Ceramic morphological organisation in the Southern Caddo Area: Quiddity of shape for Hickory Engraved bottles

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Abstract

This study expands upon a previous analysis of the Clarence H. Webb collection that resulted in the identification of two bottle shapes used in the manufacture of the Hickory Engraved type. The current sample of Caddo bottles adduces three-dimensional meshes from the Hickory Engraved specimens in the Webb collection, and 14 new meshes from six sites and one collection. Results confirm that in some cases Hickory Engraved bottle shapes differ significantly by site, that the two shapes identified in the Webb collection persist in this larger sample, and that morphological integration is not significant, meaning that those traits used to characterise bottle shape (rim, neck, body, and base) were not found to vary in a coordinated manner. Thus, these results do not support the hypothesis that Caddo potters adhered to a template of vessel shape associated with specific decorative motifs. When combined with the Webb sample, iterative improvements are achieved, and results demonstrate a general trend toward standardisation in Caddo bottle shapes through time.

Keywords: American Southeast, 3D, geometric morphometrics, morphological disparity, morphological integration

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1. Introduction

The adoption of geometric morphometric (GM) methods by the archaeological community provides access to analytical tools that yield valuable insights into questions of artefact shape. The contribution of morphology to the anatomisation of Caddo ceramics has taken many forms over the years, and spans a wide range of quantitative (Turpin et al., 1976; Turpin & Neely, 1977; Selden Jr., 2017, 2018a,b; Selden Jr. et al., 2014) and qualitative treatments (Krieger, 1946, 1947; Perttula, 2015). In addition to vessel shape, allusions to the contribution of allometry in Caddo vessels have been posited, which may have utility in demarcating between adult and juvenile or infant sepultures (Perttula, 2000).

Taxonomic definitions for Caddo ceramics integrate semiotics and morphology (Suhm & Jelks, 1962; Suhm et al., 1954), and each type is characterised by a variety of vessel shapes that often includes bottles, bowls, carinated bowls, ollas, and others. The Hickory Fine Engraved (now Hickory Engraved) type was defined by Newell & Krieger (1949) at the George C. Davis site (41CE19) in northeast Texas, and is believed to date to the Formative Caddo period (CE 800-1000); although, others working in the region now prefer a broader temporal span from the Formative to Early Caddo periods (CE 850-1200; Perttula, personal communication), or ranging from Formative to Middle Caddo periods (CE 800-1450; Girard, personal communication). Defined as "a vessel with a spheroid or oval body, surmounted by a slender, cylindrical neck," Caddo bottles were initially seen as a somewhat homogeneous ceramic form (Harrington, 1920, 187); some with shapes and decorative motifs so similar that they were deemed to be the work of a single maker (Harrington, 1920, 188). In a more recent study, Caddo bottles were found to be more symmetrical than bowls and ollas (Selden Jr., 2017); however, additional work is needed to identify whether—and to what extent—this holds true across an expanded range of categories and types (Selden Jr., 2018b). A qualitative evaluation of Caddo vessel shapes proposed a division of the Caddo bottle category into 27 shapes for the northeast Texas region (Perttula, 2015, Figure 2).

This effort capitalises upon the variation in Caddo bottle morphology that occurs across the Hickory Engraved (HE) type. Morphological variability for HE bottles included in the Webb study demonstrated two shapes that were possibly delimited by geography (Selden Jr., 2018b). This study expands the sample to include three-dimensional (3D) meshes for the Webb Collection and 14 new samples from six sites and one collection (Table 1 and Figure 1) used to test whether a significant difference in shape exists for HE bottles by site, followed by a test of morphological integration. The pairwise test of morphological integration provides a means of assessing whether Caddo potters adhered to a template of vessel shape associated with a specific decorative motif (Early, 2012). If the sample is significantly integrated, then this test would provide support for that hypothesis; if not, then the hypothesis should be rejected.

Figure 1: Locations of Allen Plantation, Hatchel, Belcher Mound, Crenshaw Mound, Frank Norris Farm, Gahagan Mound, George C. Davis, Haley Place, Mustang Creek Mound (also known as T. N. Cole), Paul Mitchell (Mitchell), specimens from the Pohler Collection (Clark County, Arkansas), and Smithport Landing.

Table 1: Caddo bottles used in the analyses.

