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Continent-wide or region-specific? A geometric morphometrics-based assessment of variation in Clovis point shape

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Abstract Researchers have debated the existence of regional variation in Clovis points for over 60 years. Here, we report an attempt to resolve this argument using a large sample of Clovis points from dated assemblages and a suite of shape analysis methods known as geometric morphometrics. The study tested the two main hypotheses that have been put forward in the debate: the continent-wide adaptation hypothesis, which holds that Clovis points do not vary regionally, and the regional environmental adaptation hypothesis, which holds that there is regional variation as a consequence of Clovis groups adjusting their food-getting toolkits to local conditions. We used discriminant function analysis and a multivariate extension of the *t* test to assess whether differences in shape exist at two scales. The first set of analyses compared points from the most obvious environmental regions in North America, the East and the West. The second set of analyses investigated differences among points from subregions within the East and West. The analyses revealed significant differences between points from the East and the West and among points from some subregions. Follow-up analyses demonstrated that these differences are not the result of the most common confounding factors, raw material quality and resharpening. As such, the analyses support the regional environmental adaptation hypothesis rather than the continent-wide adaptation hypothesis. We conclude from this that Clovis people modified their points to suit the characteristics of local prey and/or the habitats in which they hunted.

Keywords Clovis points · Continent-wide adaptation · Regional environmental adaptation · Geometric morphometrics

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Introduction

Clovis points have been the focus of considerable research in recent years (e.g., Anderson and Faught 2000; Buchanan and Collard 2007, 2010; Buchanan and Hamilton 2009; Buchanan et al. 2012; Ellis 2004; Morrow and Morrow 1999; O'Brien et al. 2001, 2012; Prasciunas 2011; Sholts et al. 2012; Smallwood 2012). Despite this attention, a number of basic questions about them remain unresolved. Here, we report a study designed to answer one of the most persistent of these questions: Did Clovis hunter-gatherers adjust the shape of their points to deal with regional environmental conditions?

Produced by bifacial flaking, Clovis points have parallel to slightly convex sides and concave bases (Buchanan and Collard 2010; Wormington 1957). They usually also have a channel flake removed from each face. Typically, these extend from the base to about a third of the way to the tip. Points with the foregoing characteristics have been found throughout the contiguous USA, southern Canada, and northern Mexico (Anderson and Faught 2000; Anderson et al. 2005; Haynes 1964; Sanchez 2001; Wormington 1957). In the American West, dates associated with Clovis range from ca. 13,500 calendar years before present (calBP) to ca. 12,800 calBP, whereas in the East, they range from ca. 12,800 to ca. 12,500 calBP (Gingerich 2011; Haynes et al. 1984; Haynes et al. 2007; Holliday 2000; Levine 1990). Based on these dates, Clovis points are among the earliest artifacts in North America.

There are two main hypotheses concerning regional variation in Clovis points. The *regional environmental adaptation hypothesis* proposes that Clovis groups adapted their hunting equipment to the characteristics of their prey and local habitat, which resulted in regional differences in their toolkits, including differences in the shape of their points. This hypothesis can be traced back to Witthoft (1952, 1954). The hypothesis gained additional support in the late 1980s and early 1990s from studies conducted by Meltzer (1988, 1993), Anderson (1990), and Storck and Spiess (1994), who concluded that Clovis groups developed different cultural adaptations within the diverse environments of eastern North America. Recently, Smallwood (2012) revisited the regional environmental adaptation hypothesis in an examination of points and bifaces from sites located in Tennessee, South Carolina, and Virginia. She identified technological differences among the specimens from these states and concluded that they represent different cultural adaptations.

The other hypothesis holds that Clovis groups did not adjust the shape of their points in relation to local environmental conditions. This *continent-wide adaptation hypothesis* was first outlined in the 1950s (e.g., Byers 1954; Krieger 1954; Willey and Phillips 1958) but is best known from the later work of Haynes (1964) and Kelly and Todd (1988). Haynes (1964) compared variation in Clovis points within and between regions of North America and suggested that the former exceeded the latter, from which he concluded that there is no regional variation in Clovis points. Kelly and Todd (1988) outlined a model in which Clovis groups used a highly portable and flexible toolkit in hunting different prey species across the diverse environments of North America. With respect to Clovis point form, they argued that "frequent range shifts may not have been conducive to in situ development of regional projectile point styles" (p. 236). Recently, two studies have reported results that are consistent with the continent-wide adaptation hypothesis. Buchanan and Hamilton (2009) used morphometric data and multivariate statistical techniques to investigate whether Clovis point shape correlates with measures of regional environmental diversity. They found no association between point shape and regional environmental diversity and interpreted this as evidence that not enough time had elapsed during the Clovis expansion for local selective regimes to have led to shape change. More recently still, Sholts et al. (2012) used laser scanning and Fourier analysis to examine flake scar patterns on Clovis points from the Great Plains, Southwest, and Midatlantic areas. They found few differences among these areas and argued that this supports a model of widespread standardization of Clovis technology.

The failure of researchers to reach consensus on the existence of regional variation among Clovis points is unfortunate because the competing hypotheses have markedly different implications. If we can determine which of them is correct, we will be able to infer important aspects of Clovis lifeways and perhaps develop a better understanding of the colonization of North America. With this mind, we decided to revisit the question of whether Clovis groups adjusted the shape of their points to deal with regional environmental conditions.

In the study, we employed a suite of shape analysis methods from biology called geometric morphometrics (GM). Within the GM framework, shape is defined as the geometric properties of an object that are invariant to location, scale, and orientation (Slice 2005). GM methods deal with coordinate data as opposed to the interlandmark distances of standard morphometrics and allow patterns of variation in shape to be investigated within a well-understood statistical framework that yields easily interpreted numerical and visual results (for detailed reviews of GM see Adams et al. 2004; Bookstein 1991; Bookstein et al. 1985; Dryden and Mardia 1998; O'Higgins 1999, 2000; Rohlf and Bookstein 1990; Rohlf and Marcus 1993; Slice 2005, 2007; Webster and Sheets 2010; Zelditch et al. 2004).

Briefly, GM analysis begins by standardizing landmark configurations so that they are directly comparable. To do this, a superimposition method (generalized Procrustes analysis) iteratively minimizes the sum of the squared distances among landmarks of each configuration by translating (shifting the configurations together in a fixed direction), rotating ("spinning" the configurations around a fixed point), and scaling the configurations. Scaling is accomplished by dividing the coordinates of each form by its centroid size, which is defined as the square root of the sum of the squared distances between the geometric center of the form and its landmarks (Bookstein 1991). The remaining differences in landmark position, which are called the "Procrustes residuals," represent the shape differences among the objects. Lastly, because landmark configurations describing a particular form are maintained throughout each step of the analysis, they can be visualized in a number of ways. For example, to visualize differences between pairs of landmark configurations representing two different forms, aligned landmark coordinates are fitted to an interpolation function such as the thin-plate spline.

Recent studies in which GM methods have been applied to stone tools suggest that they are well suited to testing the competing hypotheses regarding regional variation in Clovis point shape (Archer and Braun 2010; Buchanan and Collard 2010; Buchanan et al. 2011; Cardillo 2010; Charlin and González-José 2012; Costa 2010; Lycett and von Cramon-Taubadel 2013; Lycett et al. 2010; Thulman 2012; Wang et al. 2012). With this in mind, we carried out two sets of GM-based analyses to test for differences in point shape at two scales. The first set of analyses focused on differences between points from the two most obvious environmental regions in North

America—the East and the West. The second set of analyses investigated differences among points from environmental subregions within each region. We reasoned that if differences in point shape were found between the regions and/or among the subregions within each region, then the continent-wide adaptation hypothesis would be refuted and the regional environmental adaptation hypothesis supported.

Materials and methods

In line with comparable previous studies (e.g., Buchanan and Collard 2007; Buchanan and Hamilton 2009; Sholts et al. 2012), only Clovis points recovered from unmixed contexts were included in the sample. Thousands of isolated, surface-collected Clovis points have been found in North America (Anderson and Faught 2000), but incorporating such points likely would have biased our results. This is because isolated, surface-collected points that have been typed are necessarily distinctive and therefore tend to be less morphologically variable than those found in assemblages of points. Consequently, including isolated, surface-collected points in our sample would have falsely increased the chances of finding no shape differences across the continent.

