0025 / 2 = 0.00125 .$$

Hypothesis 4: Variance in projectile point size should be statistically constant across time, and all higher moments should be non-significant.

DATA AND METHODS

Clovis projectile point sample

Our sample consists of 232 Clovis projectile points from 26 assemblages from across the continent (see Table 3.1 and Figure 3.4). Projectile point size was calculated using a morphometric digitizing process that utilizes multiple landmarks to demarcate the outline of points, described in detail elsewhere (Buchanan, 2006; Buchanan and Collard, 2007; 2008; Buchanan and Hamilton, submitted). An estimate of projectile point surface area is then calculated from the polygon described by the landmarks (Buchanan, 2006; Buchanan and Collard, 2007). This method is associated with a very low measurement error rate (Buchanan and Hamilton, submitted).

The data consist of projectile points from three site types: caches ($n = 66$), camps ($n = 102$), and kills ($n = 64$). Rather than controlling our data set subjectively, by limiting the sample to projectile points from certain site types while excluding others, we control for the potential effects of site type statistically. We feel this approach is particularly important because although points from different site types may reflect different stages of use, all points from all site types must be included in order to analyze the full archaeological range of variation in projectile point form.

Radiocarbon data

To measure time, we use calibrated radiocarbon dates from 23 Clovis-aged sites from across the continent (Table 3.2). Calibrated dates were calculated using the Intcal04.14 curve (Reimer et al., 2004) in Calib 5.0.

Spatial gradients

To quantify both time and space we followed similar methods to Hamilton and Buchanan (2007). We first calculated the great-circle arc distances (in km) of each assemblage from the point of assumed origin, in this case, Edmonton, Alberta. Projectile point size was then regressed against distance using a General Linear Model (GLM), controlling for both site type, and raw material type. We also include an interaction term between site type and distance because of the non-uniform distribution of Clovis site types across the continent. Potential founder effects were analyzed by regressing intra-assemblage variation as a function of distance.

Temporal gradients

To analyze temporal gradients, radiocarbon dates were organized into bins 450 km wide as measured from the point of origin (see Hamilton and Buchanan, 2007 for details). Projectile point dimensions were also binned into gradient bins of the same width, and means, variances, skewness and kurtosis were measured for the distribution of artifact sizes within each bin. To assess rates of change in the mean, variance, skewness and kurtosis of projectile point sizes over time the moments per bin were regressed against time, measured by the mean calibrated radiocarbon date per gradient bin, producing estimates of the infinitesimal moments (Figure 3.9). To estimate transmission bias, following the methods outlined above, we regressed mean point size, $\bar{S}(t+1)$ as a function of $\bar{S}(t)$.

RESULTS

Hypothesis 1:

Figure 3.5 illustrates that although the sample size is relatively small, the frequency distribution is well fit by a lognormal distribution, indicating that the sample displays the expected distribution of the total population of Clovis points predicted by the ACE/BACE model.

Hypothesis 2:

A one-way ANOVA of log point size indicates significant differences between the three site types (ANOVA: $F_{2,231} = 108.65, p < 0.001$), and multiple comparisons indicate that cached points are significantly larger than both camp and kill site points,

though the variances are similar (Figure 3.6). This result is not surprising given that cached projectile points seem to reflect tools near the beginning stages of use-life (Kilby, 2008; Kilby and Huckell, 2003), while camp and kill site points are either discards or hunting losses, generally at the latter stages of their use-life. The projectile point sample also includes tools manufactured from several different raw materials, another potential source of variation. However, a one-way ANOVA of log point size shows no significant difference between raw material types (ANOVA: $F_{8,231} = 1.55$, $p = 0.14$) suggesting that raw material type does not significantly influence this analysis.

A least squares regression of intra-assemblage variance by distance is not significantly different from zero (Linear regression: $F_{25} < 0.01$, $r^2 < 0.01$, $p = 0.97$) and so we find no evidence of founder effects in these assemblages. The regression of projectile point size as a function of linear distance from the point of origin shows that projectile point size decreases significantly as a function of distance (Figure 3.7). Although there is a significant linear relationship between log point area and distance from origin (Linear Regression: $F_{1,231}$, $p < 0.001$, $r^2 = 0.34$, $AIC = 90.19$), the amount of variation in point size is better explained by a quadratic model (Quadratic Regression: $F_{2,230}$, $p < 0.001$, $r^2 = 0.41$, $AIC = 67.62$). The quadratic model is $y = y_0 + \beta_1 x + \beta_2 x^2 + \varepsilon$, where x is distance, and so the quadratic term $x^2 = (\text{distance})^2$ is straightforwardly interpreted as area.

Therefore, point size not only decreases with linear distance from origin, but also as a function of the area that distance encompasses. This may be a result of the internal dynamics of a spatially expanding population. As a population grows in size on a 2-dimensional landscape, the leading edge of the colonizing wave advances linearly with time at a velocity determined by the population growth rate and the rate of diffusion.

Diffusion is a function of the mean square displacement of an individual over their lifetime, measured as the average distance between birth and first reproduction, or marriage (Hamilton and Buchanan, 2007; Hazelwood and Steele, 2004; Steele et al., 1998). In a spatially expanding population individuals will, on average, disperse during their lifetime as the population expands in space. This dispersal is not linear, but is best modeled as a random walk in 2-dimensions (see Hazelwood and Steele, 2004). Thus, on an individual level, lifetime mobility is related to the 2-dimensional area covered by the diffusive movement as well as the 1-dimensional linear distance between place of birth and place of marriage or reproduction. Therefore, processes occurring within an expanding population at the individual, inter-generational level, such as the manufacture, use, and transmission of projectile point traditions are likely not only to be a function of distance, but also of area.

Results of the GLM indicate that while distance and area remain significant, site type and the interaction of site type and distance are non-significant, though the overall fit of the model is improved by considering these additional factors (GLM: see Table 3.3). Indeed, the GLM explains over half of the variation in point size as a function of distance from origin, space, and site type. The non-significance of site type likely results from the fact that although site type is non-uniform in space as generally camps occur in the east, and kills in the west, there is no significant difference in point size between kills and camps. In addition, although cached points are significantly larger than points at kill or camps, although primarily a western Clovis phenomena, caches also occur in the east (i.e., Rummells-Maske and Lamb).

In sum, after controlling for the potential confounding factors of site type and raw material, point size decreases with distance from origin, as predicted by the combined model.

Hypothesis 3:

Figure 6A shows the frequency distribution of projectile point size, per gradient bin. Figure 6B is a boxplot of log point size decomposed by gradient bin. The distribution within each bin is approximately lognormal, and the mean size decreases significantly with bin number. The slope of the regression of point size by time gives a direct estimate of the drift parameter (Figure 9A). The regression results show that the drift parameter $\alpha = -0.002$, which gives the standard deviation of the copying error rate $\sigma_\varepsilon = 0.063$ (0.044-0.078) (5.3%). The confidence limits around this estimate encompass the Weber fraction (0.05, or 5%).

In terms of estimating structural error, the standard deviation of the residuals from the autoregressive model is $\sigma_R = 0.145$, which gives the standard deviation of the error term in the transmission bias model $\sigma_\phi = 0.130$. Given that we have an estimate of the Weber fraction, and $\sigma_\varepsilon = 0.063$, the standard deviation of the structural error is then $\sigma_\kappa = \sigma_\phi - \sigma_\varepsilon = 0.067$. The relative proportion of the total variance due to copying error is given by $\sigma_\varepsilon^2 / \sigma_\phi^2$, which is about 23%, therefore copying error constitutes about one quarter of the variance in Clovis projectile point size. Considering that the structural error term we use here includes all other sources of variation in projectile point size, including

sampling bias, raw material size and quality, use life, and preservation among many other factors, copying error is a considerable source of variation in Clovis projectile point size.

Hypothesis 4:

A least-squares regression of variance per gradient bin by time shows no significant slope (Linear regression: $F_6 < 0.02$, $r^2 < 0.01$, $p > 0.9$) indicating that variance remains statistically constant over time. This suggests that variance is bounded by transmission bias as predicted by the BACE model. The first-order autoregressive model gives the transmission bias parameter $\lambda = 0.38$. As indicated in Figure 3.3, a bias parameter of > 0.1 results in a rapid approach to equilibrium, and so an estimated parameter of about 0.4 indicates that biased transmission played an important role in the teaching and learning of Clovis projectile point technology.

As predicted both the rate of change in skewness and kurtosis are non-significant, consistent with the predictions of the model.

DISCUSSION

Our analyses demonstrate that the Clovis projectile point sample provides support for all four hypotheses derived from the combined model, indicating that the BACE model is the appropriate null model for the cultural transmission of quantitative data. First, the frequency distribution of Clovis projectile points is lognormal, as predicted by the multiplicative process of the cultural transmission.

Second, on average Clovis projectile point sizes decrease with distance from the opening of the ice-free corridor, as predicted by the gradient model. This gradient maps

onto a similar gradient in the average age of radiocarbon dates shown in Hamilton and Buchanan (2007), where the earliest dates of Clovis occupation per gradient bin increase across North America with distance from the ice-free corridor. Therefore, our findings show that average point size decreases through time, as well as space. It then follows that these results indicate that the wave-like expansion of Clovis populations into North America is not only reflected in the spatiotemporal distribution of radiocarbon dates, but also in the average size of projectile points.

The lack of founder effects in the evolution of Clovis projectile point size suggests that rapidly growing Clovis populations were relatively demographically stable and did not fluctuate widely over time. Or at the least, localized extinctions of regional populations were rare enough not to affect the amount of cultural variation within the population as a whole. The absence of founder effects also suggests that as Clovis populations spread rapidly over the landscape they did not become geographically isolated. Instead, Clovis populations likely maintained broad social networks over large geographic expanses, which would have facilitated the flow of both genetic and cultural information over time and space (see Hamilton et al., 2007a; Hamilton et al., 2007b). These social networks thus would have had the effect of stabilizing local and global demographic and cultural variation across the continent via horizontal transmission and/or shared cultural phylogenetic histories (Buchanan and Collard, 2008; Buchanan and Hamilton, submitted). Indeed, despite some regional differences there is a noticeable qualitative similarity in Clovis projectile point form across the continent, and a clear historical relationship to subsequent Paleoindian projectile point styles in many areas of

the continent (e.g., Folsom on the Plains and in the Southwest, Barnes in the Great Lakes, and Suwannee in the Southeast).

Third, Clovis projectile point size decreases through time at a rate predicted by the Weber fraction, suggesting that spatial variation in Clovis projectile point size is due to drift processes caused by the accumulation of copying errors over multiple transmission events. Because the rate of reduction in projectile point size is almost exactly the rate predicted by drift due to copying errors, there is no evidence to suggest that the empirical size reduction at the continental level was driven by directional selection for smaller points, either due to changing ecological conditions, perhaps resulting in smaller prey sizes in the east, or as megafaunal prey went extinct toward the end of the Clovis period. However, while there is no evidence for direct selection for smaller points through time it is plausible that performance criteria, particularly the lower bound of the functional size of Clovis points also reduced through time as prey body size decreased, and so the rate of drift may have mapped onto changes in performance criteria. We want to emphasize that our results do not suggest that directional selection for point size never occurred, but that the overall trend in point size reduction over time at the continental scale was most likely due to neutral drift processes. Indeed, it is more than likely that some traits were under direct selection, while others were subject to drift.

It is interesting to note that the results we present here are consistent with the hypothesis that the variation in Clovis projectile point form across North America was primarily the result of drift (Morrow and Morrow, 1999), a hypothesis that finds support from a multivariate correlation analysis between regional measures of ecology, prey availability, and projectile point form (Buchanan and Hamilton, submitted). However,

while regional variation in projectile points is primarily the result of drift, this does not mean that all aspects of Clovis projectile point form were a result of drift. On the contrary, this suggests that Clovis projectile point technology was highly stable and capable of performing well in the diverse environments of the North American Late Pleistocene, a result consistent with the finding of strong bias transmission in Clovis projectile point technology we present here.

Fourth, variance in projectile point size is statistically constant over time, consistent with bias social learning practices within Clovis populations. This finding is not surprising given that biased transmission is recognized as a dominant force in social learning within human societies (Henrich, 2001), and, as such, it is easily understandable why biased learning strategies would have played an important role in Clovis technologies. Clovis projectile point technology is complex and would have required a significant amount of investment both in terms of time and energy to learn effectively. Under these conditions it is likely that there was a significant amount of variation among the skill-level of flintknappers, such that recognized master flintknappers likely would have held considerable prestige. Indeed, judging from the size, quality, and over-engineering of some archaeological examples, especially cached points, flintknapping may also have been a form of costly signal. Additionally, in a fast moving and fast growing population subject to the widespread environmental changes of the North American Late Pleistocene landscape conformist bias would also have been a highly effective strategy for social learning (see Boyd and Richerson, 1985; Henrich and Boyd, 1998). This is because under circumstances where ecological conditions change on a generational level, the mean trait value is often optimal, leading to frequency-dependent

bias, or conformism (Henrich and Boyd, 1998). If ecological conditions change much faster than this, social learning will favor trial and error learning leading to increased variance. Although the Clovis time period would have seen widespread ecological change over time and space, the rate of this change may not have been experienced within a lifetime (Alroy, 2001). As such, Clovis social learning likely involved a combination of both prestige bias and conformism, which had the effect of limiting variance over time.

Our mathematical model development and analysis indicates that the ACE model is a special case of the BACE model when the strength of bias, λ , is zero. So, in general the BACE model is the appropriate null model for the evolution of continuous traits over time, as the strength of bias is always likely to be greater than zero in human populations. Importantly, the null model's major prediction is that the mean value of a continuous trait subject to cultural transmission will drift negatively through time due to the inherently multiplicative process of social learning. Deviations from this expectation can then be used to generate further hypotheses. For example, if the average size of projectile points decreased faster than the null model, this may suggest strong directional selection for smaller projectile points over time. For example, If we assume there are strict performance criteria to point sizes, direct selection for smaller point sizes would be expected to correlate with smaller prey sizes. On the other hand, if point size remained constant over time, this would suggest stabilizing selection for point size, and may suggest a relatively stable prey population. Similarly, increasing point size through time may suggest directional selection for larger points, or some other major shift in lithic economy or behavior. However, note that neither the ACE nor BACE models allow for positive drift in point sizes. This is due to the mathematics of the learning process.

Equations 6 and 15 show that whenever the variance of the copying error rate is greater than zero (i.e., which could only occur in cases of 100% copying accuracy, perhaps due to standardized production), negative drift occurs deterministically. Positive drift could only occur mathematically if the probability distribution of copying error rates was heavily skewed to the left, in which case the model would violate the assumption of neutral unbiased copying errors, and so would reflect some form of directional selection.

The second major prediction of the BACE null model is that variance should asymptotically approach equilibrium, and so should remain statistically constant over time. This equilibrium is simply a mathematical result of the mean-reversion processes, where the probability of copying the mean is greater than zero (i.e., $\lambda > 0$). When the strength of bias is zero, then variance will increase linearly with time (see Figure 3.3). However, as stated above, situations where the strength of bias is zero are expected to be extremely rare given the highly interactive nature of social learning in human societies.

In conclusion, in this paper we have shown that the original formulation of the ACE model by Eerkens and Lipo (2005) leads to a remarkably rich body of quantitative theory with which to explore the archaeology of cultural transmission in human societies. Markov models of cultural transmission incorporate the essential stochasticity of social learning that contributes to the generation of archaeological variation, and are a flexible, yet straightforward method of generating the statistical predictions of cultural transmission over the long-term.

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FIGURES

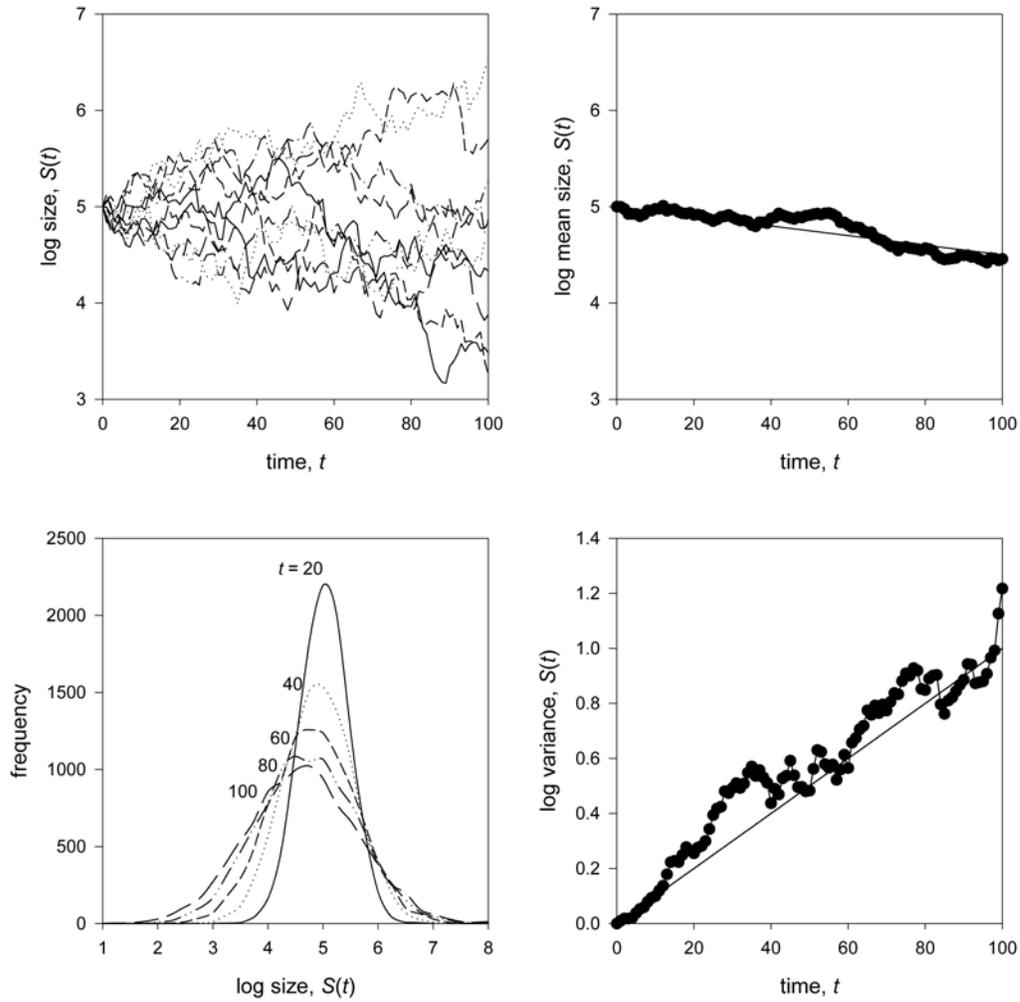


Figure 3.1. Monte Carlo simulations of the unbiased transmission ACE model, equation 13 (parameters: $S_0 = 5$, $\sigma_\varepsilon = 0.1$). A: Ten sample paths of the ACE model (equation 13). B: Monte Carlo results (10,000 iterations) of point sizes over time, showing that under the conditions of the ACE model the mean decreases through time, while the variance increases. C: Trend in the mean over time indicating that the average point size decreases through time at a rate of half the variance of the copying error. D: Trend in the variance over time. The variance increases approximately linearly with time.

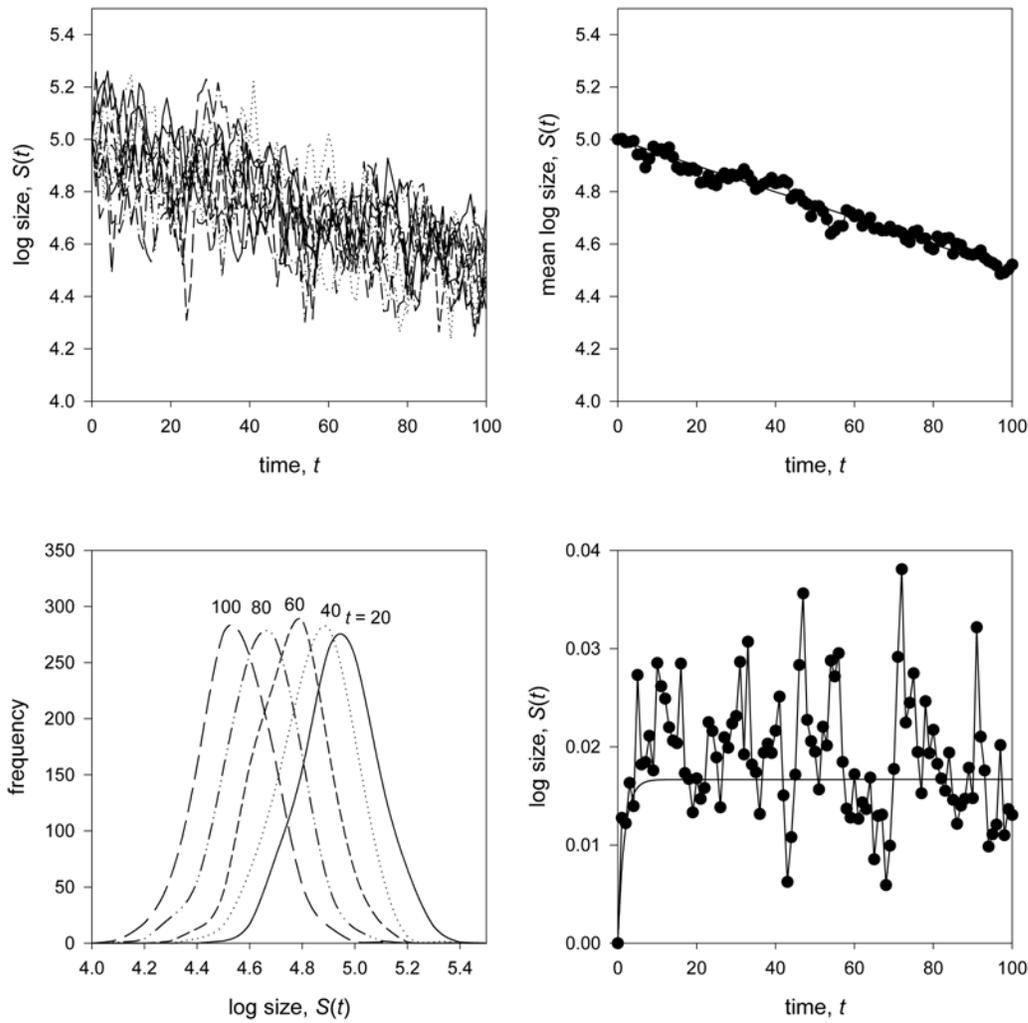


Figure 3.2. Monte Carlo simulations of the biased transmission (BACE) model, equation 17 (parameters: $S_0 = 5$, $\sigma_\epsilon = 0.1$, $\lambda = 0.3$). A: Ten iterations of the BACE model (equation 17). B: Monte Carlo results (10,000 iterations) of point sizes over time, showing that under the conditions of the biased transmission model the mean decreases through time, while the variance remains approximately constant. C: Trend in the mean over time indicating that the average point size decreases through time at a rate of half the variance of the copying error, as in the ACE model. D: Trend in the variance over time. Initially the variance increases rapidly, but quickly reaches equilibrium at $\sigma_\epsilon^2 / 2\lambda$.