Vessel No	Site Name	Trinomial	Context	Repository	Type
142	Allen Plantation	16NA6	Unknown	WMNSU	Hickory Engraved
269	Belcher Mound	16CD13	Burial 5	WMNSU	Belcher Engraved
361	Belcher Mound	16CD13	Burial 9	WMNSU	Belcher Engraved
363	Belcher Mound	16CD13	Burial 10	WMNSU	Belcher Engraved
404	Belcher Mound	16CD13	Burial 11	WMNSU	Hickory Engraved
405+	Belcher Mound	16CD13	Burial 11	WMNSU	Hickory Engraved
430+	Belcher Mound	16CD13	Burial 12	WMNSU	Hickory Engraved
775	Belcher Mound	16CD13	Burial 15	WMNSU	Belcher Engraved
788	Belcher Mound	16CD13	Burial 15	WMNSU	Belcher Engraved
805	Belcher Mound	16CD13	Burial 15	WMNSU	Belcher Engraved
845	Belcher Mound	16CD13	Burial 17	WMNSU	Belcher Engraved
852	Belcher Mound	16CD13	Burial 17	WMNSU	Keno Trailed
897	Belcher Mound	16CD13	House 6	WMNSU	Belcher Engraved
997	Belcher Mound	16CD13	Burial 24	WMNSU	Belcher Engraved
1073	Belcher Mound	16CD13	House 6	WMNSU	Taylor Engraved
955	Gahagan Mound	16RR1	Mound A	WMNSU	Hickory Engraved
95	Smithport Landing	16DS4	Burial 1	WMNSU	Smithport Plain
96	Smithport Landing	16DS4	Burial 1	WMNSU	Hickory Engraved
152	Smithport Landing	16DS4	Burial 10	WMNSU	Smithport Plain
No #	Smithport Landing	16DS4?	Unknown	WMNSU	Hickory Engraved
956	Gahagan Mound	16RR1	Mound A	LSUMNS	Hickory Engraved
2002-01-20*	Unknown (Clark County, Arkansas)	Pohler Coll	Unknown	CNO	Hickory Engraved
2002-01-23*	Unknown (Clark County, Arkansas)	Pohler Coll	Unknown	CNO	Hickory Engraved
55-1-8*	Crenshaw Mound	3MI6	Unknown	CNO	Hickory Engraved
FS7	Hatchel	41BW3	Unknown	TARL	Hickory Engraved
6-2-132	Paul Mitchell	41BW4	Unknown	TARL	Hickory Engraved
341-427	Paul Mitchell	41BW4	Burial 9	TARL	Hickory Engraved
341-464	Paul Mitchell	41BW4	Burial 21	TARL	Hickory Engraved
7	Frank Norris Farm	41RR2	Unknown	TARL	Hickory Engraved
2	Mustang Creek Mound	41RR3	H. O. #568	TARL	Hickory Engraved
2015-1	George C Davis	41CE19	Burial F-154	TARL	Hickory Engraved
HFE1	Haley Place	3MI1	Unknown	LSEM	Hickory Engraved
HFE2	Haley Place	3MI1	Unknown	LSEM	Hickory Engraved
HFE3	Haley Place	3MI1	Unknown	LSEM	Hickory Engraved
HFE4	Haley Place	3MI1	Unknown	LSEM	Hickory Engraved
HFE5	Haley Place	3MI1	Unknown	LSEM	Hickory Engraved

*The bottle without a number (Webb Collection) is assumed to have come from the Smithport Landing site in fragments. The bottle was later reassembled, but a number was never assigned. + = base/body morphology only; * = repatriated to the Caddo Nation of Oklahoma. WMNSU = Williamson Museum Northwestern State University; LSUMNS = Louisiana State University Museum of Natural Science; CNO = Caddo Nation of Oklahoma; TARL = Texas Archeological Research Laboratory; LSEM = Louisiana State Exhibit Museum.*

All Caddo bottles used in this analysis, excepting those from House 6 at the Belcher Mound site (Table 1), fall under the purview of the Native American
 45 Graves Protection and Repatriation Act (NAGPRA). Permission to scan these collections was provided by the Caddo Nation of Oklahoma with the provision that only those scan data without the texture (colour) file could be used in the analysis. Full-resolution scan data were forwarded to the Caddo Nation of Oklahoma with the texture applied. This provides the Caddo Nation of
 50 Oklahoma with an accurate 3D record of each vessel and a means of viewing this widely-distributed collection as a whole.