An assemblage had to meet three criteria to be included in the study. First, it had to be reliably dated to the Clovis period, meaning that it either was associated with radiometric dates in the ca. 13,500–12,800 calBP range in the West and ca. 12,800–12,500 calBP range in the East (Gingerich 2011; C. Haynes et al. 1984; Haynes et al. 2007; Holliday 2000; Levine 1990) or contained diagnostic artifacts that are radiometrically dated to these ranges at another site. We used different age ranges for Clovis in the West and East because Clovis appears to be time-transgressive in that a diffusion process began in the West around 13,500 calBP and ended in the Northeast by 12,500 calBP (Hamilton and Buchanan 2007). Second, chronologically diagnostic objects in an assemblage had to be restricted to those about which there is general agreement that they were produced only during the Clovis period. Third, an assemblage's points, or epoxy casts of its points, had to be available for measurement.

We measured points from a total of 30 assemblages (Fig. 1 and Table 1). In terms of regional coverage, we do not have assemblages from the Far West or the Southeast. Both regions have points that are thought to date to the Early Paleoindian period (e.g., Clovis and Great Basin Stemmed in the Great Basin (Beck and Jones 1997, 2010; Bryan 1991; Willig 1991) and Clovis, Cumberland, Redstone, and Quad in the Southeast [Anderson 1990; Boulanger et al. n.d.; O'Brien et al. 2001]), but at the time the data were collected, neither region had an assemblage that met the criteria for inclusion in the study (see Buchanan and Collard 2007).

We included all complete and nearly complete points from the 30 assemblages. Casts were used in lieu of original specimens in 15 % of cases. Morphometric comparison of a sample of casts and original points revealed no significant differences in form between the casts and the original points (Buchanan 2005). All told, 241 points and point casts were measured.

Shape data were obtained from the points in the same manner as in Buchanan et al. (2011). The procedure involved the following steps:

Image acquisition Digital images of points were used to capture landmark data. Thickness undoubtedly plays a role in the performance of points (e.g., Cheshier and Kelly 2006), but our focus here is on the plan shape of the points.

Choice and digitization of landmarks We used three landmarks and 20 semilandmarks to capture point shape. Two of the landmarks were located at the base of the point and were defined by the junctions of the base and the blade edges. The third landmark was located at the tip. Line segments with equally spaced perpendicular lines were used to place the semilandmarks along the edges of the blades and base. These "combs" were superimposed on each image using MakeFan6 (www.canisius.edu/~sheets/morphsoft.html). Placement of landmarks along the equally spaced segments of the combs allows these semilandmarks to be compared across specimens. The 23 landmarks and semilandmarks we digitized for each point are shown in Fig. 2. The landmarks and semilandmarks were digitized using the tpsDig program (Rohlf 2010).

Superimposition of landmarks This procedure was carried out to reduce the confounding effects of the digitizing process and to remove size differences among the specimens (Rohlf 2003a; Rohlf and Slice 1990). Landmark superimposition entails three steps. First, landmark coordinates are centered at their origin, or "centroid," and all configurations are scaled to unit centroid size. Second, the consensus configuration is computed. Third, each landmark configuration is rotated to minimize the sum-of-squared residuals from the consensus configuration. The superimposition of landmarks was carried out using tpsSuper (Rohlf 2004).

Projection to tangent Euclidean space In order to subject the shape data to statistical analysis, it is necessary to project the landmarks to tangent Euclidean space (Kendall 1984; Rohlf 1998; Slice 2001). This procedure was also carried out using tpsSuper (Rohlf 2004). To determine the fit between the specimens in shape space and linear tangent space, we conducted a regression of the distances in tangent space against the Procrustes distances. This test was carried out using tpsSmall (Rohlf 2003b). The correlation between the two

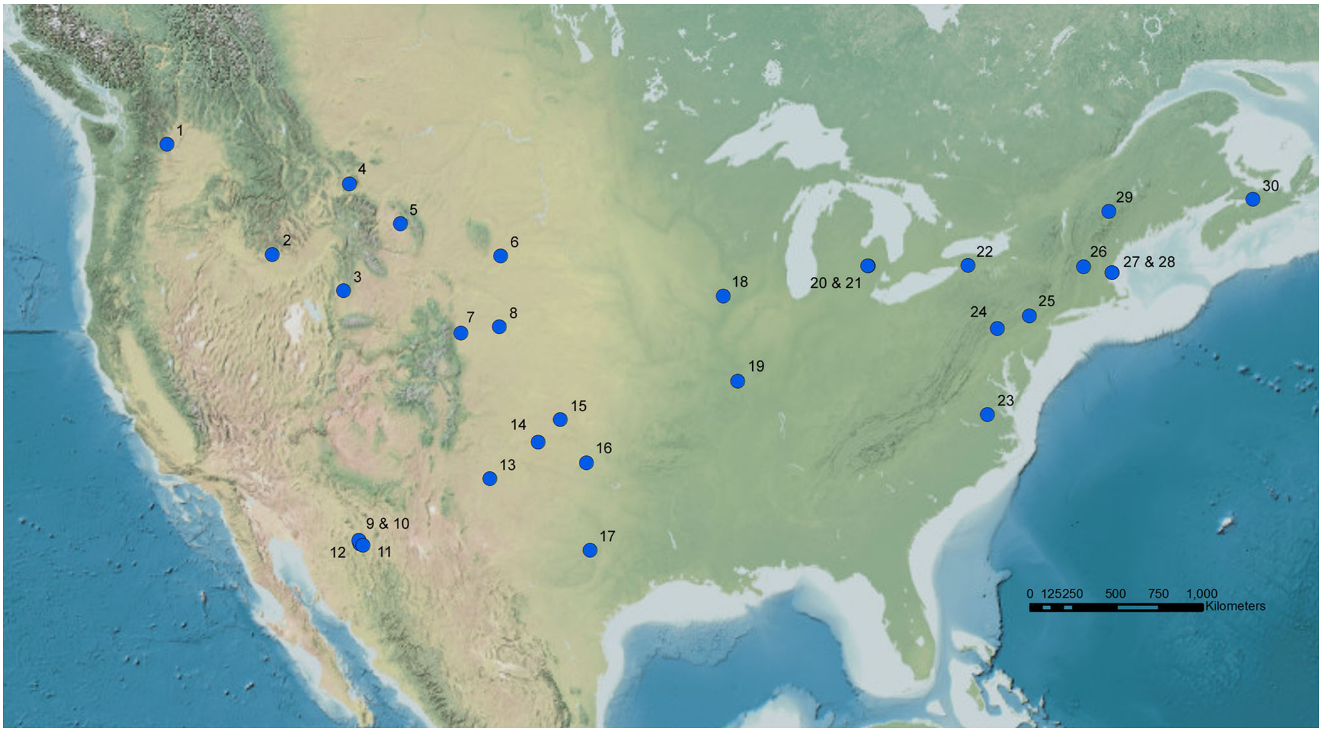


Fig. 1 Distribution of Clovis sites with point assemblages included in the analysis: *1* East Wenatchee; *2* Simon; *3* Fenn; *4* Anzick; *5* Colby; *6* Lange–Ferguson; *7* Dent; *8* Drake; *9* Murray Springs; *10* Escapule; *11* Lehner; *12* Naco; *13* Blackwater Draw; *14* Miami; *15* Jake Bluff; *16* Domebo; *17* Gault; *18* Rummells–Maske; *19* Kimmswick; *20* Butler; *21* Gainey; *22* Lamb; *23* Cactus Hill; *24* Shoop; *25* Shawnee–Minisink; *26* Whipple; *27* Bull Brook I; *28* Bull Brook II; *29* Vail; *30* Debert

distances was strong and highly significant (slope=0.9963; correlation=0.9999; root MS error=0.00004), indicating that the projection was adequate.

Extraction of partial warps and the uniform component Partial warps are eigenvectors of the bending energy matrix that describe local deformation along a coordinate axis. Uniform components express global information on deformation. The first uniform component accounts for variation along the X-axis of a configuration, and the second uniform component accounts for variation along the Y-axis. Together, partial warps and uniform components represent all information about the shape of specimens (Rohlf et al. 1996; Slice 2005). Partial warps and uniform components were computed using tpsRelw (Rohlf 2008).

Relative warps computed from partial warps Relative warps are the principal components of the shape variables—in this case, the partial warp and uniform component scores—and therefore reflect the major patterns of shape variation within a group of specimens. They were computed using tpsRelw (Rohlf 2008).

After following the steps above, we compared point shape in the shape space defined by the first two relative warps. To do this, we created a bivariate plot showing the points' scores on the first two relative warps. We then displayed the shape of points at the extremes of the axes representing the first two relative warps. This analysis was carried out with the tpsRelw program. Next, we carried out two set of analyses in which discriminant function analysis (DFA) was used to determine how well point shape discriminates among environmental regions. The first set of analyses focused on differences between points from the East and points from the West. The Mississippi River forms the dividing line between these regions (Fig. 3). In the late Pleistocene, environments of the East were tundra to open spruce parklands and boreal/deciduous forests (Meltzer 1988), whereas those in the West were deserts, grasslands, and temperate scrub woodlands (Adams 1997). Thirteen assemblages in the sample were assigned to the East (n=116) and 17 assemblages to the West (n=125)[1]. Partial warps and uniform component were entered into a DFA, with region selected as the grouping variable.