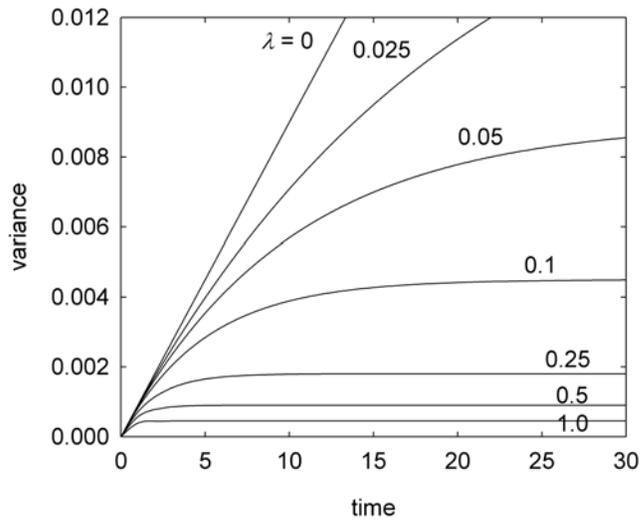


Figure 3.3. Plots of equation 21 showing variance as a function of both transmission bias, λ , and time, t . When transmission bias is greater than zero (unbiased transmission), variance asymptotically approaches equilibrium at $Var[x] = \sigma_x^2 / (2\lambda)$ at a rate $1 - \exp(-2\lambda t)$. This means that transmission bias always constrains long-term variance, whereas variance increases linearly under unbiased transmission ($\lambda = 0$).

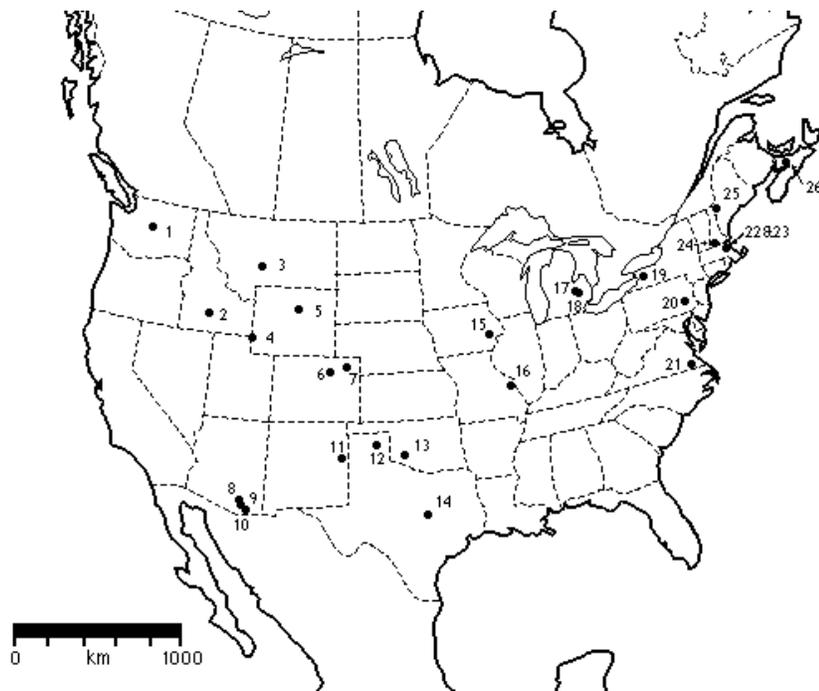


Figure 3.4. Distribution of Early Paleoindian sites with projectile point assemblages examined in the analysis (1, East Wenatchee; 2, Simon; 3, Anzick; 4, Fenn; 5, Colby; 6, Dent; 7, Drake; 8, Murray Springs; 9, Lehner; 10, Naco; 11, Blackwater Draw; 12, Miami; 13, Domebo; 14, Gault; 15, Rummells-Maske; 16, Kimmswick; 17, Butler; 18, Gainey; 19, Lamb; 20, Shoop; 21, Cactus Hill; 22, Bull Brook I; 23, Bull Brook II; 24, Whipple; 25, Vail; 26, Debert).

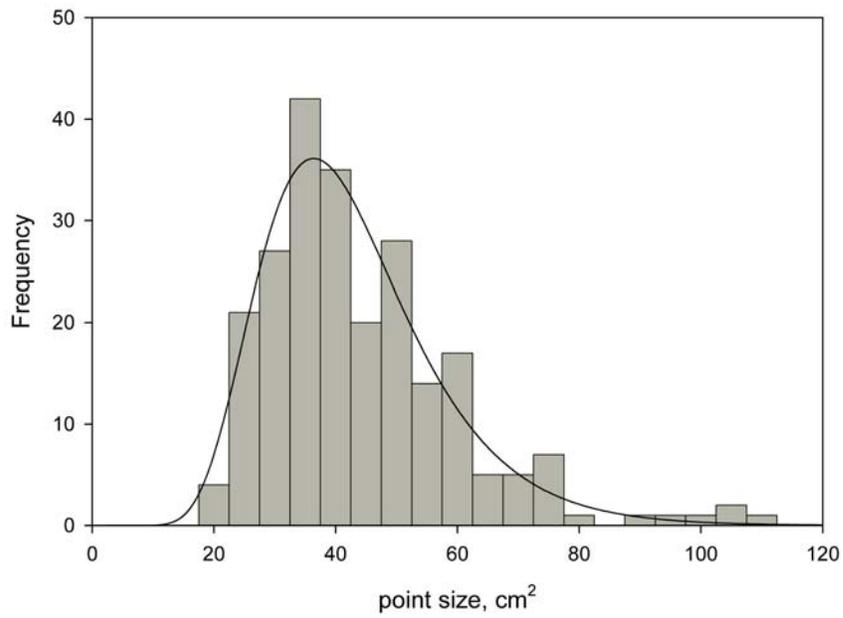


Figure 3.5. Frequency distribution of the projectile point sizes ($n = 232$). The distribution is skewed to the right and well-fit by a lognormal distribution, as predicted (solid line).

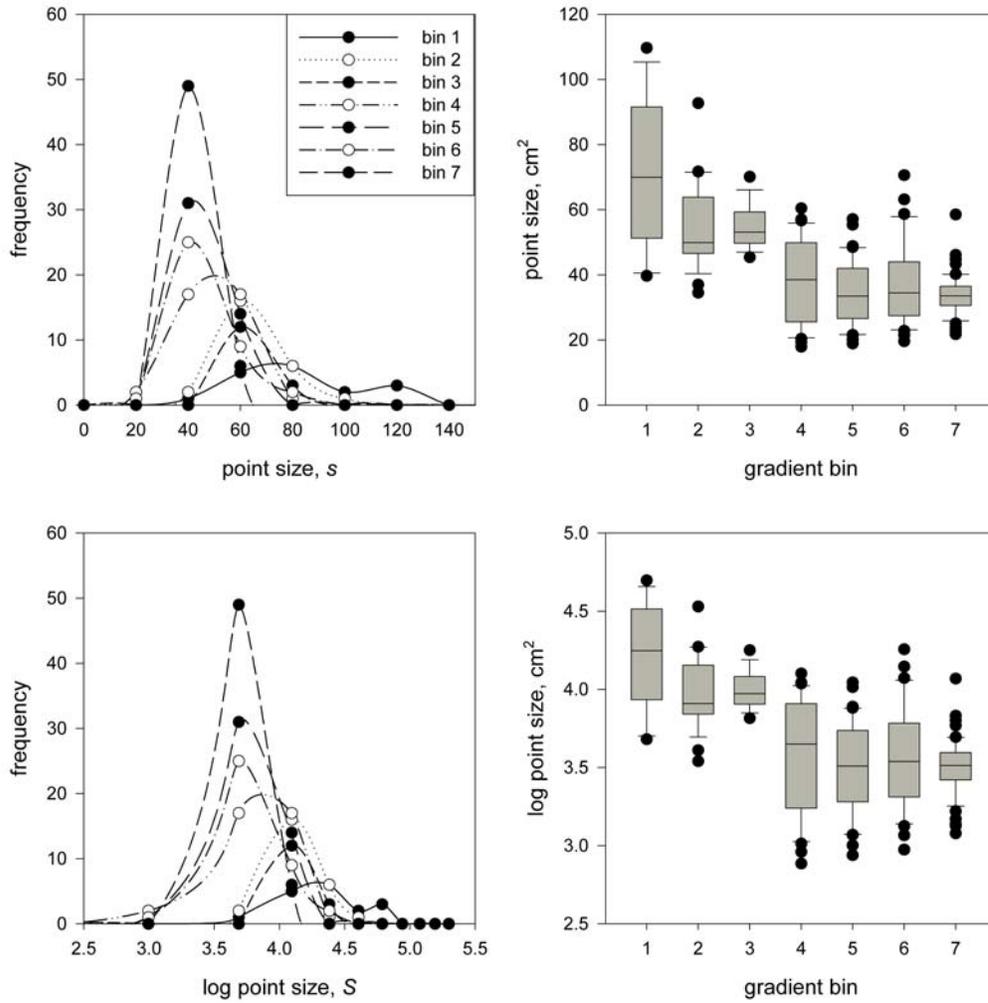


Figure 3.6. Distributions of the Clovis projectile point sample. A: Frequency distributions of the Clovis sample separated into the seven gradient bins. Each distribution is lognormal and shifts to the left with increasing bin number (see Figure 8 for more details). B: Boxplots of point sizes within each bin. C: The same frequency distributions as A but linearized to the log scale. D: Boxplots of point sizes within each bin.

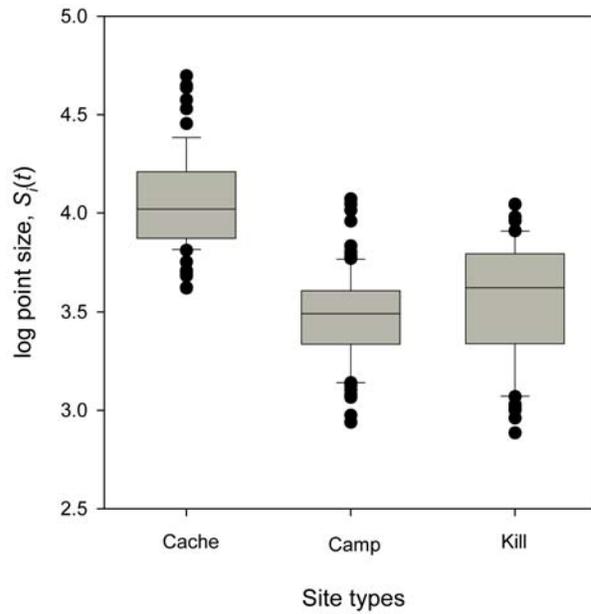


Figure 3.7. Boxplots of log point sizes for the three primary site types; caches, camps, and kills. All distributions are approximately normal on the log scale and the variances are similar. Cached points are significantly larger than both camp and kill site points (see text for details), while camp and kill sites points are not significantly different from each other.

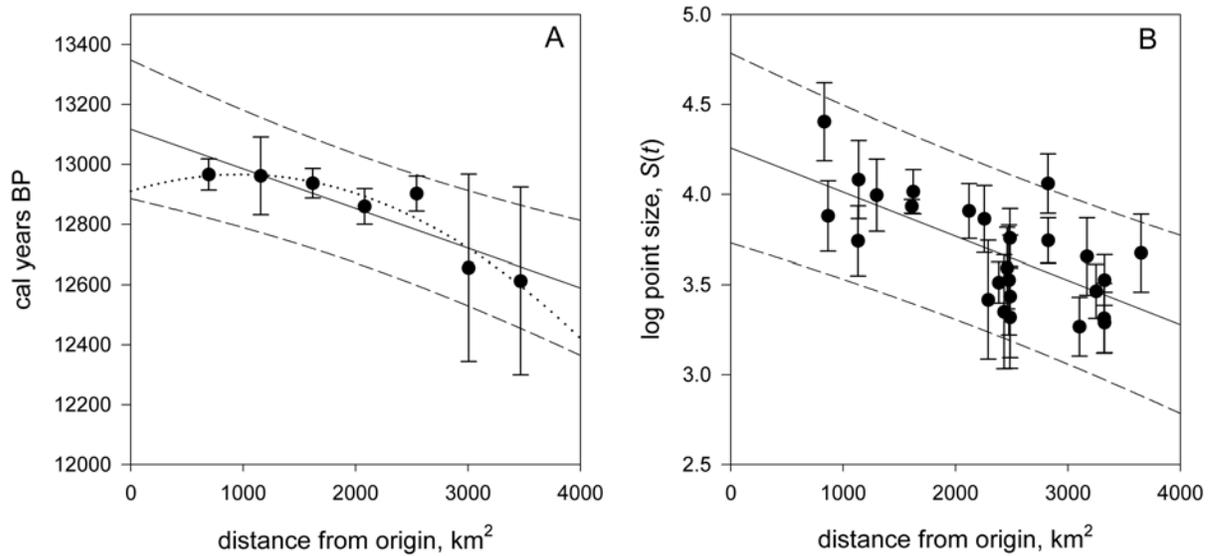


Figure 3.8. Spatiotemporal gradients in Clovis radiocarbon dates and projectile point sizes. Solid lines are the fitted slopes, and the dashed lines are the 95% prediction intervals. A: Plots of the average calibrated radiocarbon date per gradient bin by linear distance from origin (i.e., the mouth of the ice-free corridor), demonstrating that mean Clovis-age radiocarbon dates are younger the further from origin. The dotted line shows the quadratic regression fit, which is used in the GLM (see text and Table 3). B: Regression of mean log point size (± 1 standard deviation) for each of the 26 assemblages used in the analysis. The slope indicates that mean point size decreases with distance as predicted.

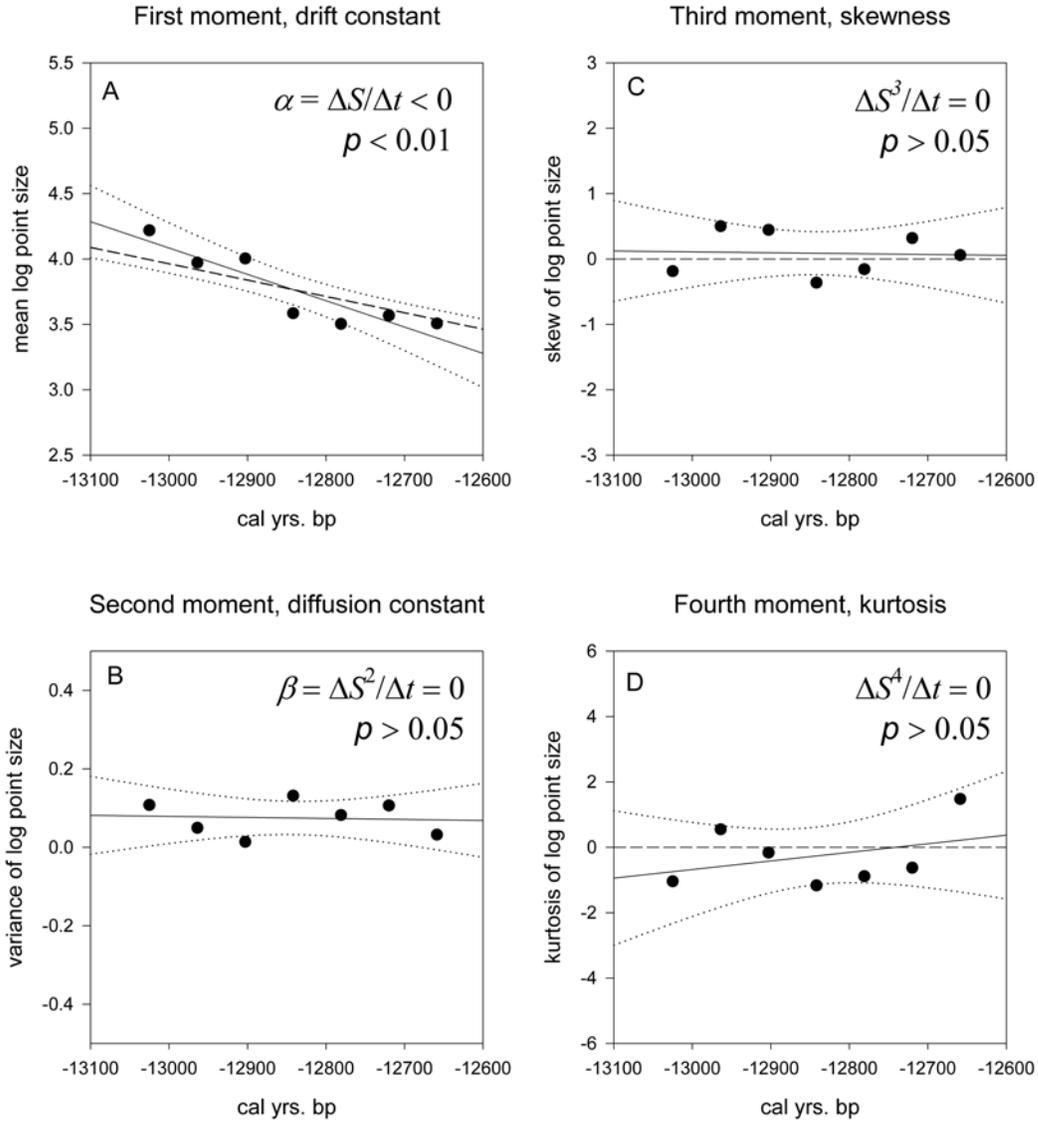


Figure 3.9. Regressions of moments per gradient bin by time (cal. years BP), giving estimates of the first four infinite moments. Dotted lines are 95% confidence limits around the fitted slopes, and dashed lines are the theoretically predicted moments. A. Mean log point size decreases significantly with time, at a rate given by the drift constant, $\alpha = -0.002$, which encompasses the theoretically predicted value of -0.00125 . B. Point size variance remains constant over time, such that the diffusion constant $\beta = 0$ as predicted. C. As predicted, skewness remains constant over time, and also bounds the predicted value of zero. D. Although the kurtosis of the distributions has a slight positive

trend over time (see Figure 3.2B and C), the rate is non-significant as predicted, and bounds the predicted value of zero.

Table 3.1. Projectile Point Assemblage Metrics from Early Paleoindian Sites Included in the Analysis (Figure 3.4).

Site	Mean size, ln cm ²	Variance, ln cm ²	Distance, km ²	Number of points	Reference(s)
Anzick ^a	3.8797	0.0379	866.3	6	(Jones and Bonnicksen, 1994; Lahren and Bonnicksen, 1974; Owsley and Hunt, 2001; Wilke et al., 1991)
Blackwater Draw ^b	3.4158	0.1086	2291.1	24	(Boldurian and Cotter, 1999; Cotter, 1937; 1938; Hester, 1972; Howard, 1935; Warnica, 1966)
Bull Brook ^c	3.5246	0.0195	3326	39	(Byers, 1954; 1955; Grimes, 1979)
Bull Brook II ^c	3.29	0.028	3326	2	(Grimes et al., 1984)
Butler ^c	3.434	0.115	2485.5	4	(Simons, 1997)
Cactus Hill ^c	3.3129	0.0376	3321.8	6	(McAvoy and McAvoy, 1997b)
Colby ^b	3.7414	0.0375	1133.3	4	(Frison and Todd, 1986)
Debert ^c	3.6737	0.0466	3650.9	6	(MacDonald, 1966; 1968)
Dent ^c	3.9325	0.0015	1610.8	2	(Brunswick and Fisher, 1993; Figgins, 1933; Haynes et al., 1993)
Domebo ^b	3.5107	0.013	2385.4	4	(Leonhardy, 1966)
Drake ^b	4.0143	0.0151	1624.1	13	(Stanford and Jodry, 1988)
East Wenatchee ^b	4.4036	0.0471	832.7	11	(Gramly, 1993; Lyman et al., 1998)
Fenn ^d	3.9947	0.0401	1298.7	16	(Frison, 1991; Frison and Bradley, 1999)
Gainey ^c	3.3185	0.0804	2484.8	11	(Simons, 1997; Simons et al., 1984; 1987)
Gault ^c	3.7439	0.0157	2824.3	2	(Collins et al., 1992; Collins and Lohse, 2004; Hester et al., 1992)
Kimmswick ^b	3.349	0.1	2432.7	3	(Graham et al., 1981; Graham and Kay, 1988)
Lamb ^a	4.0598	0.0272	2823.1	5	(Gramly, 1999)
Lehner ^b	3.525	0.0929	2475.6	10	(Haury et al., 1959)
Miami ^b	3.863	0.034	2257	3	(Holliday et al., 1994; Sellards, 1938; 1952)
Murray Springs ^b	3.5912	0.0511	2459.3	6	(Haynes and Hemmings, 1968; Haynes and Huckell, 2007;

Naco ^b	3.7568	0.0271	2485.2	8	Hemmings, 1970) (Haury et al., 1953)
Rummells- Maske ^a	3.9075	0.0231	2120.9	10	(Anderson and Tiffany, 1972; Morrow and Morrow, 2002)
Shoop ^c	3.2661	0.0266	3103.4	14	(Cox, 1986; Witthoft, 1952) (Butler, 1963; Butler and Fitzwater, 1965; Titmus and Woods, 1991; Woods and Titmus, 1985)
Simon ^a	4.0815	0.0472	1137.6	5	(Gramly, 1982; Gramly, 1984; Gramly and Rutledge, 1981)
Vail ^c	3.655	0.0462	3169.6	16	(Curran, 1984; 1987; 1994)
Whipple ^c	3.463	0.023	3250.7	2	

^a Indicates projectile point assemblage was identified in the literature as a cache.