2. Methods

Bottles were scanned with a Creaform GoSCAN 50 at a 0.8 mm resolution or a Creaform GoSCAN20 at 0.5 mm resolution in VXelements depending on
 55 their size. Scanner calibration was optimised prior to each scan, with positioning targets required for increased accuracy, and shutter speed reconfigured in each instance. A clipping plane was established to reduce the amount of superfluous data collected during each scan. Following data collection, resolution for the GoSCAN 50 meshes was increased to 0.5 mm, and the point clouds from
 60 both scanners were transferred to VXmodel where the mesh was rendered following application of the *clean mesh* function, used to remove isolated patches, self-intersections, spikes, small holes, singular vertices, creased edges, narrow triangles, outcropping triangles, narrow bridges, and non-manifold triangles prior to export as an ASCII stl and ASCII ply. The stl functions as a backup, and
 65 the ply was subsequently imported to Geomagic Design X (Dx).

In advance of pursuing an analysis that employed data from two different scanners, two meshes of the same object—produced with the Creaform GoSCAN 50 and GoSCAN 20—were imported to a computer-aided inspection program (Geomagic Control X) to identify any significant deviations that may exist be-
 70 tween them (Figure 2). The tolerance level for the inspection was selected by using the highest resolution of the GoSCAN 20 (0.1 mm). Small areas of the rim

exhibit minor differences and the remainder of the vessel is within the arbitrary 0.1 mm tolerance, thus results of the inspection fall within an acceptable error range.

Result Data - 1: 3D Compare1

Product Name	41BW4-341-464	Department	CRHR	Date	Mar 11, 2018
Part Name	41BW4_341-464	Inspector	Selden	Unit	mm

Figure 2: Results of 3D compare for the GoSCAN 50 and GoSCAN 20 meshes of HE bottle 41BW4 341-464 indicating that 99.6905 percent of the vessel falls within the arbitrary 0.1 mm tolerance.

75 The histogram shown in Figure 2 illustrates the Gaussian distribution for the number of errors over the whole deviation. The graph is split into six segments: 1-Sigma at 31 percent from the average to the maximum deviation in each direction, 2-Sigma at 69 percent from the average to the maximum deviation in each direction, and 3-Sigma at 93.3 percent from the average to the maximum deviation in each direction. The average (AVG) is the sum of all deviations divided by the number of all deviations, and the RMS is the square root of all squared deviations divided by the number of all deviations (sometimes referred to as the effective deviation). In tolerance (In Tol) and out

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tolerance (Out Tol) percentages indicate the percentage of deviations in or out
85 of a given tolerance, and over tolerance (Over Tol) and under tolerance (Under
Tol) percentages indicate the percentage of deviations over (positive direction)
or under (negative direction) the tolerance range by the mesh normal of the
reference mesh.

2.1. Alignment and reference geometry

90 Following transfer to Dx, each mesh was subjected to an additional qual-
ity check to eliminate non-manifold poly-vertices, folded poly-faces, dangling
poly-faces, small clusters, small poly-faces, non-manifold poly-faces, crossing
poly-faces, and small tunnels. Due to the paucity of homologous landmarks on
cultural artefacts (Lycett, 2009), reference geometry was constructed around
95 each vessel in a manner that yields a replicable configuration of nine landmarks,
and 46 equidistant semilandmarks along the widest vessel profile, with notable
similarities to previous landmark configurations used by Gिररुलत (2006, Figure
4), Selden Jr. (2018b, Figure 2), Selden Jr. et al. (2014, Figure 5), and Topi
et al. (2017, Figure 4). The current constellation of landmarks and semiland-
100 marks expresses some degree of influence from Birkhoff (1933), where utility
was found in his use of characteristic points and tangents.

The first component of reference geometry added, and principal assumption,
was a reference vector. A sampling ratio of 100 percent was used to apply the
reference vector on a revolving axis, after which a reference point was added by
105 projecting it atop the mesh surface at the location where the reference vector
exits the base of the vessel. A reference plane was inserted using the *pick multiple
points* function, by adding a series of 10 points around the circumference of the
bottle’s base. Each element of reference geometry (vector, point, and plane) was
then used in an interactive 3-2-1 alignment where the vessel was aligned to a
110 global origin, orienting it in 3D space where it sits upright atop a planar surface
(assumed to be the intent of the maker). Following alignment, the reference
plane and point were deleted.