[1] Rummells–Maske and Kimmswick both lie within the Mississippi River drainage and therefore are located in the border area for the division between the western and eastern regions. Rummells–Maske and Kimmswick are situated approximately 30 and 1.5 km, respectively, west of the Mississippi River, but we included them in the East because they were located closer to other sites in the East than to sites in the West (both Rummells–Maske and Kimmswick are closest to themselves, followed by Gainey and Butler). This decision did not affect our findings. Results of discriminant function analysis and pairwise comparison of regions are similar if we assign Rummells–Maske and Kimmswick to the West (Mahalanobis distance=2.4162; p<0.0001).

Table 1 Points from Clovis assemblages used in the analysis

Site	State or province	No. of points in analysis	Primary reference(s)
Anzick[a]	MT	6	Lahren and Bonnichsen (1974), Owsley and Hunt (2001), Wilke et al. (1991)
Blackwater Draw[b]	NM	27	Boldurian and Cotter (1999), Cotter (1937, 1938), Hester (1972), Howard (1935), Warnica (1966)
Bull Brook[c]	MA	38	Byers (1954, 1955), Grimes (1979), Robinson et al. (2009)
Bull Brook II[c]	MA	2	Grimes et al. (1984)
Butler[c]	MI	4	Simons (1997)
Cactus Hill[c]	VA	6	McAvoy and McAvoy (1997)
Colby[b]	WY	3	Frison and Todd (1986)
Debert[c]	NS	6	MacDonald (1966, 1968)
Dent[b]	CO	2	Brunswig and Fisher (1993), Figgins (1933), Haynes et al. (1998)
Domebo[b]	OK	3	Leonhardy (1966)
Drake[a]	CO	13	Stanford and Jodry (1988)
East Wenatchee[a]	WA	13	Gramly (1993), Lyman et al. (1998)
Escapule[b]	AZ	1	Hemmings and Haynes (1969)
Fenn[a]	UT/WY/ID[d]	16	Frison (1991), Frison and Bradley (1999)
Gainey[c]	MI	10	Simons (1997), Simons et al. (1984, 1987)
Gault[c]	TX	4	Collins and Lohse (2004), Collins et al. (1992), Waters et al. (2011, b)
Jake Bluff[b]	OK	4	Bement and Carter (2010)
Kimmswick[b]	MO	3	Graham and Kay (1988), Graham et al. (1981)
Lamb[a]	NY	5	Gramly (1999)
Lange–Ferguson[b]	SD	2	Hannus (1985, 1990)
Lehner[b]	AZ	10	Haury et al. (1959)
Miami[b]	TX	3	Holliday et al. (1994), Sellards (1938, 1952)
Murray Springs[b]	AZ	5	Haynes and Hemmings (1968), Haynes and Huckell (2007), Hemmings (1970)
Naco[b]	AZ	8	Haury et al. (1953)
Rummells–Maske[a]	IA	10	Anderson and Tiffany (1972), Morrow and Morrow (2002)
Shawnee–Minisink[c]	PA	2	Gingerich (2007, 2011), McNett (1985)
Shoop[c]	PA	13	Cox (1986), Witthoft (1952)
Simon[a]	ID	5	Butler (1963), Butler and Fitzwater (1965), Titmus and Woods (1991), Woods and Titmus (1985)
Vail[c]	ME	15	Gramly (1982, 1984), Gramly and Rutledge (1981)
Whipple[c]	NH	2	Curran (1984, 1987, 1994)

[a] Point assemblage identified in the literature as a cache

[b] Point assemblage identified in the literature as recovered from a kill

[c] Point assemblage identified in the literature as recovered from a habitation or camp

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

The second set of DFAs examined differences among points from four subregions within each region. The subregions are widely recognized physiographic areas. They differ in geologic structure and in their environmental and biotic characteristics (Buchanan and Hamilton 2009; Cannon 2004; Hunt 1967). The East was divided into the Northeast, Midatlantic, Great Lakes, and Midcontinent; the West into the Southern Plains, Southwest, Northern Plains, and Northwest. The characteristics of the subregions are listed in Table 2, and the distribution of sites by subregion is shown in Fig. 4. The sample with the most Clovis points is from the Northeast ($n=63$), followed by the Southern Plains ($n=43$), Northwest ($n=34$), Northern Plains ($n=26$), Southwest ($n=24$), Midatlantic ($n=21$), Great Lakes ($n=19$), and Midcontinent ($n=13$) (Table 2). In the second set of analyses, the partial warps and uniform component were entered into a DFA, with subregion selected as the grouping variable.

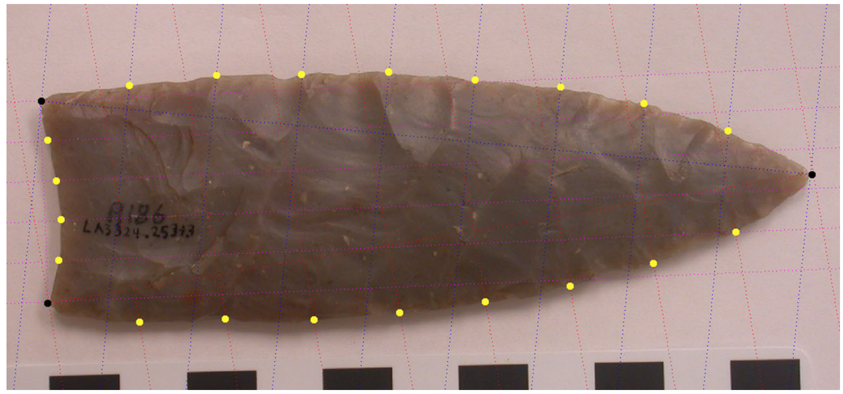


Fig. 2 Digital image of a Clovis point with the locations of three landmarks (black circles) and 20 semilandmarks (yellow circles) marked along the edges. The lines superimposed on the point image were produced with the MakeFan program

Evaluation of the significance of the differences between the regional groups of points and among the subregional groups of points was carried out with pairwise Hotelling's T-squared tests, the multivariate extension of Student's t test. Significance was determined using p values derived from a permutation test that compared the observed difference between means with a distribution of pairwise mean differences from 1,000 random permutations of the data. We used a permutation test to derive p values because the samples did not approximate multivariate normality. Given that we performed several pairwise tests, we modified the critical level used in evaluating the comparisons. This procedure has been recommended for unadjusted permuted p values in the context of multiple hypothesis testing (Dudoit et al. 2003). We used Benjamini and Yekutieli's (2001) method for controlling the false discovery rate. The method uses the following equation to determine the critical value:

$$\alpha/\sum_{i=1}^{k}(1/i),$$

where k is the number of hypothesis tests conducted. Narum (2006) has shown that Benjamini and Yekutieli's (2001) method optimizes the reduction of both type I and type II error rates relative to several other methods. We used MorphoJ 1.03d (Klingenberg 2011) to conduct the DFAs, the Hotelling's T-squared tests, and the calculation of the Mahalanobis distances.