^b Indicates projectile point assemblage was identified in the literature as recovered from a kill.

^c Indicates projectile point assemblage was identified in the literature as recovered from a camp.

^d The actual location of the Fenn cache is unknown; however, it was most likely recovered from the three-corners area where Utah, Wyoming, and Idaho meet (Frison and Bradley, 1999)

Table 3.2. Radiocarbon and calibrated dates used in the paper.

Map Number	Site	Mean calibrated date BP	Reference(s)
1	Anzick	12948	(Waters and Stafford, 2007)
2	Arlington Springs	12901.5	(Waters and Stafford, 2007)
3	Big Eddy	12842.5	(Ray et al., 1998)
4	Bonneville Estates	12922.5	(Waters and Stafford, 2007)
5	Casper	13106	(Frison, 2000)
6	Colby	12855.5	(Waters and Stafford, 2007)
7	Debert	12429	(Levine, 1990)
8	Dent	12910.5	(Waters and Stafford, 2007)
9	Domebo	12895	(Waters and Stafford, 2007)
10	East Wenatchee	13025	(Waters and Stafford, 2007)
11	Hedden	12437.5	(Spiess and Mosher, 1994; Spiess et al., 1995)
12	Hiscock	12828.5	(Laub, 2003)
13	Indian Creek	12925	(Waters and Stafford, 2007)
14	Jake Bluff	12817.5	(Waters and Stafford, 2007)
15	Kanorado	12906.5	(Waters and Stafford, 2007)
16	Lange-Ferguson	12994	(Waters and Stafford, 2007)
17	Lehner	12891	(Waters and Stafford, 2007)
18	Lubbock Lake	13010	(Waters and Stafford, 2007)
19	Murray Springs	12862.5	(Waters and Stafford, 2007)
20	Paleo Crossing	12912.5	(Waters and Stafford, 2007)
21	Shawnee-Minisink	12883	(Waters and Stafford, 2007)
22	Sloth Hole	12969	(Waters and Stafford, 2007)
23	Vail	12255	(Levine, 1990)

Table 3.3. Results for the General Linear Model of point size by distance, area and site type.

ANOVA table

Source	<i>DF</i>	Seq SS	Adj SS	Adj MS	<i>F</i>	<i>p</i>
distance	1	9.998	0.560	0.560	9.20	0.003
area	1	1.958	0.534	0.534	8.77	0.003
site type	2	3.806	0.043	0.021	0.35	0.704
site type* distance	2	0.095	0.095	0.047	0.78	0.460
Error	225	13.687	13.686	0.061		
Total	231	29.543				

Coefficients

Term	Coef	SE Coef	<i>T</i>	<i>p</i>
Constant	4.730	0.373	12.68	0.000
distance	-0.001	<0.001	-3.03	0.003
area	<0.001	<0.001	*	*
site type				
cache	0.078	0.2047	0.38	0.704
camp	0.037	0.3445	0.11	0.915
distance*site type				
cache	0.0001	0.0001	1.24	0.216
camp	-0.0001	0.0001	-0.89	0.376

Goodness of fit statistics

$r^2 = 53.67\%$

CHAPTER 4:

THE MOCKINGBIRD GAP SITE AND CLOVIS LAND-USE IN THE CENTRAL RIO GRANDE VALLEY AND THE NORTHERN AND WESTERN MOUNTAINS OF NEW MEXICO.

To be submitted: Hamilton, M.J., B. Buchanan, R. H. Weber, B. B. Huckell, V. T. Holliday, and M. S. Shackley.

ABSTRACT

Clovis assemblages are rare, and so data from new Clovis assemblages are invaluable in constructing a more complete picture of late Pleistocene hunter-gatherer adaptations in North America. Here we present data and the initial results of analyses on two new Clovis projectile point assemblages from the central Rio Grande Valley of New Mexico: 1) The Mockingbird Gap Clovis site assemblage; and 2) The Socorro County Clovis point assemblage. We show that these assemblages are two components of the same Clovis occupation of the central Rio Grande Valley and adjacent mountains. Raw material sources from both collections point to an almost exclusive use of the western and northern mountains of New Mexico, with very limited tentative ties to the San Pedro River Valley, Arizona to the west, and the Southern High Plains of Texas to the east. Analyses of projectile point sizes suggest that the size of complete points is biased by tool stone recycling behavior at Mockingbird Gap, but the overall size of points in the region fits the prediction of spatiotemporal gradients in Clovis projectile point sizes detailed in previous publications (Hamilton and Buchanan, 2007; submitted). The Clovis record of the central Rio Grande Valley suggests the use of both high elevation

mountains and grasslands, and lower elevation savannah-grasslands along major river drainages, within a large, but well-defined home range.

INTRODUCTION

Although excavated Clovis assemblages are rare in the Southwest US, the region includes several of the best-known Clovis sites in North America, including the Clovis type-site, Blackwater Draw, New Mexico (Boldurian and Cotter, 1999; Hester, 1972) and the famous cluster of Clovis sites in the San Pedro River Valley, Arizona, including Naco, Lehner, Murray Springs, and Escapule (Haury et al., 1953; Haury et al., 1959; Haynes and Huckell, 2007; Hemmings and Haynes, 1969). Other Clovis sites occur on the neighboring Southern High Plains at Lubbock Lake and Miami (Holliday, 1997; Holliday et al., 1994; Johnson, 1987), the Rolling Plains, Gault and Aubrey (Ferring, 2001), and western Sonora, El Bajio (Robles Ortiz, 1974; Sanchez, 2001) (see Figure 4.1).

In this paper we present the initial results of analyses of two major Clovis projectile point assemblages from the central Rio Grande Valley, New Mexico. The first assemblage is a collection of 222 projectile points surface collected from the Mockingbird Gap Clovis site, Socorro County (Huckell et al., submitted; Huckell et al., 2007; Huckell et al., 2006; Weber and Agogino, 1997), and the second is a collection of 70 Clovis projectile points surface collected from across Socorro County, New Mexico. Both assemblages were collected, catalogued, and mapped by Dr. Robert H. Weber over a period of about 50 years and represent the vast majority of known Clovis occurrences in this part of the Southwest (Huckell, 2004). In order to place the Clovis occupation of the central Rio Grande Valley within the broader framework of Clovis in the Southwest and across the continent, we focus on three aspects of the collections: 1) the spatial

distribution of Clovis sites and artifacts in the central Rio Grande Valley and neighboring mountains; 2) the location and distribution of known raw material sources for Clovis stone tools found within the central Rio Grande Valley; and 3) the relative size of Clovis points in this region in comparison to other Clovis assemblages across the continent. In specific we use the Clovis assemblages from the central Rio Grande Valley to test a model detailed in Hamilton and Buchanan (submitted), which predicts diminution in Clovis projectile point size as function of distance from the mouth of the ice-free corridor. Our goal is to introduce the two assemblages and present our initial impression of Clovis land-use patterns in this part of the southwest based on the results of our analyses.

LATE PLEISTOCENE PALEOECOLOGY OF THE CENTRAL RIO GRANDE VALLEY

Topographically, the central Rio Grande Valley lies on the eastern edge of the Basin and Range province and the southeastern edge of the Colorado Plateau, a region of western North America characterized by northwest-southeast trending block-fault mountain ranges separated by broad inter-montane river valleys. Today, the central Rio Grande Valley is characterized primarily by desert grasslands and lies at the far northern extent of the Chihuahuan Desert (Van Devender, 1995). At the close of the Late Pleistocene (~11.5 yr BP), the higher elevations were dominated by mixed conifer forest above about 1,675 m, grading into juniper woodlands, and pinyon-juniper-oak woodlands on rocky slopes at lower elevations, and grading into grassland-savannahs in the river basins (Van Devender, 1990), while riparian corridors probably maintained substantial gallery forests. The presence of C4 grasses and shrubs in packrat middens of the Late Pleistocene attests

to late spring/summer rains, suggesting an intact monsoonal regime while the lack of C3 shrubs suggests cold winters (Holmgren et al., 2006; Holmgren et al., 2007; Holmgren et al., 2003). Annual precipitation during the Late Pleistocene was bimodal and would have followed predictable elevational and latitudinal gradients (Holmgren et al., 2007). The hydrology of the region was complex during the Late Pleistocene, composed of widespread pluvial lakes throughout northern Mexico (Reeves, 1969; Van Devender, 1990) and the Southwest US (Allen, 2005; Allen and Anderson, 2000; Anderson et al., 2002), some of which were inter-connected in complex ways . By the later stages of the Late Pleistocene (~14 k yr BP) the pluvial lakes of the region had receded substantially from their recorded high-stands, but would have held substantial amounts of water on a seasonal basis (Holmgren et al., 2003; Van Devender, 1990).

MOCKINGBIRD GAP: PALEOECOLOGY AND SITE STRUCTURE

The Mockingbird Gap Clovis site is probably one of the largest but least known Clovis sites in North America. The site is located about 65 km southeast of Socorro, and about 30 km east of the Rio Grande at the northern end of the Jornada del Muerto (Figure 4.1). The site was first recorded in the late 1950s by Dr. Robert H. Weber. Over the next six decades, Weber piece-point plotted, collected and catalogued several hundred Clovis artifacts including projectile points, end scrapers and other flaked stone tools. The site covers an area of about 800 m by 150 m along a low-lying gravel ridge adjacent to Chupadera Wash. The site has seen very limited excavation over two periods; 1966 and 1968 by Eastern New Mexico University, under the direction of George Agogino (Weber and Agogino, 1997), and from 2005 to 2007 by the Universities of New Mexico and

Arizona, under the direction of Bruce Huckell and Vance Holliday (Huckell et al., submitted; Huckell et al., 2007; Huckell et al., 2006).

The artifacts are concentrated into two main areas of the site, a northern cluster and a southern cluster (Figure 4.2). Internal structure within these clusters is clearly apparent, suggesting the presence of about a dozen or so spatially discrete surface loci (Figure 2c and d), one of which has been the focus of the recent test excavations (Huckell et al., submitted; Huckell et al., 2007; Huckell et al., 2006). Archaeological and geoarchaeological testing at the site has revealed a shallow but extensive intact stratigraphy over large portions of the site, and the excavations have yielded well over a thousand Clovis artifacts including projectile point bases, biface fragments, gravers, flaked-tools, and debitage associated with large mammal bone scrap, probable *Bison antiquus* tooth fragments and charcoal (Huckell et al., submitted; Huckell et al., 2007). The archaeology at this locus suggests a short-term occupation, which included both the butchering and processing of bison or other prey, and the manufacture and retooling. Geoarchaeological coring of Chupadera Wash indicates that the arroyo was deeply incised during the Late Pleistocene with a marshy stream-like environment during the Clovis period (Huckell et al., submitted, Holliday et al., forthcoming). Undoubtedly this wetland environment would have attracted game along the arroyo, which in turn would have attracted Clovis foragers. As such, the geoarchaeological and paleoecological setting of Mockingbird Gap is not unlike other well-known early Paleoindian sites in the greater southwest such as Lubbock Lake and Blackwater Draw.

THE COLLECTIONS

Mockingbird Gap Projectile Point Collection

The Mockingbird Gap surface collection includes not only projectile points but a variety of other tools, including end scrapers, side scrapers, a more informal tools. However, in the following analyses we focus solely on the projectile point assemblage, but future analyses will address other tool types.

The Mockingbird Gap surface projectile point collection consists of a total of 222 points, 27 (12%) of which are complete, while the rest are basal, midsection, or tip fragments (Figures 4.3 – 4.7). Of the 27 complete points, 3 are preforms, while the remaining 24 are finished points. Out of the 195 fragmentary points, 66 (34%) are preform fragments while the remaining 129 (66%) are fragments of finished points. During the excavation seasons in 2005 and 2007, four more points were recovered: 2 on the surface, one of which was a preform, and 2 in situ, 1 complete base and 1 basal ear (Huckell et al., submitted; Huckell et al., 2006).

The complete points include both standard, diagnostic Clovis points and miniature points manufactured on flakes (Figure 4.3). The standard Clovis points exhibit the suite of diagnostic characters associated with Clovis projectile point manufacture, including bifacial manufacture, remnant overshot flaking, basal fluting, and ground margins. However, many of the points seem surprisingly small in comparison to other Clovis projectile point assemblages (Weber and Agogino, 1997). Some of the small sized points are simply heavily resharpened functional points, and several points exhibit evidence of later reworking into bifacial tools. There is also evidence of point recycling where large point fragments were being repaired and returned to service. However, it is clear from the

basal widths of the points, and the size of some of the preforms that some of the standard points at Mockingbird Gap were manufactured simply as small points. We return to this issue in greater detail below.

The miniature points are clearly technologically different from the standard Clovis points, and vary widely in manufacturing quality, ranging from simple flakes that have been crudely shaped to mimic the general shape of Clovis points, to others that are clearly manufactured by accomplished flint knappers (Figure 4.4). While flake-based miniature points are not abundant in early-Paleoindian projectile point assemblages, they do occur with noticeable frequency in both Clovis and especially Folsom contexts. Although their functional interpretation is open to opinion, they are likely associated with the learning of hunting and flint knapping skills by children. This interpretation is suggested by several lines of evidence. First, the size of the miniature points clearly precludes them from being functional components of a Clovis hunting tool-kit, though they may have been used to hunt such child appropriate prey as large insects, lizards, or perhaps small mammals. While small Clovis points have been recovered from several Clovis megafaunal kill sites (e.g., Lehner, Murray Springs, and Blackwater Draw), these points are clearly reworked functional Clovis points, similar to the smaller standard points at Mockingbird Gap. Second, while several of the miniature points are extremely crudely-worked flakes that have simply been shaped into the approximate form of a Clovis point others were clearly manufactured by knappers familiar with Clovis projectile point manufacturing techniques, and display at least rudimentary familiarity with key Clovis point attributes such as fluting, basal grinding, and fine edge retouch.

Given the working hypothesis that Mockingbird Gap represents a repeatedly reoccupied camping locale, possibly a Clovis regional aggregation site, and the large sample size of points at the site, it is more than likely that the Mockingbird Gap assemblage includes many aspects of Clovis behavior and material culture that are usually invisible in the archaeological record due to small sample sizes, the rarity of Clovis campsites in general, and the common pattern of relatively short-term, non-redundant site use. One of these archaeologically visible behaviors is likely the learning of flint-knapping and foraging skills; two skills that would have been central to Clovis life-ways and two skills that require significant investments of time and energy to accomplish in foraging societies (see Gurven et al., 2006; Walker et al., 2002).

Bases and basal fragments make up the vast majority (73%) of the Mockingbird Gap projectile point assemblage (Figures 5 and 6), consistent with campsite retooling activities such as the discard, manufacture and replacement of broken points. The shape of the basal concavities in the Mockingbird Gap collection varies widely, ranging from flat, through varying degrees of concavity to distinctly triangular, though the degree and shape of the base does not appear to be related to raw material type. Both basal width (ANOVA: $F_{9,92} = 1.47$, $p = 0.17$) and the depth of basal concavity (ANOVA: $F_{8,80} = 0.90$, $p = 0.52$) do not vary with raw material type, suggesting that much of the basal variation is the result of manufacturing decisions, rather than mechanical constraints imposed by the properties of the individual raw materials. Fluting characteristics vary in the collection from single to multiple flutes.

There are 14 (6%) projectile point tip fragments in the Mockingbird Gap collection, and of those 13 are tip fragments from preforms (Figure 7). There are 16 (8%)

other projectile point fragments, which include both midsection and edge fragments. Of course, small projectile point fragments are likely to be vastly under-represented in the collection, simply due to size and recognition, though small fragments are likely to be abundant at Mockingbird Gap given the extent of occupation at the site and the seeming concentration on the manufacture and replacement of broken and fragmentary points, in addition to the butchery and processing of prey carcasses, which may have included use of fragments of broken points.

Raw Materials

Projectile point raw materials at Mockingbird Gap are dominated by sources relatively local to the site (within about 50 km (Weber and Agogino, 1997)), however, the less abundant raw materials indicate an almost exclusive use of lithic sources to the north and west of the site, a region of rugged mountain and basin country bisected by several major river valleys.

The most abundant raw material is “Socorro red jasper”, a highly silicified rhyolite that outcrops at several locations in the central Rio Grande Valley, all within a few days walking distance from Mockingbird Gap (Dello-Russo, 2004). The toolstone within these sources varies in quality from fine-grained rhyolites to an almost quartzitic coarseness, and range in color from deep maroon, through red and mottled yellow. An XRF analysis conducted by Dello-Russo (2004) found a positive match between a single Clovis point from Mockingbird Gap, and the Black Canyon rhyolite quarry on the east slopes of the Chupadera Mountains on the west side of the Rio Grande.

The second-most dominant raw material is a green-gray-black chert, which, again, varies widely in quality. The source of this chert is unknown at present, but likely outcrops in one of the many nearby mountain ranges, which include extensive outcrops of Paleozoic limestones. This same chert dominates the lithic raw material assemblage from the excavated locus 1214, and includes several biface fragments, informal tools, and a large projectile point base, as well as considerable amounts of debitage, suggesting that this source may have been among the last raw material sources visited prior to the arrival of this particular Clovis group to Mockingbird Gap (Huckell et al., submitted; Huckell et al., 2006). Locally-available tan/brown cherts are the third-most abundant raw material. These cherts are widely available as secondary deposits in the Rio Grande gravels, perhaps even occurring at the site or in nearby arroyos. As might be expected, there are also several other cherts and chalcedonies from unknown sources.

Chuska chert (also known as Washington Pass and Narbona Pass), a distinctive lustrous, fine-grained orange-pink chert from the Chuska Mountains of northwestern New Mexico in the Four Corners country occurs in surprising abundance given that the source is over 300 km from the site. Chuska chert constitutes about 7% of the assemblage. In addition, Pedernal chert, a fine-grained white chalcedony characterized by faint black bands and red inclusions, also occurs at the site. Pedernal chert primary outcrops occur in the Jemez Mountains of northern New Mexico, about 200 km north of the site. Pedernal chert also occurs in secondary fluvial contexts along the Rio Grande south from the Jemez range.

Obsidian from various sources occurs in the Mockingbird Gap assemblage. X-ray fluorescence (XRF) analyses of ten Clovis points from the site suggest an extensive use

and knowledge of the mountains to the north and west of the site (Shackley, n.d). Eight of the points were sourced to obsidian outcrops in the Jemez Mountains (six points from Cerro Toledo and two from Valles rhyolite sources). One point was sourced to Mount Taylor, New Mexico and one to Cow Canyon, Arizona. The use of the Jemez and Mount Taylor sources is consistent with the northwestern origin of the Chuska and Pedernal cherts suggesting that Clovis travel across the northern mountains and San Juan Basin may have utilized the major drainages of the region, including the northern Rio Grande, Chama, Puerco, and the San Juan rivers. Several of these raw materials are available from secondary deposits, and so do not necessarily require direct procurement. For example, the Mount Taylor obsidians occur in the gravels of the Rio Puerco and Rio Grande, and the Cerro Toledo obsidians also occur in the Rio Grande, though nodules of the size needed to manufacture bifaces generally do not occur as far south along the Rio Grande as Socorro (Shackley, 2005). The Valles rhyolite, however, has not eroded outside the Valles caldera and so must have been procured directly from the Jemez Mountains originally. Whether the Clovis occupants at Mockingbird Gap visited the source directly, or acquired the obsidian through trade is unclear at this time.

The Cow Canyon projectile point is particularly interesting. Cow Canyon is the source for the obsidian tools recovered at the Murray Springs Clovis site, in the San Pedro river valley, Arizona (Shackley, 2007; n.d). This source is located near the Mogollon Rim and would have required either traveling across the Gila Mountains via the San Francisco river, or down the Rio Grande Valley, and west across the Lordsburg Gap to the Gila River, a journey of several hundred kilometers. The shared use of Cow Canyon obsidian indicates a connection between the Clovis occupation of the Rio Grande

Valley and the San Pedro River Valley, if nothing more than a shared knowledge of the landscape. Interestingly, the Cow Canyon source would have required a detailed knowledge of the Mogollon Rim country and would have required considerable time and effort to access from either location.

Socorro County Collection

The Socorro County collection consists of 70 Clovis points, ranging from fragments to complete points collected by Weber over 50 years from various regions of Socorro County, New Mexico (Figures 4.1, 4.8 and 4.9). Socorro County is a large county spanning 6,625 km² of the central Rio Grande Valley, at the far northern end of the Jornada de Muerto, the northernmost extent of the present Chihuahuan Desert. The county includes several major drainages, including parts of the Rio Grande, Rio Salado, and Rio Puerco, and includes all major biomes of the Southwest, from high elevation coniferous forests in the Gila Mountains and the several smaller ranges in the county, to the grasslands and Chihuahuan desertscrub of the Rio Grande Valley and the Jornada del Muerto. During the Late Pleistocene, in this region current biomes occurred approximately 1000 m below current elevational gradients such that much of the Southwestern landscape above ca. 1,675 m would have been boreal forest, and the valleys would have been a mixture of extensive pinyon-juniper-oak woodlands grading into savannah-like C₄ grasslands and C₃ shrublands at the lower elevations (Holmgren et al., 2007; Van Devender, 1990; 1995).