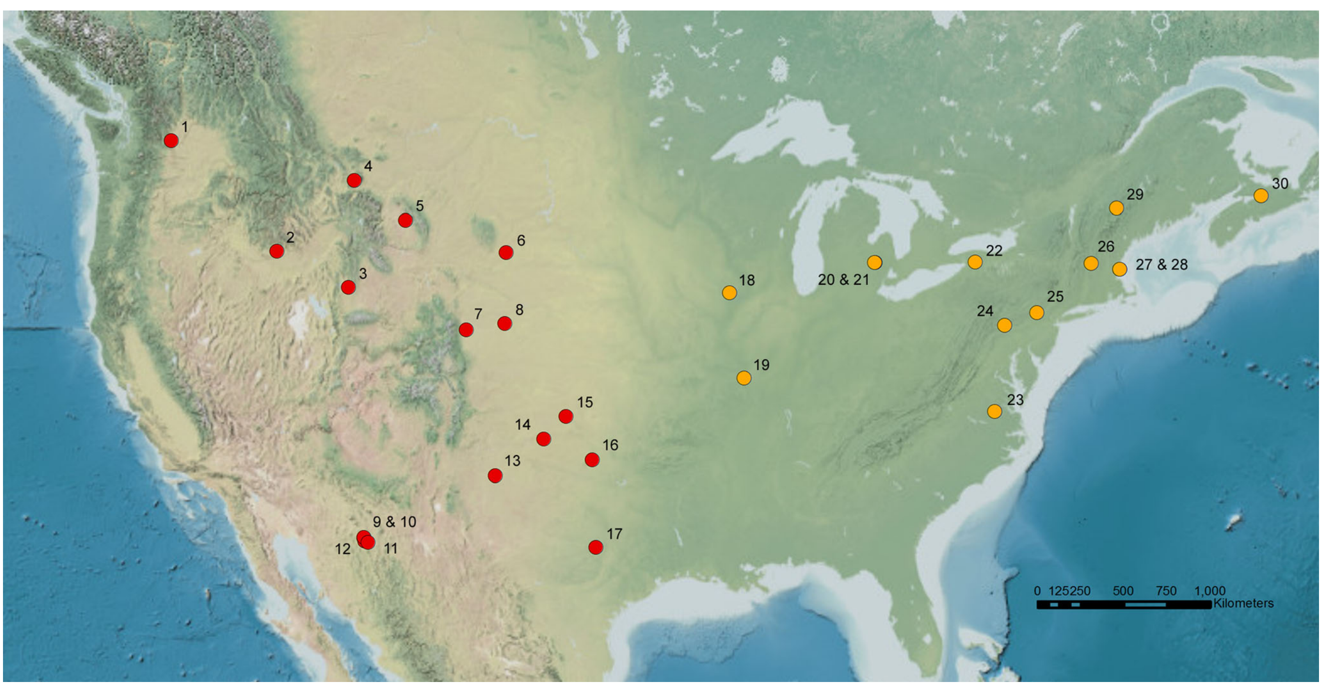


Fig. 3 Distribution of Clovis sites with point assemblages with regional affiliation denoted: *1* East Wenatchee; *2* Simon; *3* Fenn; *4* Anzick; *5* Colby; *6* Lange–Ferguson; *7* Dent; *8* Drake; *9* Murray Springs; *10* Escapule; *11* Lehner; *12* Naco; *13* Blackwater Draw; *14* Miami; *15* Jake Bluff; *16* Domebo; *17* Gault; *18* Rummells–Maske; *19* Kimmswick; *20* Butler; *21* Gainey; *22* Lamb; *23* Cactus Hill; *24* Shoop; *25* Shawnee–Minisink; *26* Whipple; *27* Bull Brook I; *28* Bull Brook II; *29* Vail; *30* Debert. *Colors* indicate regional affiliation: *red* (1–17), West; *orange* (18–30), East (see footnote 1 regarding Rummells–Maske and Kimmswick)

Table 2 Descriptions of subregions (adapted from Buchanan and Hamilton 2009)

Subregion	Physiographic description[a]	Paleo-biome[b]	NPP[c]	Assemblages in subregion	No. of points in sample
Northwest	Intermontane Plateau–Columbia Plateau	Semi-desert and mountain mosaic	230	East Wenatchee, Simon, Fenn	34
Northern Plains	Interior Plains–Great Plains Province (northern)	Dry steppe	214	Anzick, Colby, Lange–Ferguson, Dent, Drake	26
Southwest	Southern Basin and Range—Sonoran Desert Section	Semi-desert	129	Murray Springs, Escapule, Lehner, Naco	24
Southern Plains	Interior Plains–Great Plains Province (southern)	Dry steppe	214	Blackwater Draw, Miami, Jake Bluff, Domebo, Gault	41
Midcontinent	Central Lowland–Interior Low Plateaus	Prairie	335	Rummells–Maske, Kimmswick	13
Great Lakes	Great Lakes Section	Spruce forest	173	Butler, Gainey, Lamb	19
Midatlantic	Coastal Plain and Piedmont	Spruce forest	238	Cactus Hill, Shoop, Shawnee–Minisink	21
Northeast	New England Province	Parkland to tundra	147	Whipple, Bull Brook I, Bull Brook II, Vail, Debert	63

[a] Physiographic descriptions of regions are from Hunt (1967)

[b] Paleoenvironmental biomes are from Adams (1997) and Steele et al. (1998)

[c] Net primary production (NPP) values are from Melillo et al. (1993). Their estimates of NPP are in grams of carbon per meter per year

Lastly, we compared the results with the predictions of the two hypotheses. We reasoned that the presence of significant differences between points from the East and the West would support the regional environmental adaptation hypothesis, whereas the absence of differences between points from the East and West would support the continent-wide adaptation hypothesis. We also reasoned that the presence of significant differences among points from the subregions would further support the regional environmental adaptation hypothesis.

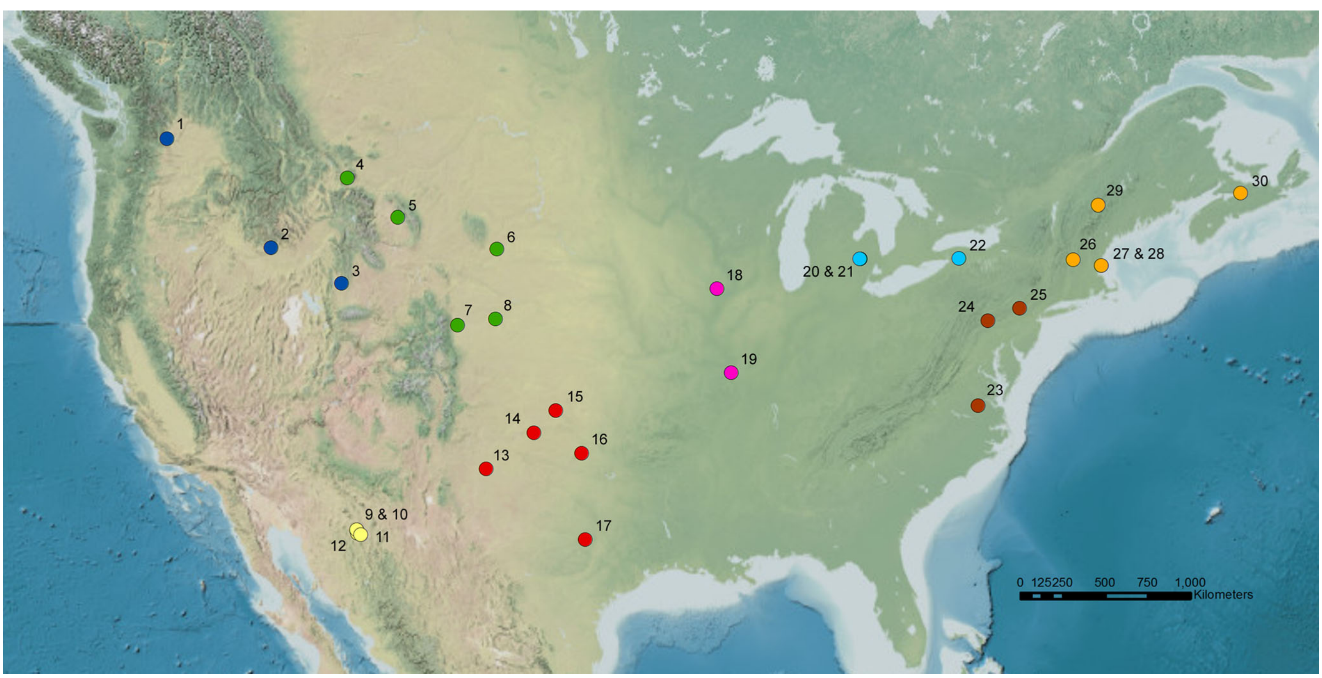


Fig. 4 Distribution of Clovis sites with point assemblages, with subregional affiliation denoted: *1* East Wenatchee; *2* Simon; *3* Fenn; *4* Anzick; *5* Colby; *6* Lange–Ferguson; *7* Dent; *8* Drake; *9* Murray Springs; *10* Escapule; *11* Lehner; *12* Naco; *13* Blackwater Draw; *14* Miami; *15* Jake Bluff; *16* Domebo; *17* Gault; *18* Rummells–Maske; *19* Kimmswick; *20* Butler; *21* Gainey; *22* Lamb; *23* Cactus Hill; *24* Shoop; *25* Shawnee–Minisink; *26* Whipple; *27* Bull Brook I; *28* Bull Brook II; *29* Vail; *30* Debert. *Colors* indicate regional affiliation: *blue* (1–3), Northwest; *green* (4–8), Northern Plains; *yellow* (9–12), Southwest; *red* (13–17), Southern Plains; *magenta* (18–19), Midcontinent; *light blue* (20–22), Great Lakes; *brown* (23–25), Midatlantic; *orange* (26–30), Northeast

Results

Figure 5 (top) shows the consensus configuration derived from the superimposition analysis. This configuration of landmarks represents the average shape of the 241 Clovis points in the sample. The average point represented in the consensus configuration has a lanceolate-shaped blade and a concave base. The two basal landmarks (landmarks 2 and 3) are the most variable; variation associated with individual landmarks decreases toward the tip (Fig. 5 [bottom]).

Figure 6 plots the first two relative warps by region. The first relative warp, representing 84.95 % of the overall variation, is plotted on the X-axis; the second relative warp, representing 4.34 % of the overall variation, is plotted on the Y-axis. Overlap among the regions is evident, but points from the East are more variable than those from the West, particularly along the second relative warp. The wireframes in Fig. 6 show deformation from the consensus configuration at the positive and negative ends of each axis to illustrate Clovis shape space. The shape space is defined along the first relative warp by elliptical blades with deeply concave bases to the left (negative end)—represented by the point from Shoop (Pennsylvania)—and by more linear blades with shallow, rounded concave bases to the right (positive end)—represented by the point from Simon (Idaho). Along the second relative warp, Clovis shape space is defined by lanceolate blades with straight bases at the upper (positive) end—represented by the point from Murray Springs (Arizona)—and more deltoid blades with deep, concave bases at the lower (negative) end—represented by the point from Vail (Maine).

The DFA between East and West subsamples indicated that they can be distinguished with a reasonable level of confidence (12 % overall misclassification rate), and the pairwise test between the difference in mean shapes showed that the two are significantly different (Mahalanobis distance=2.2977; $p<0.0001$). Figure 7 shows the differences between the mean point shapes from the East and West regions. The deformation grid in this figure indicates that points from the East have, on average, deeper basal concavities and wider bases and tips than points from the West.

The DFA and significance tests also revealed several differences in point shape among the subregions (Tables 3 and 4). Within the East, the Northeast is different from all other subregions, whereas the Midatlantic, Great Lakes, and

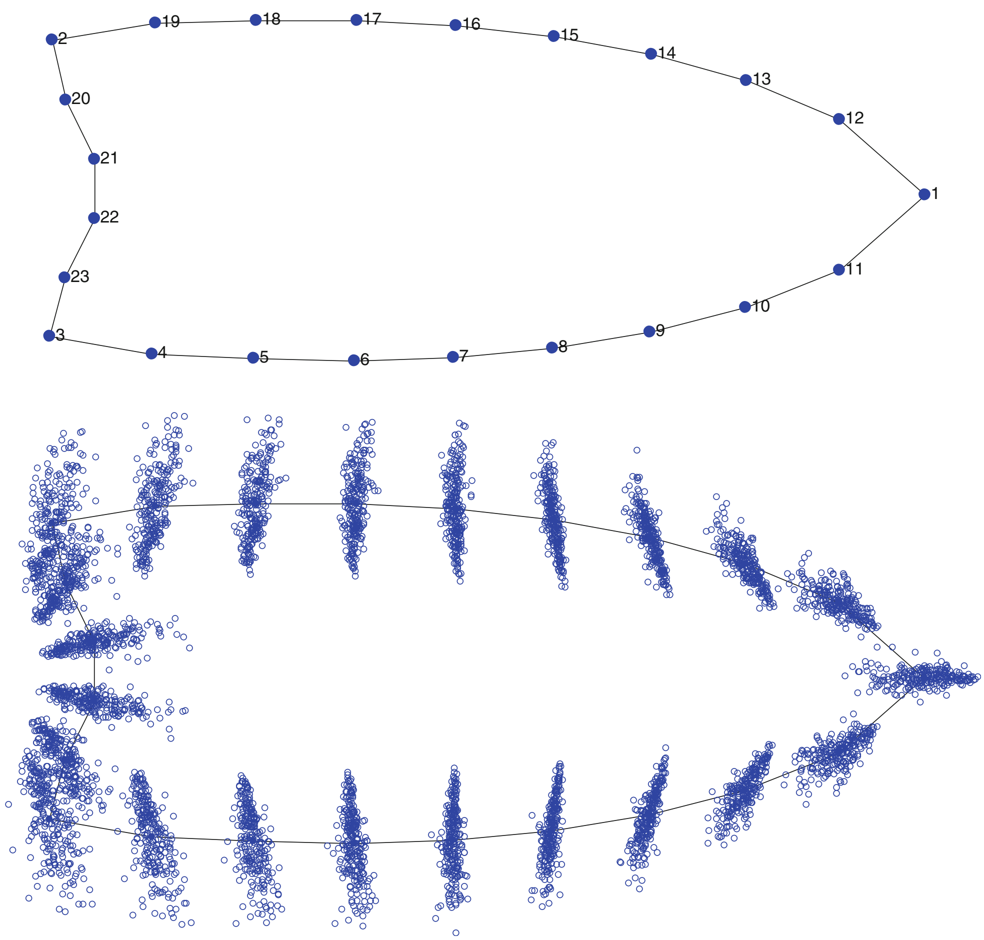


Fig. 5 Results of the superimposition method using the generalized orthogonal least-squares Procrustes procedure: *top*, consensus configuration of 241 Clovis-point landmark configurations; *bottom*, variation in point landmark configurations after being translated, scaled, and rotated

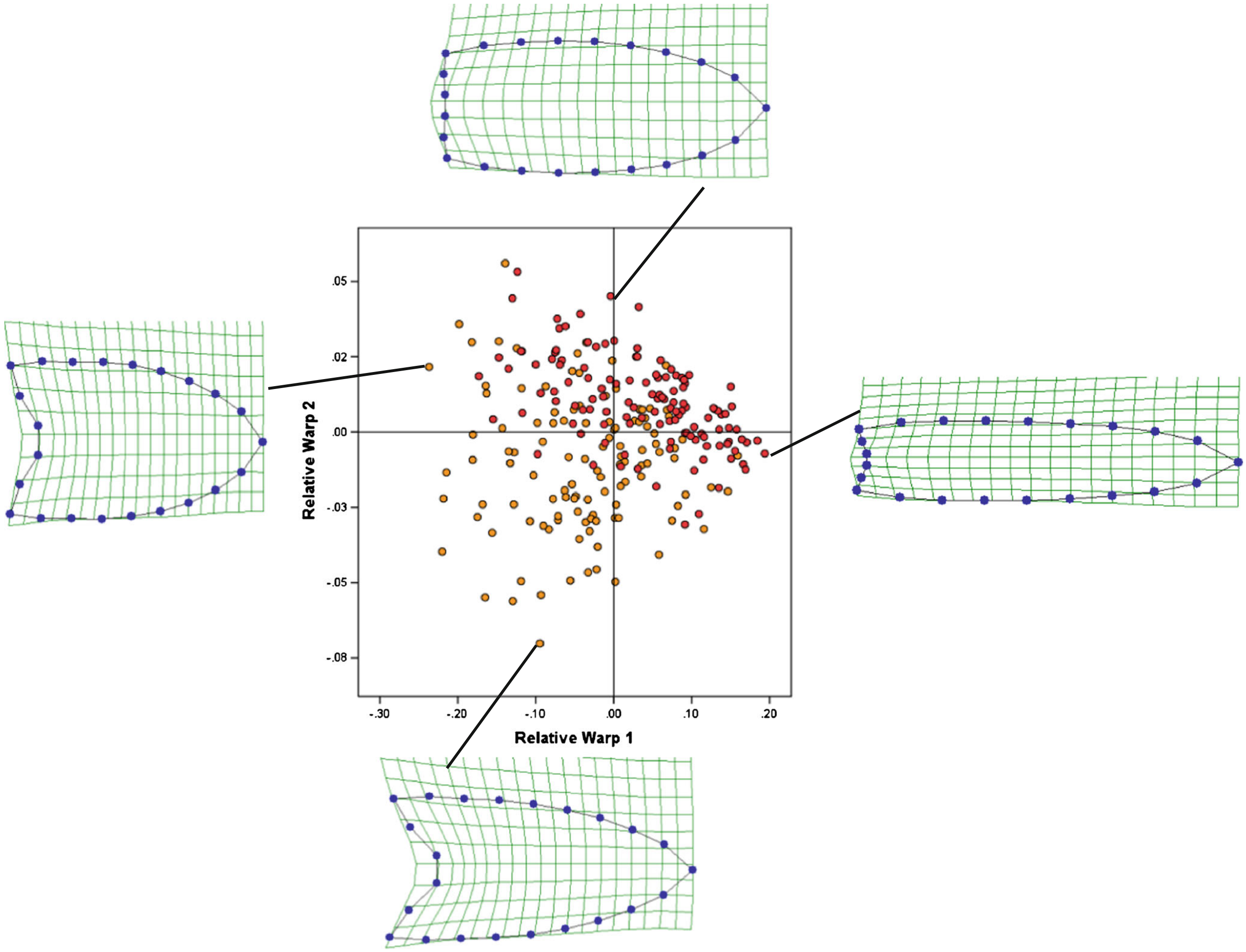


Fig. 6 Bivariate plot of relative warp 1 (85 %) against relative warp 2 (4.3 %) for all Clovis points. *Red circles* indicate points from the West and *orange circles* indicate points from the East. The four images are deformations from the consensus configurations and display the shape space defined by the first two relative warps. The upper point is from Murray Springs, the point at the right is from Simon, the lower point is from Vail, and the point at the left is from Shoop

Midcontinent are not different from each other (Table 3). Within the West, the Northwest is significantly different from both the Southwest and Southern Plains, and the Northern Plains is different from the Southern Plains (Table 4). The Southern Plains and Northern Plains are not different from the Southwest, and the Northwest is not different from the Northern Plains.