The points are concentrated in three main areas of the county:

1) The Jornada del Muerto and the Rio Grande valley ($N = 54$ points), about 1,200-1,500 m a.s.l.; particularly associated with the Chupadera Arroyo drainage system and associated springs, both upstream from MBG toward Chupadera Mesa, and downstream into the Jornada del Muerto basin.

2) Plains of St. Agustin ($N = 10$ points), above 2,100 m a.s.l.. A cluster of finds at the northern end of the San Mateo Mountains in the pass leading into the Plains of St. Agustin.

3) Eastern edge of the Magdalena Mountains along the west side of the Rio Grande ($N = 6$), ca. 1,800 m a.s.l.. Finds are associated with two springs, Torreon and Molino in the foothills of the Magdalenas, and a cluster of four points on the eastern slopes of Socorro Mountain behind the city of Socorro. This is the same region as some of the known silicified-rhyolite sources.

The elevational distribution of the collection suggests a concentration of occupation in the Jornada del Muerto basin and the Rio Grande Valley, but significant, probably seasonal, use of the high country of the Gila to the west of the Rio Grande.

Raw Materials

The Socorro County material shows a similar suite of raw materials to those found at Mockingbird Gap, including the dominant use of red jasper. The gray-green chert and tan brown Rio Grande chert occur in the Socorro County collection but with less frequency than at Mockingbird Gap, perhaps reflecting availability. The other dominant raw materials include obsidians, cherts, and chalcedonies, all of which occur at Mockingbird Gap, but at lower frequencies. The cherts in the Socorro County collections are from

unknown sources, but some of the chalcedony points are likely Pedernal, as at Mockingbird Gap. Of the six obsidian points, five are sourced to the Jemez Mountain sources, Valles Caldera and El Ruchelos, and one point from the Socorro Mountains, sourced to Cow Canyon, AZ (Shackley, n.d). Again, this is particularly interesting as Cow Canyon obsidian is now known at Murray Springs, Mockingbird Gap, and in the mountains to the west of the Rio Grande. Surprisingly there are no Chuska points in the Socorro County collection, but there are Alibates, quartzite, and petrified wood points, none of which are found at Mockingbird Gap. However, these raw materials occur at very low frequencies and make up less than 10% of the assemblage.

GENERAL POINT MORPHOLOGY

All the points from the Socorro County collection are either finished points or preforms; there are no miniature flaked points. Points are of the same general morphology as the Mockingbird Gap assemblage, displaying quite a variation in form, but generally points are parallel sided and basal features range from flat to triangular. Like the Mockingbird Gap data, neither basal width (ANOVA: $F_{5,24} = 2.59, p > 0.05$) nor depth of basal concavity (ANOVA: $F_{7,33} = 2.24, p > 0.05$) vary with raw material type. The two largest Clovis points from the central Rio Grande assemblages were recovered just to the west of Socorro (Figure x). One is a heavily reworked Alibates point and the other is a complete point, manufactured from an unknown orange agate. The agate point in particular would seem to be consistent with the size, quality, and technology of cached points, though the point was recovered by Weber in a younger secondary alluvial deposit, but no other

Clovis points of a similar size and quality were recovered from the nearby area (Robert H. Weber, pers. comm., 2007).

ASSEMBLAGE COMPARISONS

Morphology and raw materials

Projectile points from both collections share fundamental similarities in both morphology and raw materials. Although most of the points are incomplete, the complete bases show the same general basal fluting characteristics as well as the same range of variation in the shape and extent of basal concavity. Both assemblages are dominated by the rhyolite making up about 50% of the Socorro County collection, and 45% of the Mockingbird Gap collection (Figure 10). The cherts (tan brown and gray-green), assumed to be local to the Rio Grande Valley region, are less prominent in the Socorro County collection, but are present. There is a surprising absence of Chuska in the Socorro County collection although both collections include Pedernal chalcedony as well as other unidentified chalcedonies. Similarly, Alibates chert occurs in the Socorro County collection, but not at Mockingbird Gap. There is also a conspicuous absence of Edwards chert in both projectile point collections, although a single piece of Edwards debitage was recovered from the surface at Mockingbird Gap. This absence is notable given the dominance of Edwards chert in early Paleoindian assemblages of the Southern Plains, and the greater Southwest, including significant abundances in Folsom assemblages in the Jornada del Muerto (Amick, 1996).

Both collections also include obsidian, again, both utilizing sources from the Jemez Mountains and Cow Canyon. However, within the Jemez sources although both

collections include artifacts manufactured from Valles rhyolite, only Mockingbird Gap includes Cerro Toledo obsidian, and El Ruechelos obsidian occurs only in the Socorro County collection. Additionally, Mount Taylor obsidian does not occur in the Socorro County collection, but is found at Mockingbird Gap both in the surface projectile point assemblage and in the excavated material. Of course, given the very small sample size of obsidian artifacts analyzed, these results may well be influenced by sample sizes and so these initial findings should be treated as preliminary.

Both assemblages are characterized by very similar suites of raw materials, and both assemblages are dominated by the same 5 primary sources; rhyolite, gray-green chert, Rio Grande chert, obsidian, and Pedernal cherts (~75% of the Socorro County collection and ~85% of the Mockingbird Gap assemblage). The overall similarities in tool-stone raw material sources and general point morphology suggest a technological and behavioral link between the assemblages and likely represent the archaeological residue of the same regional Clovis population using the central Rio Grande Valley region over a number of years or generations.

Point size distributions

For a more quantitative comparison of the assemblages we now turn to the analysis of point size (Figure 4.11). We concentrate on two measures: 1) point area, in cm^2 calculated using a morphological digitizing process described in detail elsewhere (Buchanan, 2006; Buchanan and Hamilton, submitted; Hamilton and Buchanan, submitted); and 2) basal width, in cm, which is the width measurement of complete bases from margin to margin at their widest point. We use these two measures for the following

reasons. Point area is a robust, multivariate measure of point size and shape, but by definition, is restricted solely to the analysis of complete points. In addition, point area can be effected by the life history of the point, where resharpening, for example, can dramatically change the shape of the point from its original form to the its resharpened form at the time of discard. Although a much simpler measure, basal width allows us to increase the sample size of analyzed points dramatically, and largely circumvents the issue of resharpening, as in the majority of cases resharpening involves the retooling of the blade segment of the point, and rarely the hafting element, except, of course, for cases where large point fragments are recycled into new points.

Point area-basal width correlation

A correlation analysis indicates that basal width correlates significantly, and positively, with point area for our sample of 257 complete Clovis points from across the North American continent (Correlation: $r = 0.83$, $p < 0.001$, slope = 0.85), and is thus a reliable measure of point area. The slope of 0.85 shows that point area increases faster than basal width, meaning that larger points are predictably more slender than shorter points, probably due to a mixture of initial manufacturing constraints and the relative loss of blade length due to resharpening over the life history of the point.

Mockingbird Gap point size distributions

Figure 4.11a shows the point area distribution for all 25 digitized complete points from Mockingbird Gap. The distribution is unimodal, and approximately normally distributed on the logarithmic scale, meaning that point area is log-normally distributed

on the linear scale, as would be expected for culturally-transmitted technologies (Hamilton and Buchanan, submitted).

However, the same data plotted by basal width rather than overall size reveals a different pattern. Figure 4.11b shows that the distribution of basal widths of complete points is truncated at about 2 cm, with the body of the distribution resembling the lower tail of a normal distribution. A plot of the basal widths from all complete bases from Mockingbird Gap shows a more standard unimodal distribution, though slightly left skewed. The peak in the distribution of all basal widths matches the truncation of the complete points, suggesting that while the total assemblage of points used, manufactured, and discarded at Mockingbird Gap is normally distributed, the sample of complete points is heavily biased toward small points. We suggest this may reflect the reuse and recycling of points at Mockingbird Gap, consistent with the hypothesis that the site was repeatedly occupied over a substantial length of time. In general, the distributions in Figure 4.11b suggest that all complete points with a basal width greater than a threshold of about 2 cm were recycled into new tools, whereas all points below that threshold were discarded and left at the site, presumably because they were regarded as too small to be reused.

Socorro County collection point sizes

Figure 4.11c shows the basal width distributions for the complete points from the Socorro County collection ($N = 8$) and all complete bases ($N = 32$). Although the sample size of complete points is very small, the distribution of complete points and all bases is similar in shape, and both are skewed to the right. Note also that there is only one complete point and two complete bases less than 2 cm wide, suggesting that on average,

the points from the Socorro County collection are larger than at Mockingbird Gap. However, plotting both distributions on the same figure (Figure 4.11d) is revealing. These distributions suggest that the points from the Socorro County collection form the upper tail of an overall Rio Grande Clovis point distribution, while the Mockingbird Gap assemblage forms the lower tail and main body of the Rio Grande Valley assemblage. Indeed, the overall distribution of all 132 complete Clovis bases from the Rio Grande Valley forms a unimodal, normal distribution.

RIO GRANDE VALLEY CLOVIS POINTS IN COMPARISON TO OTHER CLOVIS

ASSEMBLAGES

Clovis

To compare the distribution of Clovis points in the Central Rio Grande Valley with other assemblages from across the continent, we first plotted out the two frequency distributions. Figure 4.12a shows that Clovis points from the Rio Grande Valley are significantly smaller, on average, than a continent-wide sample of Clovis points (T -test: $T_{248} = 8.03, p < 0.001$). Because the Rio Grande Valley distribution is composed of both complete and fragmentary points, whereas the continent-wide sample is composed only of complete points, we also ran the same test only on complete points from the Rio Grande Valley to check the robustness of our results, and indeed we find the same result (T -test: $T_{33} = 5.80, p < 0.001$).

Southwest-Southern Plains

We then conducted the same analysis at a finer-grained spatial scale, using a subset of the continent-wide Clovis sample, representing Clovis assemblages from the Southwest and

Southern Plains (including Blackwater Draw, Domebo, Miami, Lehner, Naco, and Murray Springs), with a sample size of 56 points (Figure 12b). Figure 4.12b shows that for all Rio Grande Valley bases (T -test: $T_{127} = 2.93$, $p = 0.004$) and complete points (T -test: $T_{42} = 3.63$, $p = 0.001$), average point size is smaller than other Clovis points in the general region. The distributions in Figure 4.12b show that as the upper tails of the Rio Grande Valley bases and the wider sample are very similar, the difference is driven by the abundance of small points at the Mockingbird Gap site. To check for the effects of sample size we then ran regressions of assemblage size on assemblage mean (OLS regression: $F_{25,1} = 0.79$, $p = 0.38$) and variance (OLS regression: $F_{25,1} = 0.49$, $p = 0.49$), but in both cases there was no significant trend. This result indicates that there is no simple linear trend between sample size and assemblage statistics. The lack of this trend may be obscured by the occupation histories of the different sites used in the analysis.

Gradient bin-distance decay model

Finally, we compared the size of Clovis points in the Rio Grande Valley to known spatiotemporal gradients in Clovis point size across the continent (Hamilton and Buchanan, 2007; submitted). In a previous publication we showed a statistically significant trend in the gradient of radiocarbon dates across the North American continent, where radiocarbon dates from Clovis-age sites get predictably younger the farther away they are from the mouth of the ice-free corridor, in a pattern indicative of a population expansion (Hamilton and Buchanan, 2007). In a further publication we showed that, as predicted by a cultural transmission model, Clovis projectile points reduce in size over time and space along these same gradients (Hamilton and Buchanan,

submitted). We can then use this model to predict the size range of Clovis points expected in Socorro County given its distance from the ice-free corridor.

Figure 4.13a shows a statistically significant gradient of size reduction in Clovis projectile point sizes (as measured by basal width) in 23 assemblages across the continent as a function of their linear distance from the mouth of the ice-free corridor. Figure 13a shows both the Mockingbird Gap assemblage and the Socorro County assemblage in relation to the gradient model. The upper tail of the Mockingbird Gap assemblage falls within the model's prediction intervals, though the lower tail extends well below the predicted range. The Socorro County collection also falls within the prediction intervals, suggesting that this assemblage is exactly within the size range predicted by Socorro County's distance from the ice-free corridor.

Figure 4.13b shows that once both assemblages are compiled into a greater Rio Grande Valley assemblage, the range of observed point sizes encompasses the prediction intervals of the model, but also extends well below the lower prediction interval.

However, Figure 4.13c shows that if we take averages within each gradient bin, plot the gradient, and plot the average size of Clovis points in the Rio Grande Valley, the points are, on average, a little smaller than expected, but well within the model's prediction interval. In fact, the model suggests that average point size between about 2,000 and 3,000 km from the mouth of the ice-free corridor are in general on the small side, similar to the size range observed in the Rio Grande Valley. As such, these results suggest that while the Rio Grande Valley Clovis points are in general small compared to both a continent-wide sample of Clovis points, and a regional Southwest-Southern Plains sample, once we take into account spatial gradients in the variation of Clovis point form

due to the dynamics of an expanding population, the Rio Grande Valley assemblage falls within the size range predicted by the gradient model.

DISCUSSION

Our analyses of the Mockingbird Gap surface collections supports the contention that the site represents a redundant, multiply-reoccupied camping locale focused on the utilization of Chupadera Arroyo and the surrounding grassland-savannah (Weber and Agogino, 1997), although at this initial stage of investigation the exact nature of the site's occupational history is unclear. In addition, contour plots of projectile point densities at the site (Figure 4.2) confirm initial impressions of approximately a dozen localized surface clusters separated into two primary concentrations, i.e., northern and southern locales (Huckell et al., submitted; Huckell et al., 2006; Weber and Agogino, 1997 and Weber, pers. comm. 2004-2007). The internal structuring of Clovis points within these two main locales likely represents spatially discrete camping events, as suggested by excavations of one of these locales in 2006-2007 (Huckell et al., submitted; Huckell et al., 2006), although whether they each represent an individual occupation, or multiple simultaneous events is unclear at present. It is important to note that while there are a dozen or so discrete surface clusters of projectile points, this is a minimum number of loci and there are many surface clusters of artifacts that have no projectile points. In addition, there are likely other unexposed sub-surface clusters, as suggested by the fact that there is both a substantial intact stratigraphy over a large area in the northern portion of the site, as well as a reasonably consistent scatter of surface artifacts across the site.

The nature of the lithic assemblage across the site clearly points to butchering and processing tasks, as well as the manufacture and retooling of weaponry. Although not a part of this study, the surface assemblage includes several dozen end scrapers, as well as multiple side-scrapers and expedient tools, consistent with butchery and processing tasks (Weber and Agogino, 1997). While faunal preservation at the site is poor, the excavated locale has produced a significant amount of probable *Bison antiquus* tooth enamel and large mammal bone scrap clearly associated with the lithic materials (Huckell et al., submitted; Huckell et al., 2006). Other localized clusters of tooth enamel, including mammoth, have been recognized at, and nearby the site although with no direct archaeological association (Weber and Agogino, 1997 and Weber, pers. comm. 2004-2007). Hunting opportunities along the deeply-incised marshy Chupadera Arroyo may well have attracted Clovis foragers, and kills made along the arroyo floor were likely processed at camp sites located in the adjacent uplands. It is interesting to note the absence of recognizable blades in the surface collection. While the function of Clovis blades may vary, they, and tools manufactured from blade segments, are often associated with butchering and processing tasks (Collins, 1999). The lack of blades at Mockingbird Gap is unlikely to be due to a simple lack of appropriately-sized raw material nodules, given the widespread availability of high-quality rhyolite outcrops in the region. Blades occur at most other Clovis sites in the Southwest, including Blackwater Draw to the east and several of the San Pedro River Valley sites to the southwest. The seeming lack of blades at Mockingbird Gap suggests either that the tasks for which blades were used were not performed at Mockingbird Gap (which seems unlikely), or that this aspect of the

Clovis toolkit was no longer an operational part of the Clovis repertoire during the period of occupation in this region.

Camp activities are clearly suggested by the overwhelming dominance of the projectile point assemblage by bases, manufactured primarily from locally available raw materials, but also the many preform fragments, consistent with weaponry manufacture and retooling. In addition, the excavated assemblage includes many lithic artifacts indicative of projectile point manufacture, including biface fragments, bifacial reduction flakes, and the termination of a large overshot flake, in addition to two Clovis projectile point bases (Huckell et al., submitted; Huckell et al., 2007). Further details of lithic manufacturing at Mockingbird Gap are suggested by distinct features of the frequency distributions of projectile point basal widths from the site. Figure 10b shows that the size distribution of complete projectile point widths is clearly truncated at the mean of the distribution, around 2 cm in width. This truncation suggests that all complete projectile points above this threshold were recycled into new tools, probably including some of the miniature points evident at the site. Points below this threshold width seem to have been deemed too small to transport away from the site, and so were discarded. This pattern of raw material recycling again suggests that Mockingbird Gap was reoccupied many times. This truncation also indicates that the sample of complete points from Mockingbird Gap is clearly biased to smaller, discarded points. This bias is clearly illustrated in Figure 4.11b where the distribution of widths of complete bases displays the upper tail of the distribution, which is missing in the distribution of complete points.

Despite the large sample size and diversity of projectile point sizes at Mockingbird Gap, the suite of raw materials evidenced in the projectile point collection

points to a varied, but relatively focused use of sources to the high mountain country to the north and west of the site. Indeed, there is a conspicuous absence of high-quality raw material sources from the east, particularly Edwards chert, which is dominant in virtually all other known Clovis sites east of the Rio Grande on the Southern Plains (Holliday, 1997), as well as in the Folsom assemblages of the northern Jornada Basin (Amick, 1996). Other locally-available high quality cherts such as “Rancheria” (Amick, 1996) are also absent from the Mockingbird Gap site, both in the surface collections and the excavated materials, despite the fact that Rancheria outcrops occur only a few dozen kilometers south in the Jornada Basin. There are Rancheria Clovis artifacts in the region (Amick, pers. comm. 2007), and so presumably the chert would have been accessible, either directly or through trade, to Clovis groups only a few miles further to the north. Similarly, despite the significant presence of obsidian from a diverse suite of sources, there are no artifacts sourced to known obsidian outcrops to the south of the site (Shackley, n.d). The overall impression is that Mockingbird Gap was likely a seasonally re-occupied campsite located at the extreme southeast corner of this particular Clovis population’s home range, which seems to have focused on a large geographic area including the central Rio Grande Valley, and the adjacent mountains of western and northwestern New Mexico.

While Mockingbird Gap seems to be a primary focus of Clovis camping activity in the northern Jornada basin, there are multiple other Clovis occupations along the Chupadera Arroyo drainage, both to the north and south of the site evidenced by a combination of isolated finds and sites. This pattern likely reflects Clovis groups foraging and moving along the resource-rich Chupadera Arroyo. The concentration of Clovis

activity along Chupadera Arroyo must partly be a function of survey sampling, and no doubt hunting occurred throughout the extensive savannah-grasslands of this part of the northern Jornada Basin. However, the Clovis presence along the arroyo suggests that foraging and camping activities included the drainage systems, and perhaps Chupadera Arroyo provided a useful corridor for movement across an otherwise broad, arid river valley.

On a wider, regional scale, the Mockingbird Gap and Socorro County collections suggest that Clovis land-use in this part of the southwest focused on the Rio Grande Valley and adjacent mountains, probably using the major drainages as travel corridors. Interestingly, however, the Clovis record of the Albuquerque Basin further north in the Rio Grande Valley, is very sparse (Huckell, 2004), despite considerable archaeological survey of the area (i.e., Judge, 1973). The picture created therefore is of a high-county Clovis adaptation, where Clovis groups in the region would have utilized the major drainages and mountain ranges of the region at elevations well-above 1,400 m a.s.l.. During the Late Pleistocene the majority of this region would have been heavily forested, with wet, warm summers, and wet cold winters, probably resulting in heavy snow in the high country (Betancourt et al., 1990). As such, seasonal movements likely focused on the high country during the warmer spring and summer months, with fall/winter mobility focused primarily in the river valleys, such as the extensive grassland-savannahs of the Rio Grande and northern Jornada Basins. Perhaps Mockingbird Gap was a Clovis winter camp where foraging activities could focus on the Chupadera Arroyo and the surrounding savannah-grasslands.

The similar suites of raw materials in both collections suggests that not only are both collections the archaeological residue of the same Clovis manifestation, but that this Clovis population had access to resources across a vast geographic area. If we were to delineate a boundary encompassing all known raw material sources from the Rio Grande Valley, and assume direct acquisition, then this would imply a territory of approximately 250,000 km², a vast area, but well within the range of territory sizes found in ethnographic hunter-gatherers (Binford, 2001). While recent and historic hunter-gatherers are not direct cultural analogues of Late Pleistocene hunter-gatherers, a similar set of ecological, environmental and reproductive constraints is likely to operate on the economics of foraging socio-economies in general (Kelly, 1995; 1999). In particular, space use of all mammals, not only hunter-gatherers, is determined by individual energy demands, group size, population growth rates, trophic level of the dietary niche, and ecology (Hamilton et al., 2007a; Haskell et al., 2002; Jetz et al., 2004; Savage et al., 2004). As such, Paleoindian territory sizes during the Late Pleistocene are likely to have been large in comparison to most ethnographic foragers given a combination of cooler mean temperatures, rapid population growth rates, a northern latitude cultural and technological history, and presumably a largely hunting-based dietary niche. However, the direct acquisition of all raw materials cannot be simply assumed, and while it is likely that dominant raw materials were accessed directly during the course of seasonal residential mobility cycles, it is also likely that other high quality raw materials moved large distances across the landscape via trade and exchange through social networks (Hamilton and Buchanan, 2007; Hamilton et al., 2007b; MacDonald and Hewlett, 1999). Arguably, this could be the case for Alibates chert, for example, which is a geographic

outlier in that it is the only known source from the Southern Plains, and is a high-quality chert that occurs in low frequency in the Rio Grande Valley Clovis assemblages. The Cow Canyon obsidian points and the single petrified wood point may indicate similar trading links with Clovis groups further to the west.