Subregional differences in mean point shapes are illustrated in Figs. 8 and 9. For the East, points from the Northeast are wider and have deeper basal indentations than points from the Great Lakes and Midcontinent (Fig. 8b–c). Although points from the Northeast are significantly different from points from the Midatlantic, the differences appear to be minor, mainly in the base and tip (Fig. 8a). For the West, points from the Southern Plains and Southwest are wider and have more concave bases than points from the Northern Plains and Northwest (Fig. 9a–c).

Discussion

Over the past 60 years, archaeologists interested in the Paleoindian period have discussed whether the shape of Clovis points varies regionally, with one group of researchers arguing that point shape varies in a manner consistent with regional adaptation and another group averring that point shape is uniform across the continent. In the study reported here, we applied GM techniques to Clovis points to test these hypotheses. We used DFA and significance tests to examine differences in shape among regions at two different scales. First, we divided our sample of Clovis points into the two most obvious environmental regions in North America—the East and the West (Fig. 3). Points from the East were found to have wider blades and tips and deeper basal concavities than points from the West. The significance tests showed that these shape differences are significant. The second set of analyses

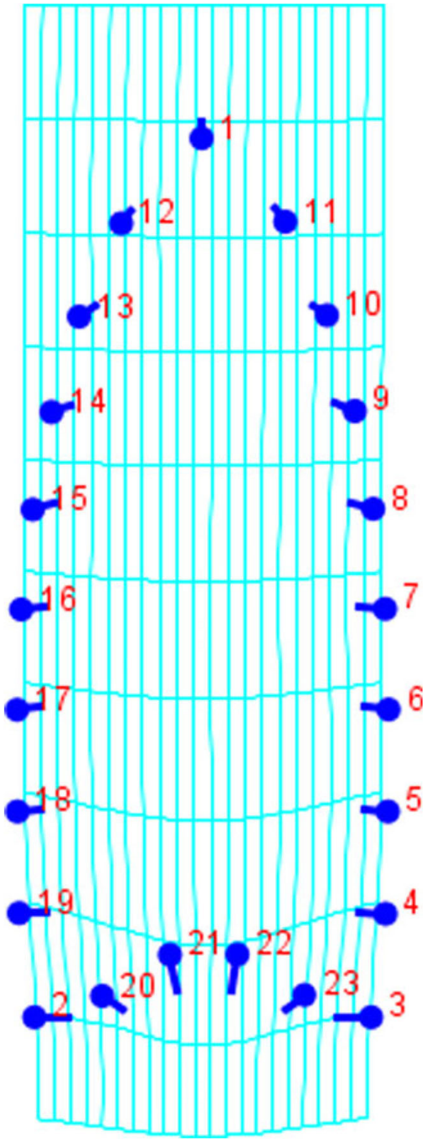


Fig. 7 Deformation grid for the pairwise comparison of mean point shapes for the East and West. The grid is warped to indicate the differences between the average regional point shapes. Landmarks are *numbered with circles* showing the average landmark configuration for the East and *lines* indicating the direction and magnitude of difference with the West

Table 3 Pairwise discrimination results of Clovis point shape by subregion within the East. The lower triangle of the matrix shows p values based on 1,000 permutations for Hotelling's T-squared tests, and the upper triangle shows Mahalanobis distances between subregions

	Northeast	Midatlantic	Great Lakes	Midcontinent
Northeast		4.367	3.605	4.310
Midatlantic	<0.0001[a]		6.209	5.274
Great Lakes	0.0060[a]	0.2080		6.690
Midcontinent	0.0170[a]	0.1710	0.0940	

[a] Significant at the critical level of p =0.02041 based on Benjamini and Yekutieli's (2001) method for controlling the false discovery rate

Table 4 Pairwise discrimination results of Clovis point shape by subregion within the West. The lower triangle of the matrix shows p values based on 1,000 permutations for Hotelling's T-squared tests, and the upper triangle shows Mahalanobis distances between subregions

	Southern Plains	Southwest	Northern Plains	Northwest
Southern Plains		3.560	4.593	4.176
Southwest	0.1260		9.503	7.586
Northern Plains	0.0030[a]	0.0270		3.459
Northwest	<0.0001[a]	0.0010[a]	0.3180	

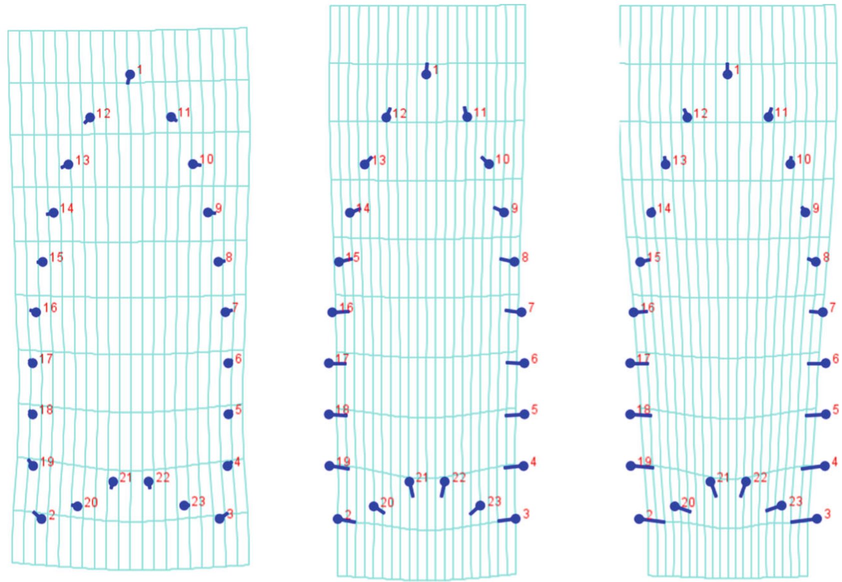
[a] Significant at the critical level of p =0.02041 based on Benjamini and Yekutieli's (2001) method for controlling the false discovery rate

investigated differences among points from environmental subregions within each region. Significance tests showed that among the subregions in the East, points from the Northeast are significantly different from those from all other subregions. Within the West, points from the Northwest are significantly different from those from the Southern Plains and Southwest, and Northern Plains points are different from Southern Plains points. Together, these results support the regional environmental adaptation hypothesis rather than the continent-wide adaptation hypothesis.

Two potential alternative explanations for the differences in point shape between regions and among subregions need to be considered. The first is resharpening, which has the potential to have a major influence on point shape (e.g., Flenniken and Raymond 1986). In principle, the regional/subregional differences in point shape could result from different amounts of resharpening. However, as noted above, most of the shape variation in our Clovis sample occurs around the basal landmarks. As bases are rarely resharpened (Ahler and Geib 2000; Musil 1988), this pattern suggests that resharpening is unlikely to be the cause of the regional and subregional differences.

To further evaluate the likely impact of resharpening on our results, we carried out additional analyses following the methods outlined by Buchanan and Collard (2010), who used GM and DFA to assess how well blade shape distinguishes among points assigned to three Paleoindian point types, one of which was Clovis. Buchanan and Collard (2010) controlled for the influence of resharpening by using point size as a proxy for degree of resharpening on the grounds that small points are more likely to have been resharpened than large points. They divided the points according to size and then tested whether the small points were more difficult to assign to type than large points. They found no difference between the two size-based groups of points, which they argued suggested that resharpening was not a major cause of the variation in their sample.

In our analyses, we sorted the points in each region by length and then took the shortest 50 % of each sample and reran the East versus West DFA. We then divided the sample of

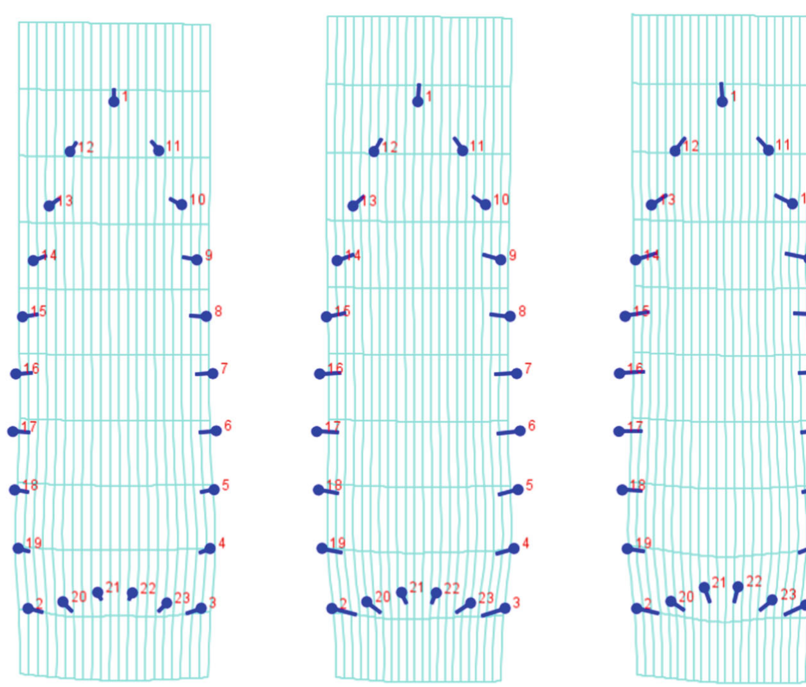


(a) NE–MA (b) NE–GL (c) NE–MC

Fig. 8 Deformation grids for significant pairwise comparisons of mean point shapes by subregion within the East. The grid is warped to indicate the differences between average subregional point shapes. Landmarks are *numbered with circles* showing the average landmark configuration for the first region and *lines* indicating the direction and magnitude of difference. Abbreviations for subregions: *NE* = Northeast; *MA* = Midatlantic; *GL* = Great Lakes; *MC* = Midcontinent

short points in half again, took the shortest 25 % from each region, and re-ran the East versus West DFA. (We did not conduct similar analyses at the subregional scale because the subregion samples are much smaller and therefore may have produced spurious results). Analysis of the shortest 50 % of the regional subsamples yielded a misclassification rate of 5.7 % (seven misclassified out of 121), whereas analysis of the shortest 25 % of the regional subsamples yielded a misclassification rate of 3.2 % (two misclassified out of 62). Both misclassification rates are lower than the misclassification rate of 12 % for the full sample. Assuming that short points are more likely to have been resharpened than long points, this result also indicates that resharpening can be discounted as an explanation for the differences we identified.

Raw material variation is another potential explanation for the differences in point shape. Because high-quality raw materials (such as chert, chalcedony, and obsidian) are generally easier to work than lower-quality materials (such as basalt, quartz, and quartzite), material quality has the potential to impact stone tool variation as it influences the ability of



(a) SP–NP (b) SP–NW (c) SW–NW

Fig. 9 Deformation grids for significant pairwise comparisons of mean point shapes by subregion within the West. The grid is warped to highlight the differences between average subregional point shapes. Landmarks are *numbered with circles* showing the average landmark configuration for the first region and *lines* indicating the direction and magnitude of difference. Abbreviations for subregions: *SP* = Southern Plains; *NP* = Northern Plains; *SW* = Southwest; *NW* = Northwest flintknappers to produce a desired tool form (Andrefsky 1994; Bamforth 1991; Gardner and Verrey 1979; Tallavaara et al. 2010; Tankersley 1994). To evaluate that possibility, we divided the points into two groups—one of low-quality raw materials and the other of higher-quality materials. Determinations of raw materials were made by visual inspection when possible; in other cases, we relied on published identifications. The points in our sample are predominately made of high-quality raw materials (93.8 %), which is consistent with past studies of Clovis assemblages (Haynes 1980; Kelly and Todd 1988), but there are some points are made of low-quality materials (6.2 %). The latter specimens were recovered from both the East ($n=6$) and West ($n=9$) regions. To assess the influence of material quality, we ran a DFA and a pairwise Hotelling's T-squared test between points made of high-quality materials and points made of low-quality materials. Results indicated that the groups are not significantly different (Mahalanobis distance=2.0132; $p=0.314$), which suggests that raw material quality does not significantly affect point shape variation in our sample and therefore can be discounted as an explanation for the differences we identified.

It appears, then, that both potential alternative causes of variation in point shape have little influence on the point shape differences identified in the present study. There seems to be no reason therefore to reject the conclusion that our analyses support the regional environmental adaptation hypothesis rather than the continent-wide adaptation hypothesis.

That our findings are inconsistent with a number of earlier studies is not particularly surprising because most early work on Clovis points was not quantitative (e.g., Byers 1954; Haynes 1964; Krieger 1954; Willey and Phillips 1958). However, discrepancies between our results and those of two recent quantitative studies (Buchanan and Hamilton 2009; Sholts et al. 2012) require consideration. Buchanan and Hamilton (2009) used morphometric data and multivariate statistical techniques to investigate whether point shape correlates with measures of regional environmental diversity. They found that point shape did not correlate with environmental measures and interpreted their results as indicating that not enough time had elapsed during the Clovis expansion for local selective regimes to have led to shape change. Sholts et al. (2012) used laser scanning and Fourier analysis to examine flake scar patterns on a sample of Clovis points from the Southwest, Southern Plains, Northern Plains, and Midatlantic. Their analyses suggested that flake scar patterns are similar among the regions, and they concluded that there was a continent-wide standardization of Clovis technology.

Although our study and the one carried out by Buchanan and Hamilton (2009) used different samples (the current study includes 30 Clovis assemblages, whereas Buchanan and Hamilton used 25 assemblages), we suspect the primary reason why the two studies differ is because Buchanan and Hamilton (2009) used interlandmark distances to capture point shape, whereas we employed GM. The latter approach is known to detect shape similarities and differences better than the former approach (O'Higgins 2000; Slice 2007), and it seems likely that the current study picked up variation that was undetected by the techniques used by Buchanan and Hamilton (2009).

We can think of two potential reasons why our findings differ from those obtained by Sholts et al. (2012). First, the samples of points used in the two studies differ. Our subregional samples for the Southern Plains and Northern Plains include all the points Sholts et al. (2012) used plus specimens from additional assemblages. Our sample of points from the Midatlantic subregion differs completely from the Midatlantic sample of Sholts et al. (2012). Thus, it is possible that differences in point samples are driving the differences between the studies. A second, and in our view, more likely, reason for the differences is that patterns of flake removal—the focus of the Sholts et al. (2012) study—are less sensitive to adaptive change necessitated by environmental conditions than is point shape because they are less strongly linked to performance than point shape. In other words, Clovis flintknappers were able to use the same knapping methods to produce points that were adapted to different environmental conditions.

Our findings are consistent with a number of studies that have been published over the past six decades. The initial formulations of regional environmental adaptation hypothesis were put forth by Witthoft (1952, 1954). Witthoft (1952, 1954) argued that there are differences between Clovis points from the East and West. The hypothesis was revisited in the 1980s and early 1990s by Meltzer (1988, 1993), Anderson (1990), and Storck and Spiess (1994). They suggested that Clovis groups developed different cultural adaptations within the diverse environments of eastern North America. More recently, Smallwood (2012) has identified technological differences among points and bifaces from Tennessee, South Carolina, and Virginia and suggested that they represent different cultural adaptations. Our work supports the conclusions of these previous studies by showing differences not only between points from the East and West, but also among points from different environmental subregions within the East and West.

The finding that there are regional and subregional differences in Clovis point shape raises two obvious questions. One is: What caused the differences? We are not in a position to answer this question at the moment, but we can offer some possibilities for future evaluation. In a previous study, we showed that prey type had an effect on the size and shape of Paleoindian points (Buchanan et al. 2011). As such, it is possible that the point shape differences identified in the present study are connected with the type of prey targeted by Clovis hunters in the different regions and subregions. Zooarchaeological evidence suggests that Clovis groups in the East primarily hunted caribou or deer, whereas Clovis groups in the West primarily hunted mammoth and bison

(Cannon and Meltzer 2004; Storck and Spiess 1994). Hence, it is possible that the East–West difference in Clovis point shape is a consequence of eastern Clovis points having been optimized for hunting caribou or deer and western Clovis points having been optimized for hunting mammoth and bison. The obvious way of testing this hypothesis is to compare points from assemblages with associated fauna. However, at the moment, there are too few Clovis assemblages with associated fauna for a robust test. As an alternative, the hypothesis can be tested with replica points and carcasses of caribou and bison. Our analyses revealed that points from the East are wider and have deeper basal concavities compared with points from the West. Hence, the hypothesis predicts that replica points that are wider with deeper basal concavities should be more effective at penetrating caribou hide than bison hide, while replica points that are narrower with shallower basal concavities should be more effective at penetrating bison hide than caribou hide. A similar study could be carried out to determine whether differences in prey species also drive the subregional differences in point shape.