The multiple reoccupations at Mockingbird Gap, and the consistent, almost exclusive, use of raw material sources from the extreme southern extent of the Southern Rockies north of the Mogollon Rim suggests a redundant use of the landscape over some unknown period of time. The diversity of known raw material sources indicates a detailed working knowledge of a vast and complex landscape, indicative of the use of an established territory (Hamilton and Buchanan, 2007; Meltzer, 2004). The distribution of points on the landscape and the location of raw material sources suggests movement along the Rio Grande Valley, and to the west via the Rio Salado, Rio San Jose, and/or Rio Puerco drainages, and perhaps further north along the Rio Chama and San Juan River. Access to the Cow Canyon obsidian source, either through trade or direct acquisition, would have involved crossing the Plains of St. Agustin and perhaps traveling down the San Francisco River toward the Mogollon Rim, a route probably best followed during the spring/summer months.

The wider regional pattern of land-use across the greater Southwest and Northern Mexico that seems to be emerging is the use of relatively localized hotspots of activity connected by the possible shared use of raw materials, separated by regions of low density Clovis occupation. Such hotspots would include the Southern Plains, the Rolling Plains, the Rio Grande Valley, the San Pedro River Valley, and the western half of Sonora. This pattern of land-use would be more consistent with models that suggest

regional Clovis populations likely preferentially established territories in favorable ecological conditions across the continent, bypassing less favorable regions (i.e., Anderson and Gillam, 2000; Hamilton and Buchanan, 2007; Meltzer, 2004), rather than models that suggest a more ephemeral, non-redundant, sweeping use of the landscape (i.e., Kelly and Todd, 1988; Martin, 1967). Of course, the recognition of such hotspots is partly the result of survey and research sampling, as well as issues of preservation and exposure. However, the primary centers of Clovis activity in the Southwest are not associated with major population centers or agricultural land use practices, unlike across the continent in general (Buchanan, 2003), which suggests we may be seeing a true spatial signal of the underlying Clovis occupation.

The size of Clovis points in the central Rio Grande Valley fits the predictive model of Clovis projectile point size evolution over space and time (Hamilton and Buchanan, submitted). That is to say that while the complete points at Mockingbird Gap seem small on average, this perspective is biased by the clear recycling of points wider than about 2 cm at the base, in addition to the presence of miniature, flake-based points at the site. The analysis of projectile point widths from the broader central Rio Grande Valley shows that points in this region are, on average, larger than first impressions suggest, and the wide variation in point size within the region is consistent with the large sample size. While the Clovis record at Mockingbird Gap is currently undated, the average size of the points in relation to the predictive model suggests that the Clovis occupation of the central Rio Grande Valley is likely late Clovis (*sensu* Weber and Agogino, 1997). While circumstantial evidence must be used with caution, it is interesting to note that the limited faunal evidence at the site suggests ungulate (bison,

horse, or camel) hunting, rather than mammoth, and the lack of blades, despite intensive surveying, suggests a later as opposed to earlier technological adaptation. In addition, the overall small size of points may reflect reductions in prey body sizes in the later stages of the late Pleistocene/early Holocene transition, though, of course, several small Clovis points have been associated with mammoth kills in the San Pedro Valley (Haury et al., 1953; Haury et al., 1959) and at Blackwater Draw (Hester, 1972). However, we suggest that the idea that the Clovis record at Mockingbird Gap may be transitional Clovis/Folsom (Weber and Agogino, 1997) should be treated with caution as there are widespread technological, raw material, and behavioral differences between both Folsom and Clovis technology, and the Clovis and Folsom archaeological record in the region (i.e., Amick, 1996).

FIGURES

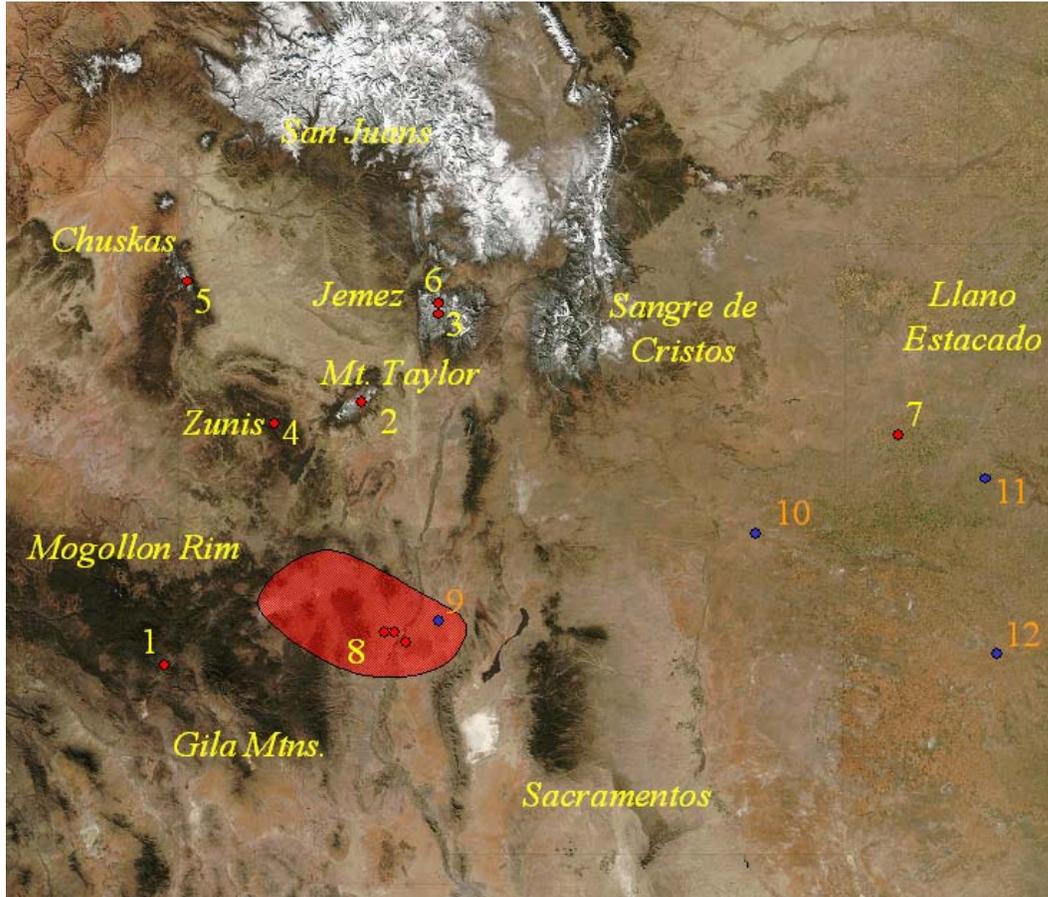


Figure 4.1. Major topographic features and raw material sources within the central Rio Grande Valley and surrounding regions. The red area represents the approximate geographic extent of the Socorro County sample. Raw Material sources: Obsidian, 1) Cow Canyon, 2) Mount Taylor and 3) Jemez sources (Valles Caldera, El Ruechelo, xxx); Chert, 4) China, 5) Chuska, 6) Pedernal chalcedony, 7) Alibates; Rhyolite, 8) various sources, including Black Canyon, Sedillo Hill, and the Chaffington Hills, and sites 9) Mockingbird Gap, 10) Blackwater Draw, 11) Miami, and 12) Lubbock Lake.

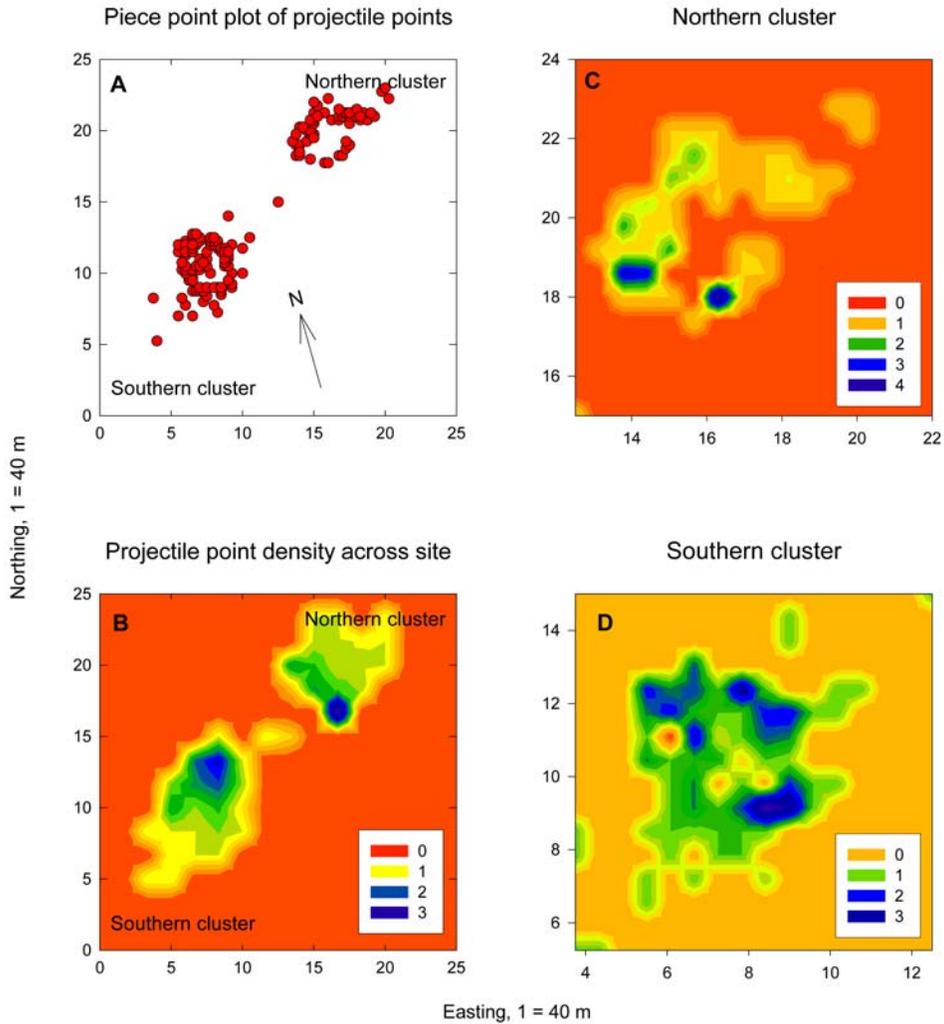


Figure 4.2. Projectile point density contour plots and site structure at Mockingbird Gap, measured in arbitrary units (1 unit = 40 meters) North and East of an arbitrary point ONOE. A. Spatial distribution of projectile points. There is a clear northeast-southwest trend to the distribution following the contours of the low-lying ridge. The projectile points are divided into two clusters, one north and one south. B. A contour plot of projectile point density. C. A contour plot of the northern cluster showing the internal structure



Figure 4.3. A selection of complete Clovis points from Mockingbird Gap. The points vary widely in raw material, size, and form.

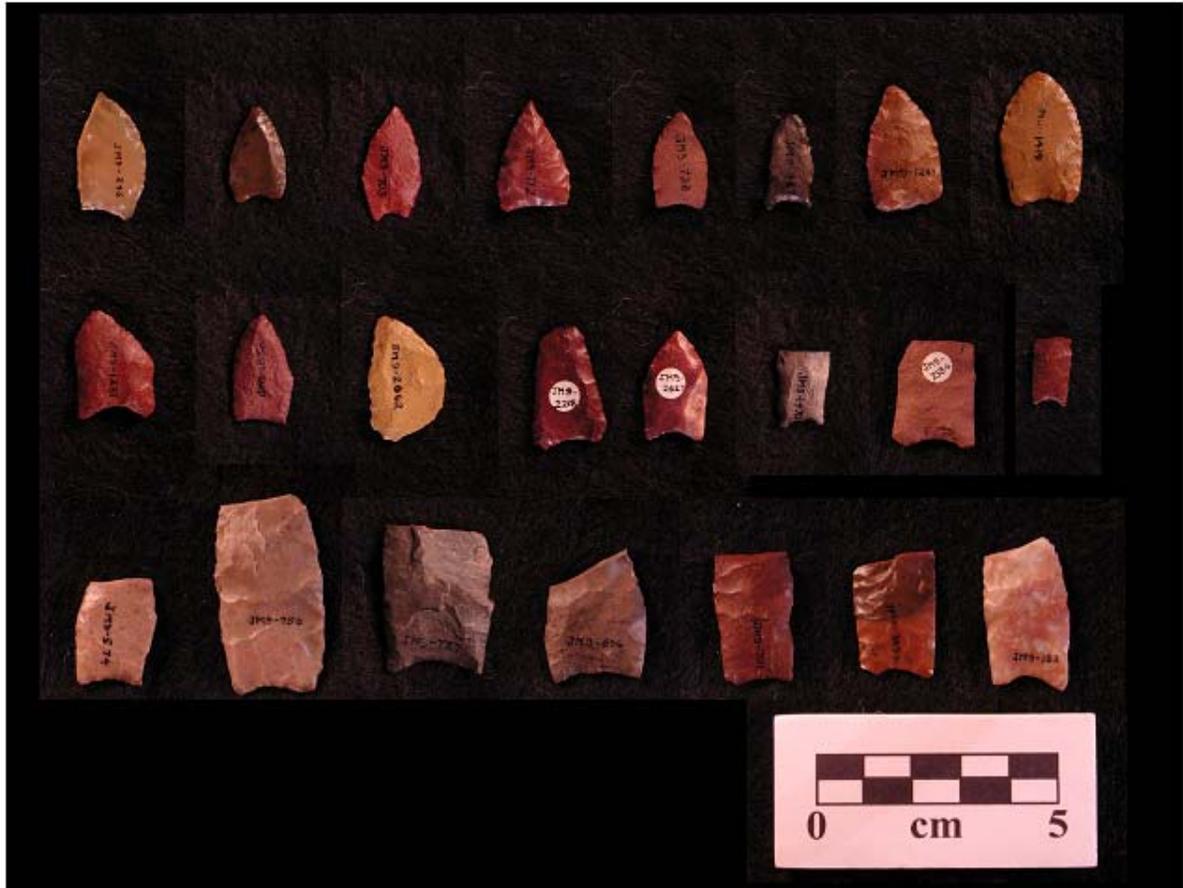


Figure 4.4. Miniature Clovis points and broken points from Mockingbird Gap. Top two rows: miniature points. Bottom row: A sample of broken points. The miniature points vary widely in the quality of manufacture, ranging from simply-shaped flakes, to expertly knapped points. The occurrence of broken miniature points (second row, last three on the right, and third row, first on the left), indicate that these points were broken after use, indicating that they were used for some function. We suggest that the miniature points are probably children's points, used to practice hunting small game.

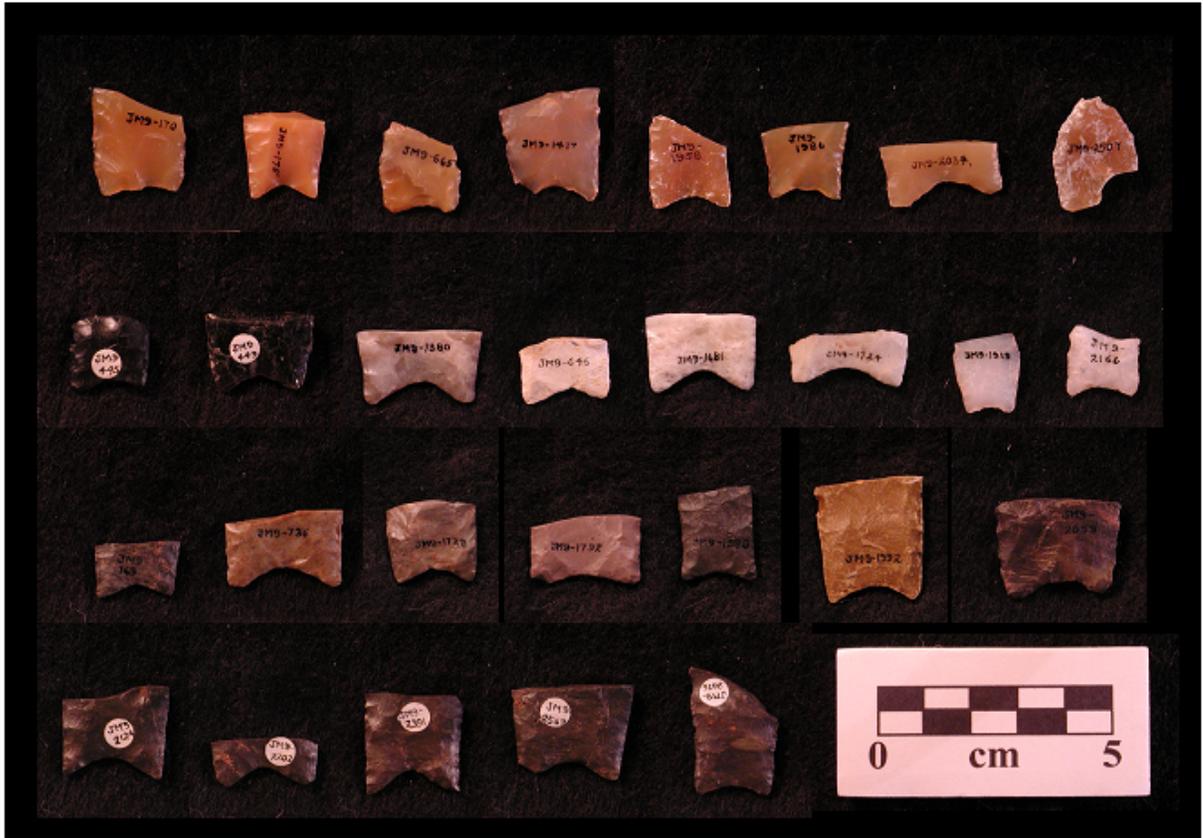


Figure 4.6. Other Clovis projectile point bases from Mockingbird Gap. Top row: Chuska fragments. Second row (left to right): obsidian and chalcedony. Third a fourth rows: gray-green-black chert.



Figure 4.8. Clovis projectile point fragments from the Socorro County Clovis collection. Points vary widely in raw material, size, and shape, but display similar ranges of variation to the point collection from Mockingbird Gap.



Figure 4.9. Cache-sized points from the central Rio Grande Valley. Left: Large unknown agate Clovis projectile point. Tip damage is from the alluvial context of the point's recovery. Right: Heavily resharpened Alibates projectile point recovered from the same general area as the point on the left. The basal width of the point suggests that originally it would probably have been of an equivalent size to the point on the left. These are by far the largest Clovis points known from the central Rio Grande Valley.

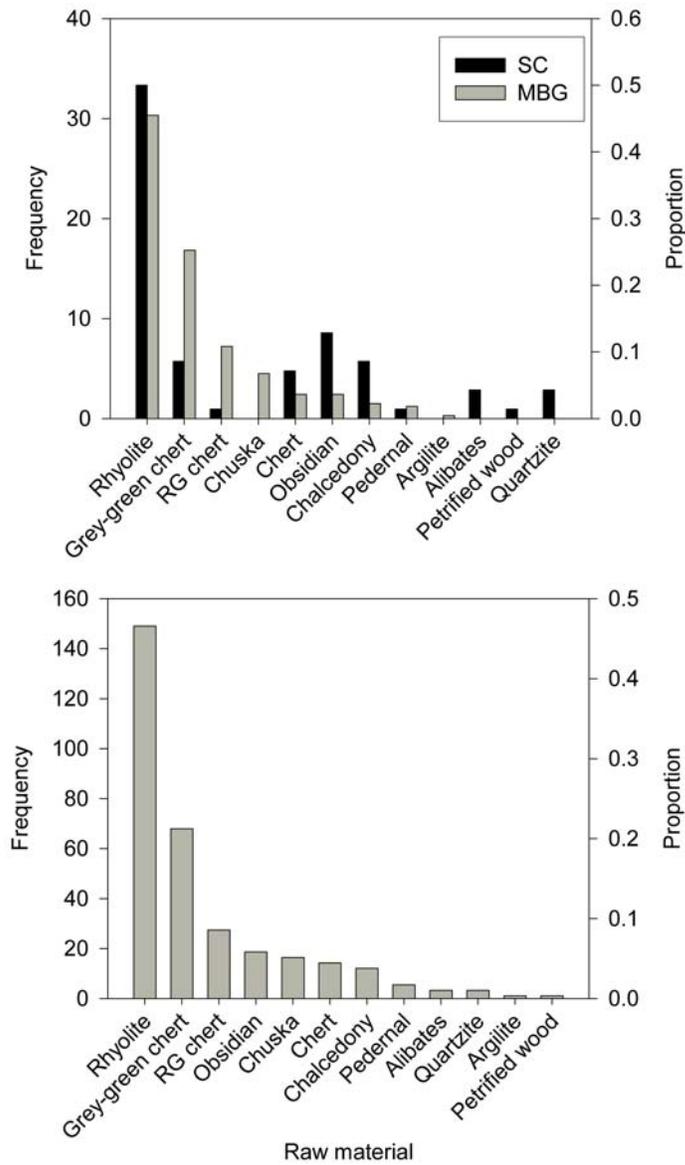


Figure 4.10. Histogram of raw material proportions at Mockingbird Gap, Socorro County and the central Rio Grande Valley. A: Frequency distributions of Mockingbird Gap and the Socorro County collections. B: Frequency distributions of the combined central Rio Grande Valley assemblage.

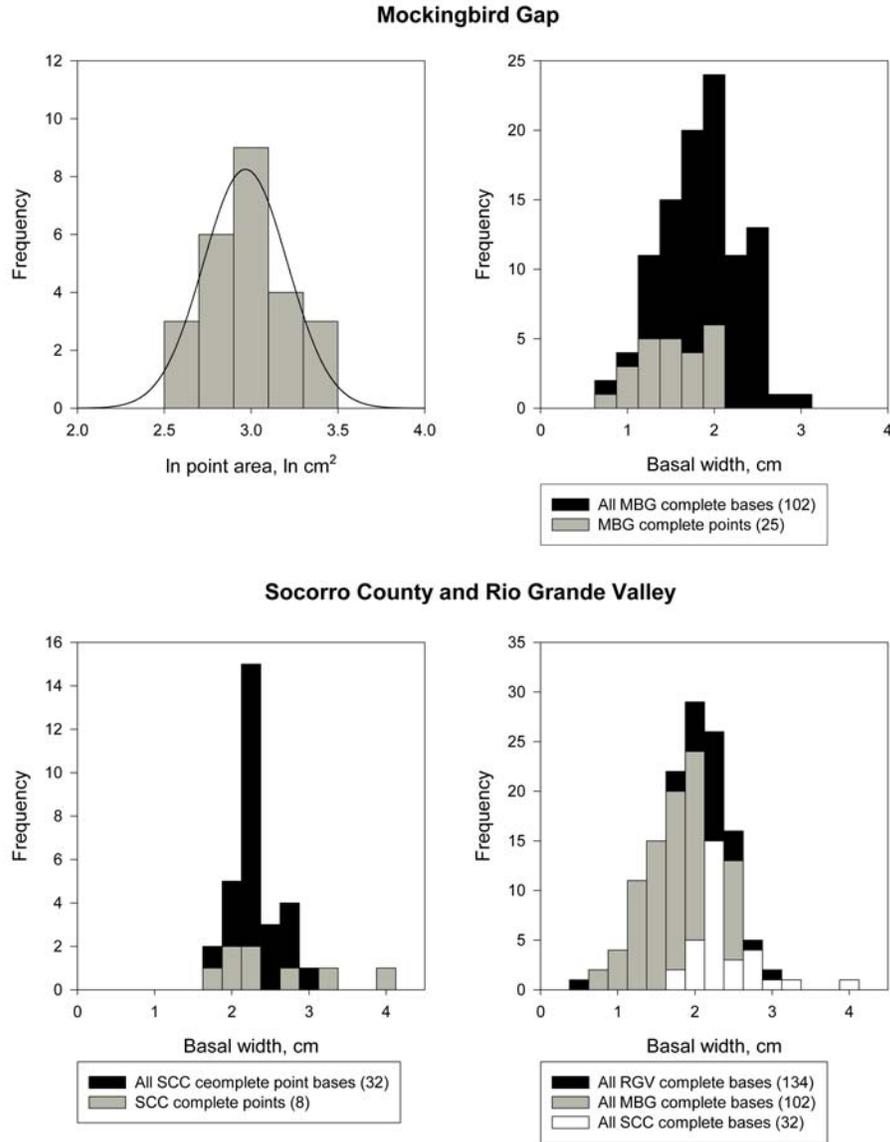


Figure 4.11. Point size distributions for the Mockingbird Gap and Socorro County collections. A: Frequency distribution of point areas of complete points from Mockingbird Gap. B: Frequency distributions of basal widths of both complete points and all complete bases (including complete points) from Mockingbird Gap. C: Frequency distributions basal widths of complete points and all complete bases from the Socorro County collection. D: Frequency distributions of all complete bases from Mockingbird

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Gap, Socorro County, and a combined distribution of all complete point bases representing the distribution of Clovis point basal widths from the Rio Grande Valley in general.

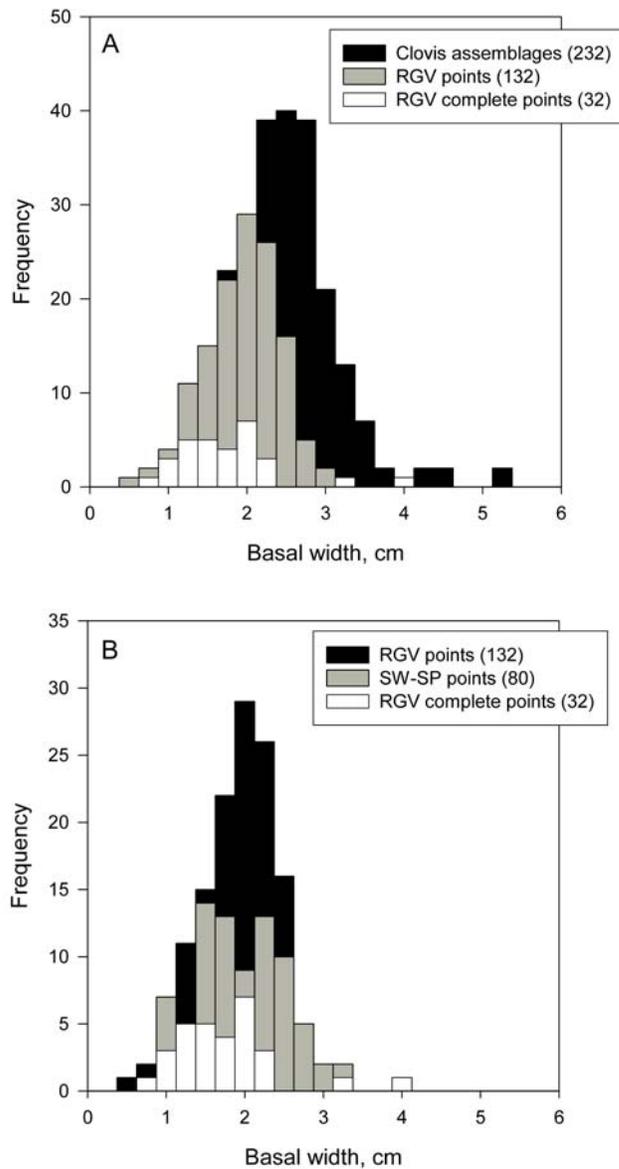


Figure 4.12. Frequency distributions comparing the Rio Grande Valley Clovis data to other Clovis assemblages continent-wide (A) and to regional Clovis assemblages from the Southwest and Southern Plains. A: Rio Grande Valley points are significantly smaller on average than the greater sample of all Clovis points continent-wide for both all complete bases (T -test: $T_{248} = 8.03, p < 0.001$) and complete points (T -test: $T_{33} = 5.80, p$

< 0.001). B: Rio Grande Valley points are equivalent in size to a distribution of combined Clovis assemblages from the Southwest and Southern Plains for both complete bases (T -test: $T_{148} = -0.82, p = 0.41$), and complete points (T -test: $T_{50} = 1.30, p = 0.17$).

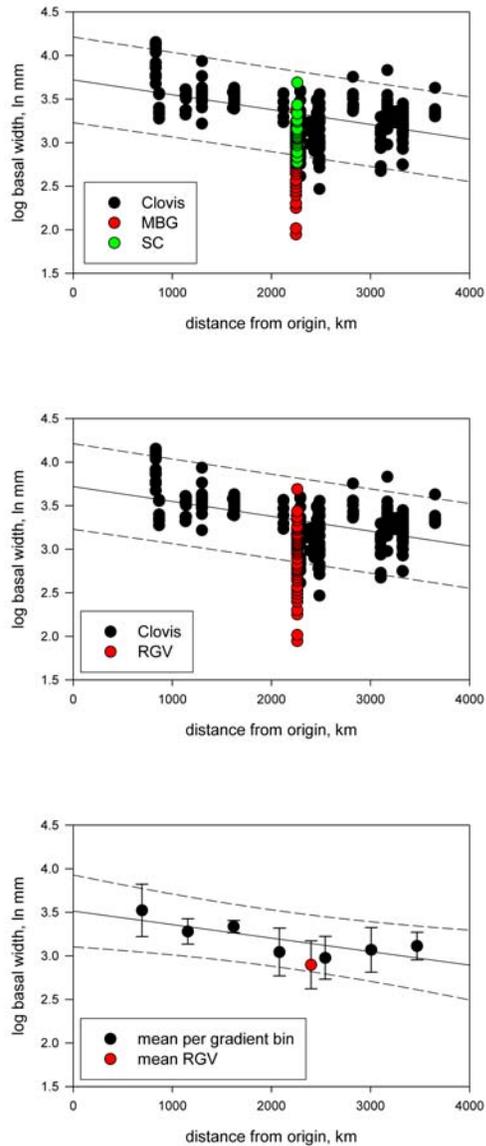


Figure 4.13. Basal width by distance from origin. A: Basal widths decrease with distance from origin (mouth of the ice-free corridor, assumed to be near Edmonton). The Socorro County collection falls well within the prediction intervals set around the model, whereas the Mockingbird Gap collection straddles the lower prediction interval. B: When the two collections are combined into a central Rio Grande Valley Clovis assemblage the overall distribution covers the prediction interval as well as falling below the lower prediction

interval. C: Taking average basal widths within each gradient bin, and across the combined central Rio Grande Valley assemblage shows that the average size of Clovis points in the central Rio Grande Valley falls within the predicted size range of Clovis points given the predictions of the gradient bin model. While Clovis points in the region may seem small, they are about the size predicted given the distance of assemblage from the mouth of the ice-free corridor.

CHAPTER 5:

CONCLUSIONS

The primary conclusion drawn from this dissertation is that the Clovis record of North America is the archaeological residue of a northwest-southeast trending population expansion that occurred toward the final stages of the Late Pleistocene, ca 11.3-10.7k ¹⁴C yrs BP. The demic expansion originated in the north/northwest of the continent, most likely from the mouth of the ice-free corridor, near Edmonton, Alberta, when tested against five alternative models. This wave-like expansion is best shown by clear spatiotemporal gradients in radiocarbon dates across the continent, which describe a rapid demic expansion driven by fast population growth rates, low conspecific competition, and settlement biases toward preferred environments, niches, and landscapes. Despite a low sample size, this gradient is robust in that the same temporal trend is seen in earliest occupation dates, average occupation dates, and, importantly, latest Clovis dates indicating that Clovis disappeared across the North American landscape just as fast as it appeared. I will return to this point later.

Given the strength of the pattern observed in the available radiocarbon date sample, it would require a significant reversal in the dating of southern and eastern Clovis-age archaeological sites to falsify this finding. However, it is possible that in the future new Clovis dates from the west could shift the predicted origin of the expansion to the west coast, given the general west-to-east spatiotemporal gradient observed in all alternative models (Figure 2.3).

The question of whether or not the Clovis expansion was wave-like or not is simply a matter of scale. As long as the expansion originated from a single point of

origin, and was time and space transgressive, then at a coarse scale the expansion is best modeled as a wave-like process. Of course, at finer scales population expansion likely occurred in a patchy, halted, and discrete fashion and undoubtedly varied in character across different landscapes and environments (Hamilton and Buchanan, 2007), but the overall wave model and rate at which the expansion occurred informs us of processes occurring at the finer scale, which should translate into archaeologically observable patterns.

For example, the fast pace of the time-delayed diffusion model employed in Chapter 2 predicts that Clovis populations would have established home ranges in favorable habitats, which could have been used over multiple generations. As local populations grew, new groups would then bud-off and established home ranges adjacent to the parental home range each new generation, resulting in a kin-structured wave of advance (Fix, 1999). Archaeologically, this model predicts the localized, heterogeneous use of Late Pleistocene landscapes isolated to patches with evidence of redundant use over time, separated by regions of little if any Clovis occupation. This pattern seems to be a good qualitative description of the Clovis settlement of the central Rio Grande River Valley, and the greater Southwest as a whole. The Clovis record of the central Rio Grande Valley suggests the focused use of the river valleys and mountain ranges of western and northern New Mexico, in a pattern more reminiscent of redundant use over some period of time than the sweeping, non-redundant land use suggested by alternative models (i.e., Kelly and Todd, 1988). Across the greater Southwest and Southern Plains there is some indication that this may be a general pattern in Clovis archaeology, in which the wider regional Clovis record consists of several localized hotspots of activity

focusing on locally available resources and particularly raw materials, with tentative connections through the use of shared, often exotic tool stone.

Changes in Clovis projectile point size over North America follow theoretically predicted trends given the northwest-southeast gradient in expansion. The data presented here suggest that Clovis points get smaller through time at a rate predicted by the accumulation of copying errors over multiple transmission events. Not only do points get smaller through time, but the analyses presented here show that the transmission of Clovis lithic technology was primarily vertical, and bounded by bias transmission, utilizing probably a mixture of both conformism and prestige bias. In other words, the Clovis technological tradition seems to have been conservative. Interestingly, from a demographic perspective, in a rapidly growing population there are likely to be multiple generations co-existing within a population, creating ideal conditions for the stable transfer of information via vertical transmission. Biased, vertical transmission is likely to have been a successful social learning strategy during the Clovis expansion because under conditions of ecological change, unless the rate of change is too drastic, both conformism and prestige bias are learning strategies likely to track environmental change. However, the observation that Clovis points get smaller through time suggests the conservative nature of Clovis projectile point technology focused primarily on producing points of a standardized form, rather than direct emphasis on size per se. The reduction in size of points over the Clovis period may reflect the diminution of prey body size through time, such that direct selection on the length of the cutting edge (i.e., blade length) may have been relaxed.

While not the focus of this dissertation, these findings have important implications for the potential pre-Clovis occupation of the North American continent. First, the speed and direction of the Clovis population expansion suggest that any pre-Clovis populations offered little, if any, territorial or competitive resistance to the colonizing Clovis wave. This non-competition may be understandable if pre-Clovis populations were absent altogether, present in low density, or in decline. However, if a pre-Clovis occupation of North America occurred, this must also have been the result of a successful population expansion, as the leading pre-Clovis candidate sites are located on the east coast of the continent, not to mention farther to the south in South America. To have persisted for any amount of time and to have covered the entire continent, these populations must have been widespread, and consisted of a viable population of genetically diverse individuals connected through extensive social networks, which must have continued for multiple generations, and would be expected to have left an archaeological residue of a widespread, if low density hunter-gatherer population, probably somewhat similar to Clovis. However, there is little to suggest that the pre-Clovis archaeology of North America resembles a population or expansion on the scale of Clovis, even if more poorly sampled (Kelly, 2003).

Second, it is important to note that the data presented here suggest that the Clovis projectile point style entered North America with the colonizing population. As such, the origins of Clovis technology likely are to be found north of the recognized geographic distribution of Clovis. While this is far from a novel suggestion (Buchanan and Collard, 2008; Goebel, 1991; Haynes, 1969), it does imply that any pre-Clovis technologies below the mouth of the ice-free corridor are extremely unlikely to be antecedent to Clovis.

Quantifying and falsifying the spread of a technology through diffusion of an innovation within a pre-Clovis population remains a methodological and theoretical challenge.

However, the initial conditions for such a modeling task must include the widespread archaeological evidence of such a population existing in North America, a condition yet to be demonstrated to the satisfaction of many researchers (but see Goebel et al., 2008; Haynes et al., 2007; Waters and Stafford, 2007).

A crucial question raised by this dissertation involves the cultural dynamics immediately following the Clovis period. As mentioned in the Chapter 1, the spatiotemporal gradient in radiocarbon dates suggests that the Clovis technocomplex disappeared across North America at about the same rate that it appeared. In the west, the transition from Clovis to Folsom corresponds to the onset of the Younger Dryas climatic event (~10.9k ^{14}C yrs BP), where temperatures abruptly reverted back to near glacial conditions over a period perhaps as short as a decade. Technologically, the transition between Clovis and Folsom saw the major reorganization of technologies toward a subsistence strategy based primarily on bison hunting (Huckell, 2003). Across the majority of the continent (excluding the Great Basin), subsequent Paleoindian technologies are clearly historically related to Clovis technology, and represent the regionalization of technological responses to more localized environmental conditions. However, the gradient analysis from Chapter 2 suggests that while the Clovis period may have lasted about 500-600 years across the continent, the actual record of Clovis occupation in any one area lasts only for about 200 years, perhaps a little longer in the far east (Figure 5.1).

This gradient begs the question of whether the Clovis complex first disappeared in the northern Plains due to regional abandonment of the area around 11.0k ^{14}C yrs BP, perhaps due to the depletion of high ranked prey resources, or whether Clovis technology was replaced by Folsom technology, which first occurred on the northern Plains, and spread rapidly to the south replacing Clovis technologies. If there were a Clovis regional abandonment, this would require a hiatus in the archaeological occupation of certain areas, implying that later Folsom reoccupation was the result of a subsequent population expansion originating elsewhere on the continent, rather than a successful technological innovation spreading through an intact and widespread Clovis population. Interestingly, the earliest known Folsom site, Indian Creek, dates to ~10.9k ^{14}C yrs BP and occurs in Montana (Davis and Greiser, 1992). Similarly, the youngest known diagnostic Clovis site, Jake Bluff, Oklahoma, dates to ~10.7-10.8k ^{14}C yrs BP (Waters and Stafford, 2007), a full 100-200 radiocarbon years after the initial appearance of Folsom on the northern Plains, and approximately coeval with the Folsom-aged bison kills at the Folsom type-site in New Mexico (Meltzer, 2006). In addition, the high-country Folsom occupation at Stewart's Cattle Guard, Colorado in the head waters of the Rio Grande dates to ~10.8k ^{14}C yrs BP (Jodry and Stanford, 1992), again, suggesting some possible temporal overlap between Folsom and Clovis occupations of western North America. Of course, temporal overlap between Clovis and Folsom must occur somewhere in the west if we exclude the possibility that the two cultures represent two separate colonization events originating from outside the continent. Deciphering the dynamics of the Clovis-Folsom transition will require detailed spatial and temporal analyses of both Clovis and Folsom occupations in western North America.

Finally, the chapters of this dissertation demonstrate the theoretical and empirical importance of analyzing archaeological dynamics. In this dissertation I have focused on the internal dynamics within a recognized archaeological culture, but the same methods may be used to look at transitions between cultures. Indeed, by comparing the dynamics within and between cultures, it may then be possible to identify the major processes that lead to larger macroevolutionary cultural changes over time, and how those processes differ from the smaller scale microevolutionary changes we observe within cultures. This perspective is perhaps best informed by the consideration of patterns across scales of analysis, from continent-wide patterns representing decades to centuries of change, to site-level analyses representing patterns created over days, weeks, or months. The consideration of multiple scales of analysis in this dissertation shows how patterns observed at one scale may lend insight into the mechanisms occurring at other scales, which lead to testable hypotheses that can be evaluated either qualitatively or quantitatively. It is only by testing hypotheses within the constraints set by data availability and quality that we can move beyond the reliance on informed opinion to the building of knowledge.

FIGURE

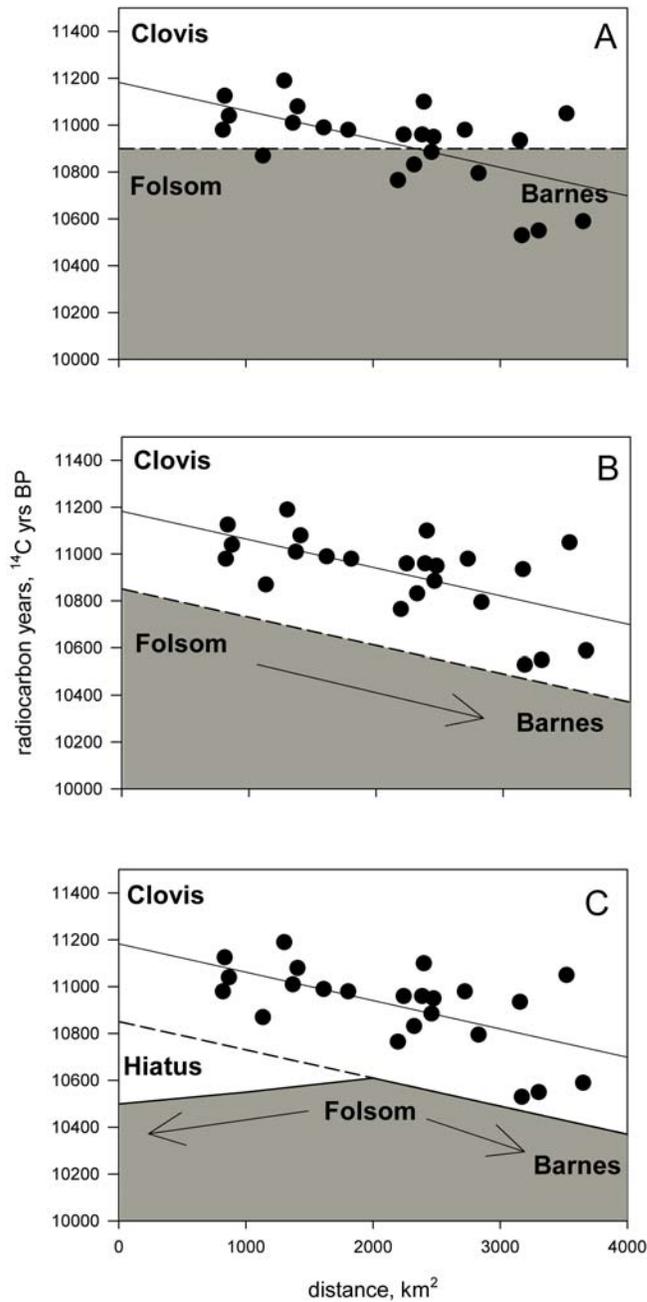


Figure 5.1. Alternative models of the Clovis-Folsom and associated Paleoindian traditions transition. A. The traditional culture history approach in which archaeological complexes are assumed to have a uniform start and end date across the continent. In the case of Clovis this would be ~11.5k-10.9 ¹⁴C yrs BP. This view may distort our

perspective as it fails to take into account the dynamics of cultural change across space. From the traditional linear view, the initial Paleoindian occupants of the south and east might be expected to be culturally affiliated with the Folsom tradition, simply because of the dating of occupations. B. Recognizing that Clovis occupations display a clear spatio-temporal gradient across the continent moves away from the traditional culture history approach. In this case it is likely that the Folsom tradition may well have been underway in the west at the same time that Clovis(-like) cultures still existed in the south and east. In panel B, because the latest Clovis dates also show a clear gradient one hypothesis is that Folsom traditions were initially established in the north and followed immediately on the heels of Clovis. In this case we would hypothesize that the Folsom radiocarbon record should show similar spatio-temporal gradients to the Clovis record. C. A third alternative is that the innovation of Folsom technology occurred somewhere in the mid-continent, and then spread to the north, south and east, replacing Clovis groups in some areas, and recolonizing other areas such as the northern Plains which had been abandoned ~11.0k ^{14}C yrs BP, such as the northern Plains. In this case one would see temporal separation in the archaeological record.