Differences in the types of wood available to make the perishable parts of the spears that the points were used with could also potentially explain the inter-regional and inter-subregional differences in point shape. Hardwoods dominate the forests of the East but are uncommon in the West. Thus, the shape difference between points from the East and West could be connected with the types of wood used to make the spears' shafts and foreshafts. According to this hypothesis, a point hafted in a foreshaft made of a hardwood needs to have a relatively wide and deep basal concavity, whereas a point hafted in a softwood can have a narrower and shallower basal concavity. The predictions of this hypothesis can be tested with replica points, foreshafts, and shafts.

A third possible explanation for the regional and subregional point shape differences concerns the type of environment in which the points were used. Different point shapes may have conferred different aerodynamic properties to the weapons in which they were hafted. Thus, in open environments, there would have been added selective pressure on the shape of points for these aerodynamic properties, whereas in more closed environments, aerodynamic properties may have been secondary to other characteristics such as wide blades to create large wounds. Consequently, we can hypothesize that the relatively narrow points with shallow basal concavities in the West have better aerodynamic properties than the wider points with deeper basal concavities in the East. This hypothesis could be evaluated by testing the range of hafted replica points to determine if replicas of the western points travel longer distances than replicas of eastern points when thrown or launched with an atlatl.

Lastly, it is possible that the point shape differences were involved in group identity signaling and therefore are stylistic. We suspect this possibility is unlikely for two reasons. First, the units of comparison used in the study—East versus West and environmental subregions within the East and West—are considerably larger than the largest territory size among historically recorded hunter-gatherer groups (Kelly 1995). This suggests that the point shape differences we identified between the East and West and among subregions are unlikely to be stylistic. Second, it seems reasonable to assume that signaling is most likely to occur in the visible parts of an artifact. For points, this would be the blade and tip sections rather than the base, which would usually have been obscured by the hafting and binding. As we noted above in relation to the issue of resharpening, most of the shape variation in Clovis points occurs in the base rather than the blade and the tip, which are the visible portions of the point. Given that the bases of the point probably would not have been visible when the points were hafted, they are unlikely to have been used in signalling. Having said that, the style hypothesis is an important alternative to the other three hypotheses and deserves formal testing.

The other obvious question raised by the finding that there are regional and subregional differences in Clovis point shape is: How fast was the process of regional point shape adaptation? Some researchers have claimed that the Clovis culture was short-lived, having estimated date ranges of between six and two centuries (e.g., Hamilton and Buchanan 2007; Haynes et al. 2007; Waters and Stafford 2007). However, others have argued that Clovis and its ancestors had a much deeper time depth in North America (e.g., Goebel et al. 2008). The latter authors contend that the Americas were colonized prior to 15,000 calBP by people who produced a different type of material culture. According to this hypothesis, Clovis either developed from this earlier culture and spread via cultural diffusion or resulted from a second migration event. The large difference in the time of first colonization associated with each hypothesis has obvious implications for how long people had to adapt to regional environments in North America.

Recently, Waters et al. (2011a) have reported a site that is important for unraveling the issue of when humans first occupied North America and thus potentially sheds light on the issue of how long Clovis had to adapt to regional environments. Waters et al. (2011a) dated a 20-cm-thick artifact-bearing horizon at the Debra L. Friedkin site in central Texas to 13,200–15,500 years ago using optically stimulated luminescence. The horizon is overlain by a 2.5-cm-thick horizon containing diagnostic Clovis artifacts. Based on the luminescence dates and differences in the composition of the Clovis assemblage and the underlying assemblage—labeled the "Buttermilk Creek Complex"—Waters et al. (2011a) argued that the lower assemblage pre-dates, and is different from, Clovis. The implication of this is that North America was colonized two thousand years earlier than the appearance of Clovis. Waters et al. (2011a) argue that Clovis must therefore represent a rapid diffusion of technology among preexisting populations or a second migration event. In either case, the claim of Waters et al. (2011a) implies that there was a short time for regional environment adaptation to take place.

However, there is another way of interpreting the data reported by Waters et al. (2011a), one that implies that the timeframe available for regional adaptation to occur was much longer. We are willing to provisionally accept that the association between the artifacts in the Buttermilk Creek Complex and the dated floodplain clays is secure, although Morrow et al. (2012) have raised some important questions about the association. We are also willing to accept as a working hypothesis the claim that the Buttermilk Creek Complex is considerably older than the previously widely accepted first appearance date for Clovis, even though there are some issues involved in comparing luminescence dates with radiocarbon dates (Briant and Bateman 2009). For present purposes, the key problem with the claim of Waters et al. (2011a) is that the Buttermilk Creek Complex artifacts do not fall outside the range of variation documented for Clovis.

In order for an archaeological assemblage to be considered distinct from Clovis, it must have characteristics that distinguish it from Clovis. This is not the case with the Buttermilk Creek Complex. The assemblage identified by Waters et al. (2011a) as Clovis that directly overlies the Buttermilk Creek Complex contains artifacts and technological traits that are commonly identified as markers of Clovis—broken bifaces, channel flakes, blade segments, and overshot flaking (Haynes and Huckell 2007; Smallwood 2010; Waters et al. 2011a). Similarly, the Buttermilk Creek Complex also contains broken bifaces, blade segments, and evidence of an overshot flake. Essentially, the only difference between the two assemblages is the absence of channel flakes in the Buttermilk Creek Complex and the presence of such flakes in the overlying Clovis assemblage. Critically, a number of widely accepted Clovis assemblages do not contain evidence of channel flakes (e.g., Aubrey in Texas (Ferring 2001) and Lehner and Murray Springs in Arizona (Haury et al. 1953; Haynes and Huckell 2007)), so their absence is not a reliable trait for identifying non-Clovis archaeological cultures. Given that there are *no* traits that unambiguously distinguish the Buttermilk Creek Complex from the Clovis assemblage at Debra L. Friedkin, we contend that the most parsimonious hypothesis is that the 15,528 artifacts from the Buttermilk Creek Complex represent an early Clovis assemblage.

If the lowest assemblage at Debra L. Friedkin is attributed to Clovis, as we contend, the regional adaptations in Clovis point shape we have identified could have developed relatively slowly, over the course of 2,000 years.

With regard to future research, two interesting studies suggest themselves. One is to broaden the scope of the present study to include point thickness, which is likely to have an important influence on function. Previous experiments have demonstrated that points with higher thickness to length ratios tend to be more durable than points with low thickness-to-length ratios (Cheshier and Kelly 2006). Consequently, a possibility for future research is to carry out three-dimensional analysis of Clovis points to investigate whether the regional and subregional shape differences identified in the present study are accompanied by differences in point thickness.

The other future research project that suggests itself is to move beyond points and test for the existence of geographic variation in other aspects of the Clovis toolkit. Previous studies have suggested that there may be significant differences in the types of tools and how tools were used in different regions and subregions. For example, Meltzer (1988) showed that different toolkits were used by Paleoindians in two different subregions of the East and, in an earlier study focused on a single tool type, Wilmsen (1970) argued that Clovis and later Paleoindian end scrapers were utilized differently between the East and West. Specifically, Wilmsen (1970) suggested that end scrapers in the East were used for wood and bone working, whereas end scrapers in the West were used predominately for butchering and hide working. It would be interesting to know whether the regional differences in point shape that we have identified are mirrored by variation in other tool types as is suggested by Wilmsen's (1970) study or by the presence/absence of different tool types as is suggested by Meltzer's (1988) study. The production techniques used to make other tools would be another focus for such a study.

Conclusions

The existence of regional variation in Clovis points has been a topic of debate for over 60 years. Both the presence and absence of such variation in Clovis points have served as foundations for models of Early Paleoindian colonization and adaptation. In the present study, we used a large sample of Clovis points from dated assemblages and a suite of advanced shape analysis methods to investigate this issue. The study tested the two main hypotheses that have been put forward in the debate: the continent-wide adaptation hypothesis, which holds that Clovis points do not vary regionally, and the regional environmental adaptation hypothesis, which holds that there is regional variation as a consequence of Clovis groups adjusting their food-getting toolkits to local conditions. Our analyses revealed that Clovis points from the East and the West have significantly different shapes. We also found a number of subregional point shape differences within the East and also within the West. These differences are not a consequence of differences in resharpening or raw materials. As such, the study supports the regional environmental adaptation hypothesis rather than the continent-wide adaptation hypothesis. We conclude from this that Clovis people modified their points to suit the characteristics of local prey and/or the habitats in which they hunted.

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