REFERENCES

- Adovasio, J.M., Pedler, D., Donahue, J., R., S., 1999. No vestige of a beginning nor prospect for an end: Two decades of debate on Meadowcroft Rockshelter. In Bonnicksen, R., Turnmire, K.L. (Eds.), *Ice Age People of North America: Environments, Origins, and Adaptations*, Oregon State University Press for the Center for the Study of the First Americans, Corvallis, Oregon, pp. 416-431.
- Allen, B.D., 2005. Ice-age lakes in New Mexico. In Lucas, S.G., Morgan, G.S., Zeigler, S.E. (Eds.), *New Mexico's Ice Ages*, New Mexico Museum of Natural History and Science, Albuquerque, pp. 107-114.
- Allen, B.D., Anderson, R.Y., 2000. A continuous, high-resolution record of late Pleistocene climate variability from the Estancia basin, New Mexico. *Geological Society of America Bulletin* 112, 1444-1458.
- Allen, L.J.S., 2003. *An Introduction to Stochastic Processes with Applications to Biology*. Pearson Prentice Hall, Upper Saddle River, NJ.
- Alroy, J., 2001. A multispecies overkill simulation of the end-Pleistocene megafaunal mass extinction. *Science* 292, 1893-1896.
- Amick, D.S., 1996. Regional patterns of Folsom mobility and land use in the American Southwest. *World Archaeology* 27, 411-426.
- Ammerman, A.J., Cavalli-Sforza, L.L., 1973. A population model for the diffusion of early farming in Europe. In Renfrew, C. (Ed.) *The Explanation of Culture Change*, Duckworth, London, pp.
- Anderson, A.D., Tiffany, J.A., 1972. Rummells-Maske: a Clovis find spot in Iowa. *Plains Anthropologist* 17, 55-59.
- Anderson, D.G., Gillam, J.C., 2000. Paleoindian colonization of the Americas: implications from and examination of physiography, demography, and artifact distribution. *American Antiquity* 65, 43-66.
- Anderson, R.Y., Allen, B.D., Menking, K.M., 2002. Geomorphic expression of abrupt climate change in Southwestern North America at the glacial termination. *Quaternary Research* 57, 371-381.
- Anikovich, M.V., Sinitsyn, A.A., Hoffecker, J.F., Holliday, V.T., Popov, V.V., Lisitsyn, S.N., Forman, S.L., Levkovskaya, G.M., Pospelova, G.A., Kuz'mina, I.E., Burova, N.D., Goldberg, P., Macphail, R.I., Giaccio, B., Praslov, N.D., 2007. Early Upper Paleolithic in Eastern Europe and implications for the dispersal of modern humans. *Science* 315, 223-226.

Barton, C.M., Schlich, S., James, S.R., 2004. The ecology of human colonization in pristine landscapes. In Barton, C.M., Clark, G.A., Yesner, D.A., Pearson, G.A. (Eds.), *The Settlement of the American Continents*, The University of Arizona Press, Tucson, pp. 138-161.

Bertuzzo, E., Maritan, A., Gatto, M., Rodriguez-Iturbe, I., Rinaldo, A., 2007. River networks and ecological corridors: reactive transport on fractals, migration fronts, hydrochory. *Water Resources Research* 43, W04419.

Betancourt, J.L., Van Devender, T.R., Martin, P.S. (Eds.), 1990. *Packrat Middens: The Last 40,000 Years of Biotic Change*. University of Arizona Press, Tucson.

Bettinger, R.L., Eerkens, J., 1999. Point typologies, cultural transmission, and the spread of bow-and-arrow technology in the prehistoric Great Basin. *American Antiquity* 64, 231-242.

Binford, L.R., 2001. *Constructing Frames of Reference: An Analytical Method for Archaeological Theory Building Using Ethnographic and Environmental Data Sets*. University of California Press, Berkeley.

Boldurian, A.T., Cotter, J.L., 1999. *Clovis Revisited, New Perspectives on Paleoindian Adaptations from Blackwater Draw, New Mexico*. The University Museum, University of Pennsylvania, Philadelphia.

Boyd, R., Richerson, P.J., 1985. *Culture and the Evolutionary Process*. University of Chicago Press, Chicago.

Bradley, B., Stanford, D., 2004. The North Atlantic ice-edge corridor: a possible Palaeolithic route to the New World. *World Archaeology* 36, 459-478.

Brantingham, P.J., 2007. A unified evolutionary model of archaeological style and function based on the Price equation. *American Antiquity* 72, 395-416.

Brantingham, P.J., Surovell, T.A., Waguespack, N.M., 2007. Modeling post-depositional mixing of archaeological deposits. *Journal of Anthropological Archaeology* 26, 517-540.

Brown, C.T., Liebovitch, L.S., Glendon, R., 2007. Levy flights in Dobe Ju/'hoansi foraging patterns. *Human Ecology* 35, 129-138.

Brunswig, J., R. H., Fisher, D.C., 1993. Research on the Dent mammoth site. *Current Research in the Pleistocene* 10, 63-65.

Buchanan, B., 2003. The effects of sample bias on Paleoindian fluted point recovery in the United States. *North American Archaeologist* 24, 311-338.

Buchanan, B., 2006. An analysis of Folsom projectile point resharpening using quantitative comparisons of form and allometry. *Journal of Archaeological Science* 33, 185-199.

Buchanan, B., Collard, M., 2007. Investigating the peopling of North America through cladistic analyses of Early Paleoindian projectile points. *Journal of Anthropological Archaeology* 26, 366-393.

Buchanan, B., Collard, M., 2008. Phenetics, cladistics, and the search for the Alaskan ancestors of the Paleoindians: a reassessment of relationships among the Clovis, Nenana, and Denali archaeological complexes. *Journal of Archaeological Science* 35, 1683-1694.

Buchanan, B., Hamilton, M.J., submitted. A formal test of the origin of variation in North American Early Paleoindian projectile points. *American Antiquity*.

Butler, B.R., 1963. An early man site at Big Camas prairie, south-central Idaho. *Tebiwa* 6, 22-33.

Butler, B.R., Fitzwater, R.J., 1965. A further note on the Clovis site at Big Camas Prairie, south-central Idaho. *Tebiwa* 8, 38-39.

Byers, D.S., 1954. Bull Brook-a fluted point site in Ipswich, Massachusetts. *American Antiquity* 19, 343-351.

Byers, D.S., 1955. Additional information on the Bull Brook site, Massachusetts. *American Antiquity* 20, 274-276.

Campos, D., Fort, J., Mendez, V., 2006. Transport on fractal river networks: Application to migration fronts. *Theoretical Population Biology* 69, 88-93.

Campos, D., Mendez, V., Fort, J., 2004. Description of diffusive and propagative behavior on fractals. *Physical Review E* 69, 031115.

Cavalli-Sforza, L.L., Feldman, M.W., 1981. *Cultural Transmission and Evolution: A Quantitative Approach*. Princeton University Press, Princeton.

Collins, M.B., 1999. *Clovis Blade Technology*. University of Texas Press, Austin.

Collins, M.B., Hester, T.R., Headrick, P.J., 1992. Engraved cobbles from the Gault site, central Texas. *Current Research in the Pleistocene* 9, 3-4.

Collins, M.B., Lohse, J.C., 2004. The nature of Clovis blades and blade cores. In Madsen, D.B. (Ed.) *Entering America: Northeast Asia and Beringia Before the Last Glacial Maximum*, The University of Utah Press, Salt Lake City, pp. 159-183.

Cotter, J.L., 1937. The occurrence of flints and extinct animals in pluvial deposits near Clovis, New Mexico, part IV-report on excavation at the gravel pit, 1936. *Proceedings of the Academy of Natural Sciences of Philadelphia* 89, 1-16.

Cotter, J.L., 1938. The occurrence of flints and extinct animals in pluvial deposits near Clovis, New Mexico, part VI-report on field season of 1937. *Proceedings of the Academy of Natural Sciences of Philadelphia* 90, 113-117.

Cox, S.L., 1986. A re-analysis of the Shoop site. *Archaeology of Eastern North America* 14, 101-170.

Curran, M.L., 1984. The Whipple site and Paleoindian tool assemblage variation: a comparison of intrasite structuring. *Archaeology of Eastern North America* 12, 5-40.

Curran, M.L., 1987. The spatial organization of Paleoindian populations in the Late Pleistocene of the Northeast. Unpublished Ph.D. dissertation, University of Massachusetts, Amherst.

Curran, M.L., 1994. New Hampshire Paleo-Indian research and the Whipple site. *The New Hampshire Archeologist* 33/34, 29-52.

Davis, L.B., Greiser, S.T., 1992. Indian Creek Paleoindians: Early Occupation of the Elkhorn Mountains' Southeast Flank, West-Central Montana. In Stanford, D., Day, J.S. (Eds.), *Ice Age Hunters of the Rockies*, Denver Museum of Natural History, Denver, pp. 225-284.

Dello-Russo, R.D., 2004. Geochemical comparisons of silicified rhyolites from two prehistoric quarries and 11 prehistoric projectile points, Socorro County, New Mexico, U.S.A. *Geoarchaeology* 19, 237-264.

Dixit, A., K., Pindyck, R.S., 1994. *Investment Under Uncertainty*. Princeton University Press, Princeton.

Dixon, E.J., 1999. *Bones, Boats, and Bison: Archaeology and the First Colonization of North America*. University of New Mexico Press, Albuquerque.

Dixon, E.J., 2001. Human colonization of the Americas: timing, technology, and process. *Quaternary Science Reviews* 20, 277-299.

Dolukhanov, P., Sokoloff, D., Shukurov, A., 2001. Radiocarbon chronology of Upper Palaeolithic sites in Eastern Europe at improved resolution. *Journal of Archaeological Science* 28, 699-712.

Dolukhanov, P.M., Shukurov, A.M., Tarasov, P.E., Zaitseva, G.I., 2002. Colonization of Northern Eurasia by modern humans: radiocarbon chronology and environment. *Journal of Archaeological Science* 29, 593-606.

Eerkens, J.W., 2000. Practice makes within 5% of perfect: visual perception, motor skills, and memory in artifact variation. *Current Anthropology* 41, 663-667.

Eerkens, J.W., Lipo, C.P., 2005. Cultural transmission, copying errors, and the generation of variation in material culture and the archaeological record. *Journal of Anthropological Archaeology* 24, 316-334.

Ferring, C.R., 2001. The Archaeology and Paleoecology of the Aubrey Clovis Site (41DN479), Denton County, Texas. US Army Corps of Engineers.

Fiedel, S.J., 2000. The peopling of the New World: present evidence, new theories. *Journal of Archaeological Research* 8, 39-103.

Fiedel, S.J., 2004. Rapid migrations by Arctic hunting peoples: Clovis and Thule. In Barton, C.M., Clark, G.A., Yesner, D.A., Pearson, G.A. (Eds.), *The Settlement of the American Continents: A Multidisciplinary Approach to Human Biogeography*, University of Utah Press, Salt Lake City, pp. 79-84.

Figgins, J.D., 1933. A Further Contribution to the Antiquity of Man in America. *Colorado Museum of Natural History Proceedings No. 12*, Denver.

Firestone, R.B., West, A., Kennett, J.P., Becker, L., Bunch, T.E., Revay, Z.S., Schultz, P.H., Belgia, T., Kennett, D.J., Erlandson, J.M., Dickenson, O.J., Goodyear, A.C., Harris, R.S., Howard, G.A., Kloosterman, J.B., Lechler, P., Mayewski, P.A., Montgomery, J., Poreda, R., Darrah, T., Hee, S.S.Q., Smith, A.R., Stich, A., Topping, W., Wittke, J.H., Wolbach, W.S., 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. *Proceedings of the National Academy of Sciences, USA* 104, 16016-16021.

Fix, A.G., 1999. *Migration and Colonization in Human Microevolution*. Cambridge University Press, Cambridge.

Fladmark, K.R., 1979. Routes: alternate migration corridors for early man in North America. *American Antiquity* 44, 55-69.

Fort, J., 2003. Population expansion in the Western Pacific (Austronesia): a wave of advance model. *Antiquity*, 520-530.

Fort, J., Jana, B., Humet, J., 2004a. Multidelayed random walks: Theory and applications to the neolithic transition in Europe. *Physical Review E* 70, 031913.

Fort, J., Mendez, V., 1999a. Reaction-diffusion waves of advance in the transition to agricultural economies. *Physical Review E* 60, 5894-5901.

Fort, J., Mendez, V., 1999b. Time-delayed theory of the Neolithic transition in Europe. *Physical Review Letters* 82, 867-870.

Fort, J., Mendez, V., 2002. Wavefronts in time-delayed reaction-diffusion systems: Theory and comparison to exponent. *Reports on Progress in Physics* 65, 895-954.

Fort, J., Pujol, T., Cavalli-Sforza, L.L., 2004b. Paleolithic populations and waves of advance. *Cambridge Archaeological Journal* 14, 53-61.

Frison, G.C., 1991. The Clovis cultural complex: new data from caches of flaked stone and worked bone artifacts. In Montet-White, A., Holen, S. (Eds.), *Raw Material Economies among Prehistoric Hunter-Gatherers*, University of Kansas Publications in Anthropology, Lawrence, pp. 321-333.

Frison, G.C., 2000. A ^{14}C date on a Late-Pleistocene Camelops at the Casper-Hell Gap site, Wyoming. *Current Research in the Pleistocene* 17, 28-29.

Frison, G.C., Bradley, B.A., 1999. *The Fenn Cache: Clovis Weapons and Tools*. One Horse Land and Cattle Company, Santa Fe.

Frison, G.C., Todd, L.C., 1986. *The Colby Mammoth Site: Taphonomy and Archaeology of a Clovis Kill in Northern Wyoming*. University of New Mexico Press, Albuquerque.

Goebel, T., 1991. The Nenana complex of Alaska and Clovis origins. In Bonnicksen, R., Turnmire, K.L. (Eds.), *Clovis: Origins and Adaptations*, Center for the Study of the First Americans. Oregon State University, Corvallis, pp. 49-79.

Goebel, T., Waters, M.R., O'Rourke, D.H., 2008. The Late Pleistocene dispersal of modern humans in the Americas. *Science* 319, 1497-1502.

Graham, R.W., Haynes, C.V., Johnson, D.L., Kay, M., 1981. Kimmswick: a Clovis-mastodon association in eastern Missouri. *Science* 213, 1115-1117.

Graham, R.W., Kay, M., 1988. Taphonomic comparisons of cultural and noncultural faunal deposits at the Kimmswick and Barnhart sites, Jefferson County, Missouri. In Laub, R.S., Miller, N.G., Steadman, D.W. (Eds.), *Late Pleistocene and Early Holocene Paleocology and Archaeology of the Eastern Great Lakes Region*, *Bulletin of the Buffalo Society of Natural Sciences*, Buffalo, pp. 227-240.

Gramly, M.R., 1982. The Vail Site: A Palaeo-indian Encampment in Maine, *Bulletin of the Buffalo Society of Natural Sciences*, Buffalo, pp.

Gramly, R.M., 1984. Kill sites, killing ground, and fluted points at the Vail site. *Archaeology of Eastern North America* 12, 101-121.

Marcus J. Hamilton: Quantifying Clovis Dynamics

Gramly, R.M., 1993. The Richey Clovis cache: earliest Americans along the Columbia River. Persimmon Press, Buffalo.

Gramly, R.M., 1999. The Lamb site: a pioneering Clovis encampment. Persimmon Press, Buffalo.

Gramly, R.M., Rutledge, K., 1981. A new Paleo-Indian site in the state of Maine. *American Antiquity* 46, 354-361.

Grayson, D.K., Meltzer, D.J., 2002. Clovis hunting and large mammal extinction: A critical review of the evidence. *Journal of World Prehistory* 16, 313-359.

Grayson, D.K., Meltzer, D.J., 2003. A requiem for North American overkill. *Journal of Archaeological Science* 30, 585-593.

Grayson, D.K., Meltzer, D.J., 2004. North American overkill continued? *Journal of Archaeological Science* 31, 133-136.

Grimes, J.R., 1979. A new look at Bull Brook. *Anthropology* 3, 109-130.

Grimes, J.R., Eldridge, W., Grimes, B., Vaccaro, A., Vaccaro, J., Vaccaro, N., Orsini, N., 1984. Bull Brook II. *Archaeology of Eastern North America* 12, 150-183.

Gurven, M., Kaplan, H., Gutierrez, M., 2006. How long does it take to become a proficient hunter? Implications for the evolution of extended development and long life span. *Journal of Human Evolution* 51, 454-470.

Hamilton, M.J., Buchanan, B., 2007. Spatial gradients in Clovis-age radiocarbon dates across North America suggest rapid colonization from the north. *Proceedings of the National Academy of Sciences, USA* 104, 15629-15634.

Hamilton, M.J., Buchanan, B., submitted. The accumulation of proportional copying errors causes drift in culturally transmitted technologies: quantifying spatiotemporal gradients in Clovis projectile point size. *Journal of Anthropological Archaeology*.

Hamilton, M.J., Milne, B.T., Walker, R.S., Brown, J.H., 2007a. Nonlinear scaling of space use in human hunter-gatherers. *Proceedings of the National Academy of Sciences, USA* 104, 4765-4769.

Hamilton, M.J., Milne, B.T., Walker, R.S., Burger, O., Brown, J.H., 2007b. The complex structure of hunter-gatherer social networks. *Proceedings of the Royal Society B: Biological Sciences* 274, 2195-2202.

Haskell, J.P., Ritchie, M.E., Olf, H., 2002. Fractal geometry predicts varying body size scaling relationships for mammal and bird home ranges. *Nature* 418, 527-530.

Marcus J. Hamilton: Quantifying Clovis Dynamics

Haury, E.W., Antevs, E., Lance, J.F., 1953. Artifacts with mammoth remains, Naco, Arizona. *American Antiquity* 19, 1-24.

Haury, E.W., Sayles, E.B., Wasley, W.W., 1959. The Lehner mammoth site, southeastern Arizona. *American Antiquity* 25, 2-30.

Haynes, C.V., 1969. The earliest Americans. *Science* 166, 709-716.

Haynes, C.V., 2005. Clovis, Pre-Clovis, climate change, and extinction. In Bonnicksen, R., Lepper, B.T., Stanford, D., Waters, M.R. (Eds.), *Paleoamerican Origins: Beyond Clovis*, Texas A&M Press, College Station, pp. 113-132.

Haynes, C.V., Donahue, D.J., Jull, A.J.T., Zabel, T.H., 1984. Application of accelerator dating to fluted point Paleoindian sites. *Archaeology of Eastern North America* 12, 184-191.

Haynes, C.V., Hemmings, E.T., 1968. Mammoth-bone shaft wrench from Murray Springs, Arizona. *Science* 159, 186-187.

Haynes, C.V., Huckell, B.B. (Eds.), 2007. *Murray Springs: A Clovis Site with Multiple Activity Areas in the San Pedro Valley, Arizona*. University of Arizona, Tucson.

Haynes, C.V., McFaul, M., Brunswig, R.H., Hopkins, K.D., 1993. Kersey-Kuner terrace investigations at the Dent and Bernhardt sites, Colorado. *Geoarchaeology* 13, 201-218.

Haynes, G., 2002. *The Early Settlement of North America*. Cambridge University Press, Cambridge.

Haynes, G., 2006. Elephant landscapes: Good country for hunter-gatherers. *Quaternary International* 142-143, 20-29.

Haynes, G., Anderson, D.G., Ferring, C.R., Fiedel, S.J., Grayson, D.K., Haynes, C.V., Jr., Holliday, V.T., Huckell, B.B., Kornfeld, M., Meltzer, D.J., Morrow, J., Surovell, T., Waguespack, N.M., Wigand, P., Yohe, R.M., II, 2007. Comment on "Redefining the Age of Clovis: Implications for the Peopling of the Americas". *Science* 317, 320b-.

Hazelwood, L., Steele, J., 2004. Spatial dynamics of human dispersals: constraints on modelling and archaeological validation. *Journal of Archaeological Science* 31, 669-679.

Hemmings, E.T., 1970. *Early Man in the San Pedro Valley, Arizona*. Unpublished Ph.D. dissertation, University of Arizona, Tucson.

Hemmings, E.T., Haynes, C.V., 1969. The Escapule mammoth and associated projectile points in the San Pedro Valley, Arizona. *Journal of the Arizona Academy of Science* 5, 184-188.

Marcus J. Hamilton: Quantifying Clovis Dynamics

Henrich, J., 2001. Cultural transmission and the diffusion of innovations: adoption dynamics indicate that biased cultural transmission is the predominant force in behavioral change. *American Anthropologist* 103, 992-1013.

Henrich, J., 2004. Demography and cultural evolution: why adaptive cultural processes produced maladaptive losses in Tasmania. *American Antiquity* 69, 197-214.

Henrich, J., Boyd, R., 1998. The evolution of conformist transmission and the emergence of between-group differences. *Evolution and Human Behavior* 19, 215-241.

Henrich, J., Gil-White, F., 2001. The Evolution of prestige: freely conferred status as a mechanism for enhancing the benefits of cultural transmission. *Evolution and Human Behavior* 22, 1-32.

Henrich, J., McElreath, R., 2003. The evolution of cultural evolution. *Evolutionary Anthropology* 12, 123-135.

Hester, J.J., 1972. Blackwater Draw Locality No. 1: A Stratified Early Man Site in Eastern New Mexico. Fort Burgwin Research Center, Ranchos de Taos.

Hester, T.R., Collins, M.B., Headrick, P.J., 1992. Notes on south Texas archaeology: 1992-4, Paleo-Indian engraved stones from the Gault site. *La Tierra* 19, 3-5.

Hewlett, B.S., van de Koppel, J.M.H., Cavalli-Sforza, L.L., 1982. Exploration ranges of Aka pygmies of the Central African Republic. *Man* 17, 418-430.

Hey, J., 2005. On the number of New World founders: a population genetic portrait of the peopling of the Americas. *PLoS Biology* 3, 0965-0975.

Holliday, V.T., 1997. *Paleoindian Geoarchaeology of the Southern High Plains*. University of Texas Press, Austin.

Holliday, V.T., Haynes, C.V., Hofman, J.L., Meltzer, D.J., 1994. Geoarchaeology and geochronology of the Miami (Clovis) site, Southern High Plains of Texas. *Quaternary Research* 41, 234-244.

Holmgren, C.A., Betancourt, J.L., Rylander, K.A., 2006. A 36,000-yr vegetation history of the Peloncillo Mountains, southeastern Arizona, USA. *Palaeogeography Palaeoclimatology Palaeoecology* 240, 405-422.

Holmgren, C.A., Norris, J., Betancourt, J.L., 2007. Inferences about winter temperatures and summer rains from the late Quaternary record of C4 perennial grasses and C3 desert shrubs in the northern Chihuahuan Desert. *Journal of Quaternary Research* 22, 141-161.

Holmgren, C.A., Pinalba, M.C., Rylander, K.A., Betancourt, J.L., 2003. A 16,000 14C yr B.P. packrat midden series from the USA-Mexico Borderlands. *Quaternary Research* 60, 319-329.

Howard, E.B., 1935. Occurrence of flints and extinct animals in pluvial deposits near Clovis, New Mexico, part I-introduction. *Proceedings of the Academy of Natural Sciences of Philadelphia* 87, 299-303.

Huckell, B.B., 2004. Clovis in the Southwestern United States. In Lepper, B.T., Bonnicksen, R. (Eds.), *New Perspectives on the First Americans, Center for the Study of the First Americans*, College Station, pp. 93-101.

Huckell, B.B., Holliday, V.T., Hamilton, M.J., Sinkovec, C., Merriman, C., Shackley, M.S., Weber, R.H., submitted. The Mockingbird Gap Clovis Site: 2007 Investigations. *Current Research in the Pleistocene*.

Huckell, B.B., Holliday, V.T., Weber, R.H., 2007. Test Investigations at the Mockingbird Gap Clovis Site: Results of the 2006 Field Season. *Current Research in the Pleistocene* 24, 102-104.

Huckell, B.B., Holliday, V.T., Weber, R.H., Meyer, J.H., 2006. Archaeological and geological test excavations at the Mockingbird Gap Clovis Site, Central New Mexico. *Current Research in the Pleistocene* 23, 115-116.

Jetz, W., Carbone, C., Fulford, J., Brown, J.H., 2004. The scaling of animal space use. *Science* 306, 266-268.

Jodry, M.A., Stanford, D.J., 1992. Stewart's Cattle Guard site: An analysis of bison remains in a Folsom kill-butchery campsite. In Stanford, D.J., Day, J.S. (Eds.), *Ice Age hunters of the Rockies*, Denver Museum of Natural History, Denver, pp. 101-168.

Johnson, E.J. (Ed.) 1987. *Lubbock Lake: Late Quaternary Studies on the Southern High Plains*. Texas A&M University Press, College Station.

Jones, S., Bonnicksen, R., 1994. The Anzick Clovis burial. *Current Research in the Pleistocene* 11, 42-43.

Judge, W.J., 1973. *Paleoindian Occupation of the Central Rio Grande Valley in New Mexico*. University of New Mexico Press, Albuquerque.

Karlin, S., Taylor, H.M., 1981. *A Second Course in Stochastic Processes*. Academic Press, New York.

Kelly, R.L., 1995. *The Foraging Spectrum: Diversity in Hunter-Gatherer Lifeways*. Smithsonian Institution Press, Washington, DC.

Kelly, R.L., 1999. Thinking about prehistory. In Beck, C. (Ed.) *Models for the Millennium: Great Basin Anthropology Today*, University of Utah Press, Salt Lake City, pp. 111-117.

Kelly, R.L., 2003. Maybe we do know when people came to the North America; And what does it mean if we do? *Quaternary International* 109-110, 133-145.

Kelly, R.L., Todd, L.C., 1988. Coming into the country: early Paleoindian hunting and mobility. *American Antiquity* 53, 231-244.

Kilby, J.D., 2008. *An Investigation of Clovis Caches: Content, Function, and Technological Organization*. Ph.D. Dissertation, University of New Mexico, Albuquerque.

Kilby, J.D., Huckell, B.B., 2003. A comparison of caches: An initial look at Clovis caching. Paper presented at 68th annual meeting of the Society for American Archaeology, Milwaukee, WI.

Kuzmin, Y.V., Tankersley, K.B., 1996. The Colonization of Eastern Siberia: an Evaluation of the Paleolithic Age Radiocarbon Dates. *Journal of Archaeological Science* 23, 577-585.

Lahren, L., Bonnicksen, R., 1974. Bone foreshafts from a Clovis burial in southwestern Montana. *Science* 186, 147-150.

Lande, R., Steiner, E., Saether, B.-E., 2003. *Stochastic Population Dynamics in Ecology and Conservation*. Oxford University Press, Oxford.

Laub, R.S., 2003. The Hiscock Site: structure, stratigraphy and chronology. In Laub, R.S. (Ed.) *The Hiscock Site: Late Pleistocene and Holocene Paleoecology and Archaeology of Western New York State*, Bulletin of the Buffalo Society of Natural Sciences, Buffalo, pp. 18-38.

Leonhardy, F.C. (Ed.) 1966. *Domebo: A Paleo-Indian Mammoth Kill in the Prairie-Plains*. Contributions of the Museum of the Great Plains No. 1, Lawton.

Levin, S.A., 1992. The problem of pattern and scale in ecology. *Ecology* 73, 1943-1967.

Levine, M.A., 1990. Accomodating age: radiocarbon dates and fluted points in northeastern North America. *Archaeology of Eastern North America* 18, 33-63.

Limpert, E., Stahel, W.A., Abbt, M., 2001. Log-normal distributions across the sciences: keys and clues. *Bioscience* 51, 341.

Lipo, C.P., Madsen, M.E., Dunnell, R.C., Hunt, T., 1997. Population structure, cultural transmission, and frequency seriation. *Journal of Anthropological Archaeology* 16, 301-333.

Lycett, S.J., 2007. Is the Soanian techno-complex a Mode 1 or Mode 3 phenomenon? A morphometric assessment. *Journal of Archaeological Science* 34, 1434-1440.

Lycett, S.J., von Cramon-Taubadel, N., 2008. Acheulean variability and hominin dispersals: a model-bound approach. *Journal of Archaeological Science* 35, 553-562.

Lycett, S.J., von Cramon-Taubadel, N., Foley, R.A., 2006. A crossbeam co-ordinate caliper for the morphometric analysis of lithic nuclei: a description, test and empirical examples of application. *Journal of Archaeological Science* 33, 847-861.

Lyman, R.L., O'Brien, M.J., Hayes, V., 1998. A mechanical and functional study of bone rods from the Richey-Roberts Clovis cache, Washington, U.S.A. *Journal of Archaeological Science* 25, 887-906.

Lyons, S.K., 2003. A quantitative assessment of the range shifts of Pleistocene mammals. *Journal of Mammalogy* 84, 385-402.

Lyons, S.K., 2005. A quantitative model for assessing dynamics of Pleistocene mammals. *American Naturalist* 165, E168-E184.

Lyons, S.K., Brown, J.H., Smith, F.A., 2004. Of mice, mastodons, and men: human mediated extinctions on four continents. *Evolutionary Ecology Research* 6, 339-358.

Macaulay, V., Hill, C., Achilli, A., Rengo, C., Clarke, D., Meehan, W., Blackburn, J., Semino, O., Scozzari, R., Cruciani, F., Taha, A., Shaari, N.K., Raja, J.M., Ismail, P., Zainuddin, Z., Goodwin, W., Bulbeck, D., Bandelt, H.-J., Oppenheimer, S., Torroni, A., Richards, M., 2005. Single, Rapid Coastal Settlement of Asia Revealed by Analysis of Complete Mitochondrial Genomes
10.1126/science.1109792. *Science* 308, 1034-1036.

MacDonald, D.H., Hewlett, B.S., 1999. Reproductive interests and forager mobility. *Current Anthropology* 40, 501-523.

MacDonald, G.F., 1966. The technology and settlement pattern of a Paleo-Indian site at Debert, Nova Scotia. *Quaternaria* 8, 59-74.

MacDonald, G.F., 1968. Debert: A Palaeo-Indian Site in Central Nova Scotia. National Museums of Canada, Ottawa.

Mandryk, C.A.S., Josenhans, H., Fedje, D.W., Mathewes, R.W., 2001. Late Quaternary paleoenvironments of northwestern North America: implications for inland versus coastal migration routes. *Quaternary Science Reviews* 20, 301-314.

Martin, P.S., 1967. Prehistoric overkill. In Martin, P.S., Wright, H.E. (Eds.), *Pleistocene Extinctions: The Search for a Cause*, Yale University Press, New Haven, pp. 75-120.

Maynard-Smith, J., Szathmary, E., 1998. *The Major Transitions in Evolution*. Oxford University Press, Oxford.

McAvoy, J.M., McAvoy, L.D., 1997a. Archaeological Investigations of Site 44SX202, Cactus Hill, Sussex County Virginia. Department of Historic Resources, Commonwealth of Virginia, Richmond.

McAvoy, J.M., McAvoy, L.D., 1997b. Archaeological Investigations of Site 44SX202, Cactus Hill, Sussex County Virginia. Virginia Department of Historic Resources Research Report Series, Department of Historic Resources, Commonwealth of Virginia.

Meltzer, D.J., 1988. Late Pleistocene human adaptations in eastern North America. *Journal of World Prehistory* 2, 1-52.

Meltzer, D.J., 1995. Clocking the first Americans. *Annual Review of Anthropology* 24, 21-45.

Meltzer, D.J., 2004. Modeling the initial colonization of the Americas: issues of scale, demography, and landscape learning. In Barton, C.M., Clark, G.A., Yesner, D.A., Pearson, G.A. (Eds.), *The Settlement of the American Continents*, The University of Arizona Press, Tucson, pp. 123-137.

Meltzer, D.J., 2006. *Folsom: New Archaeological Investigations of a Classic Paleoindian Bison Kill*. University of California Press, Berkeley.

Morrow, J.E., Morrow, T.A., 1999. Geographic variation in fluted projectile points: a hemispheric perspective. *American Antiquity* 64, 215-231.

Morrow, J.E., Morrow, T.A., 2002. Rummells Maske revisited: a fluted point cache from east central Iowa. *Plains Anthropologist* 47, 307-321.

Mosimann, J.E., Martin, P.S., 1975. Simulating overkill by Paleoindians. *American Scientist* 63, 304-313.

Neiman, F.D., 1995. Stylistic variation in evolutionary perspective: inferences from decorative diversity and interassemblage distance in Illinois Woodland ceramic assemblages. *American Antiquity* 60, 7-36.

Orr, P.C., 1962. The Arlington Spring Site, Santa Rosa Island, California. *American Antiquity* 27, 417-419.

Marcus J. Hamilton: Quantifying Clovis Dynamics

Owen-Smith, R.N., 1988. *Megaherbivores: The Influence of Very Large Body Size on Ecology*. University of Cambridge Press, Cambridge.

Owsley, D.W., Hunt, D.R., 2001. Clovis and Early Archaic period crania from the Anzick site (24PA506), Park County, Montana. *Plains Anthropologist* 46, 115-121.

Pielou, E.C., 1991. *After the Ice Age: The Return of Life to Glaciated North America*. University of Chicago Press, Chicago.

Pinhasi, R., Fort, J., Ammerman, A.J., 2005. Tracing the origin and spread of agriculture in Europe. *PLoS Biology* 3, 2220-2228.

Raposo, E.P., Buldyrev, S.V., da Luz, M.G.E., Santos, M.C., Stanley, H.E., Viswanathan, G.M., 2003. Dynamical Robustness of Levy Search Strategies. *Physical Review Letters* 91, 240601.

Ray, J.H., Lopinot, N.H., Hajic, E.R., Mandel, R.D., 1998. The Big Eddy site: a multicomponent Paleoindian site on the Ozark border, southwest Missouri. *Plains Anthropologist* 43, 73-81.

Reeves, C.C., 1969. Pluvial Lake Palomas northwestern Chihuahua, Mexico. In Cordoba, D.A., Wengerd, S.A., Shomaker, J. (Eds.), *The Border Region: Chihuahua and the United States*, New Mexico Geological Society, pp. 143-154.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 026 Cal Kyr BP. *Radiocarbon* 46, 1029-1058.

Rick, T.C., Erlandson, J.M., Vellanoweth, R.L., 2001. Paleocoastal Marine Fishing on the Pacific Coast of the Americas: Perspectives from Daisy Cave, California. *American Antiquity* 66, 595-613.

Robles Ortiz, M., 1974. Distribucion de artefactos Clovis en Sonora. *INAH Boletin* 9, 25-32.

Sanchez, M.G., 2001. A synopsis of Paleo-Indian archaeology in Mexico. *Kiva* 67, 119-136.

Santos, M.C., Raposo, E.P., Viswanathan, G.M., Luz, M.G.E.d., 2004. Optimal random searches of revisitable targets: crossover from superdiffusive to ballistic random walks. *Europhysics Letters (EPL)* 67, 734-740.

Marcus J. Hamilton: Quantifying Clovis Dynamics

Savage, V.M., Gillooly, J.F., Brown, J.H., West, G.B., Charnov, E.L., 2004. Effects of body size and temperature on population growth. *American Naturalist* 163, 429(413).

Sellards, E.H., 1938. Artifacts associated with fossil elephant. *Bulletin of the Geological Society of America* 49, 999-1010.

Sellards, E.H., 1952. *Early Man in North America*. University of Texas Press, Austin.

Shackley, M.S., 2005. *Obsidian: Geology and Archaeology in the North American Southwest*. University of Arizona Press, Tucson.

Shackley, M.S., 2007. Sources of obsidian at the Murray Springs Clovis Site. In Haynes, C.V., Huckell, B.B. (Eds.), *Murray Springs: A Clovis Site with Multiple Activity Areas in the San Pedro Valley, Arizona*, The University of Arizona Press, Tucson, pp. 250-265.

Shackley, M.S., n.d. Source provenience of obsidian artifacts from Mockingbird Gap and Socorro County Clovis sites, New Mexico. Berkeley Archaeological XRF Lab, University of California, Berkeley.

Shennan, S., 2000. Population, culture history, and the dynamics of culture change. *Current Anthropology* 41, 811-835.

Shennan, S., 2001. Demography and cultural innovation: a model and its implications for the emergence of modern human culture. *Cambridge Archaeological Journal* 41, 811-835.

Simons, D.B., 1997. The Gainey and Butler Sites as Focal Points for Caribou and People. In Jackson, L.J., Thacker, P.T. (Eds.), *Caribou and Reindeer Hunters of the Northern Hemisphere*, Avebury, Aldershot, pp. 105-131.

Simons, D.B., Shott, M.J., Wright, H.T., 1984. The Gainey site: variability in Great Lakes Paleo-Indian assemblage. *Archaeology of Eastern North America* 12, 266-279.

Simons, D.B., Shott, M.J., Wright, H.T., 1987. Paleoindian research in Michigan: current status of the Gainey and Leavitt projects. *Current Research in the Pleistocene* 4, 27-30.

Spiess, A., Mosher, J., 1994. Hedden: a Paleoindian site on the Kennebunk plains. *The Maine Archaeological Society Bulletin* 34, 25-54.

Spiess, A., Mosher, J., Callum, K., Sidell, N.A., 1995. Fire on the plains: paleoenvironmental data from the Hedden site. *The Maine Archaeological Society Bulletin* 35, 13-52.

Stanford, D.J., Bradley, B., 2002. Ocean trails and prairie paths? Thoughts about Clovis origins. In Jablonski, N.G. (Ed.) *The First Americans: The Pleistocene Colonization of the New World*, California Academy of Sciences, San Francisco, pp. 255-272.

Stanford, D.J., Jodry, M.A., 1988. The Drake Clovis cache. *Current Research in the Pleistocene* 5, 21-22.

Steele, J., Adams, J., Sluckin, T., 1998. Modelling Paleoindian dispersals. *World Archaeology* 30, 286-305.

Surovell, T., Waguespack, N., In press. How many elephant kills are 14? Clovis mammoth and mastodon kills in context. *Quaternary International*.

Surovell, T., Waguespack, N., Brantingham, P.J., 2005. Global archaeological evidence for proboscidean overkill. *Proceedings of the National Academy of Sciences, USA* 102, 6231-6236.

Surovell, T.A., Brantingham, P.J., 2007. A note on the use of temporal frequency distributions in studies of prehistoric demography. *Journal of Archaeological Science* 34, 1868-1877.

Taylor, H.M., Karlin, S., 1998. *An Introduction to Stochastic Modeling*. Academic Press, New York and London.

Titmus, G.L., Woods, J.C., 1991. Fluted points from the Snake River Plain. In Bonnichsen, R., Turnmire, K.L. (Eds.), *Clovis: Origins and Adaptations*, Center for the Study of the First Americans, Oregon State University, Corvallis, pp. 119-131.

Van Devender, T.R., 1990. Late Quaternary vegetation and climate of the Chihuahuan Desert, United States and Mexico. In Betancourt, J.L., Van Devender, T.R., Martin, P.S. (Eds.), *Packrat Middens: The Last 40,000 Years of Biotic Change*, University of Arizona Press, Tucson, pp. 104-133.

Van Devender, T.R., 1995. Desert grassland history: changing climates, evolution, biogeography, and community dynamics. In McClaran, M., P., Van Devender, T.R. (Eds.), *The Desert Grassland*, University of Arizona Press, Tucson, pp. 68-99.

Vasil'ev, S.A., Kuzmin, Y.V., Orlova, L.A., Dementiev, V.N., 2002. Radiocarbon-based Chronology of the Paleolithic in Siberia and its Relevance to the Peopling of the New World. *Radiocarbon* 44, 503-530.

Waguespack, N.M., Surovell, T.A., 2003. Clovis hunting strategies, or how to make out on plentiful resources. *American Antiquity* 68, 333-352.

Walker, R., Hill, K., Kaplan, H., McMillan, G., 2002. Age-dependency in hunting ability among the Ache of Eastern Paraguay. *Journal of Human Evolution* 42, 639-657.

Walker, R.S., Gurven, M., Hill, K., Migliano, A., Chagnon, N.A., De Souza, R., Djurovic, G., Hames, R., Hurtado, A.M., Kaplan, H., Kramer, K., Oliver, W.J., Valleggia,

C., Yamauchi, T., 2006. Growth rates and life histories in twenty-two small-scale societies. *American Journal of Human Biology* 18, 295-311.

Warnica, J.M., 1966. New discoveries at the Clovis site. *American Antiquity* 31, 345-357.

Waters, M.R., Stafford, T.W., Jr., 2007. Redefining the age of Clovis: implications for the peopling of the Americas. *Science* 315, 1122-1126.

Webb, I., T., Bartlein, P.J., Harrison, S.P., Anderson, K.H., 1993. Vegetation, lake levels, and climate in eastern North America for the past 18,000 years. In Wright, J., H., Kutzbach, J., Webb, I., T., Ruddiman, W., Street-Perrott, F., Bartlein, P. (Eds.), *Global Climates since the Last Glacial Maximum*, University of Minnesota Press, Minneapolis, pp. 415-467.

Weber, R.H., Agogino, G.A., 1997. Mockingbird Gap paleoindian site: excavations in 1967. In Durhan, M.S., Kirkpatrick, D.T. (Eds.), *Layers of Time: Papers in Honor of Robert H. Weber*, Archaeological Society of New Mexico, Albuquerque, pp. 123-128.

Wilke, P.J., Flenniken, J.J., Ozbun, T.L., 1991. Clovis technology at the Anzick site, Montana. *Journal of California and Great Basin Anthropology* 13, 242-272.

Witthoft, J., 1952. A Paleo-Indian site in eastern Pennsylvania: an early hunting culture. *Proceedings of the American Philosophical Society* 96, 464-495.

Woods, J.C., Titmus, G.L., 1985. A review of the Simon Clovis collection. *Idaho Archaeologist* 8, 3-8.

Wright, H.E., 1987. Synthesis: the land south of the ice sheet. In Ruddiman, W., Wright, J., H. (Eds.), *North America and Adjacent Oceans During the Last Deglaciation*, Geological Society of America, Boulder, pp. 479-488.

Wright, H.E., 1991. Environmental conditions for Paleoindian immigration. In Dillehay, T.D., Meltzer, D.J. (Eds.), *The First Americans: Search and Research*, CRC Press, Boca Raton, pp. 113-135.