The widest profile is defined as the location on the mesh that lies farthest

from that point where the reference vector exits the base while oriented atop the
115 planar surface. To identify that location, a mesh sketch was generated with the
planar method using the plane at the base of the vessel to identify and sketch
the widest vessel circumference. By using the plane at the base of the vessel for
the sketch, the point at which the reference vector exits the mesh remains linked
120 to the remainder of the reference geometry. A circle is then sketched using the
vector as the centre, extending outward until the whole of the vessel fits within.
Using the mesh sketch, a cylinder (surface) is extruded around the vessel. The
accuracy analyzer in Dx is then used to identify the point on the vessel with the
lowest deviation from the extruded surface, and a plane (MPlane) is inserted
coplanar to the vector and oriented to the widest point, bisecting the vessel
125 along the widest profile.

Using the MPlane as the basis for a second mesh sketch, a spline with 15
interpolation points is sketched on one rim. Above that sketch, a horizontal
line is added, and both the spline and horizontal line are used to determine the
horizontal tangent of the rim. A vertical line is subsequently added that bisects
130 the rim at the location of the tangent. This operation is repeated for the op-
posing rim. The logic behind this added step is that the surface scanner cannot
reach the interior of the vessel, so the spline needed to be cut in a replicable
location. Since the HE bottles have direct (vertical) rims, the preceding step
was extended to include one additional measure. A line was drawn between each
135 rim tangent, then a second from the intersection of the line and reference vector
to a point 10 mm down the vector, where a horizontal line (parallel with the rim
peaks) was inserted that intersects with both external walls of the vessel. It is
at this intersection that the final mesh sketch was cut to discriminate between
the neck and rim. While this step admittedly appears odd in the context of
140 a comparison of bottle shapes that all exhibit direct rims, it is of considerable
import for inter-type comparisons where other bottle types exhibit differing rim
morphologies (i.e., everted, etc.).

Using the MPlane as the basis for a third sketch, a spline was populated for
the entirety of the silhouetted profile. That spline was split at the location of the

145 horizontal tangent on each rim, and the remaining sections that continue into
the bottle interior were deleted. The second split was added at the intersection
of the spline and reference vector (centre of base). Four additional splits were
then added at the juncture of the base/body and body/neck on each side of the
vessel at the points of highest curvature. The point of highest curvature used
150 to split the spline was identified using the *curvature* function in Dx, and does
not represent an arbitrary location.

2.2. Landmarks and semilandmarks

A total of nine landmarks and 46 semilandmarks divide each bottle into four
discrete components corresponding with the rim, neck, body, and base (Table 2
155 and Figure 3). Landmarks and semilandmarks are populated along the spline,
always beginning on the side of the profile determined to include the widest
point. Divisions between each component articulate with those of the spline
splits, where landmarks were placed at each of the points in Table 2, with a
series of equidistant semilandmarks between.

Figure 3: Spline splits for discrete components (rim, neck, body, and base) used in the GM analysis (left) segregated by landmarks (blue), with equidistant semilandmarks (white) populated between (right).

160 While sliding semilandmarks were an early consideration of this research
design, the choice to use equidistant semilandmarks rather than sliding semi-
landmarks is based upon results from an earlier iteration of the Webb collection
analysis (Selden Jr., 2018b, Figure 3). The first landmark and sliding semiland-

Table 2: Landmarks used in this analysis.

Landmark	Location	Definition
Point01	Rim peak	Horizontal tangent of rim curvature on widest side of vessel
Point06	Rim/Neck	Point of highest curvature (everted rim) or intersection of horizontal line 10 mm below rim tangents (direct rim)
Point15	Neck/Body	Point of highest curvature
Point24	Body/Base	Point of highest curvature
Point28	CentreBase	Intersection of vector and external surface of the 3D mesh.
Point32	Body/Base	Point of highest curvature
Point41	Neck/Body	Point of highest curvature
Point50	Rim/Neck	Point of highest curvature (everted rim) or intersection of horizontal line 10 mm below rim tangents (direct rim)
Point55	Rim peak	Horizontal tangent of rim curvature

mark configuration did not split the spline between the neck and rim, and when
165 mean shapes were generated for each type, an anomaly (from the everted rims
of Belcher Engraved bottles, in that case) was added to the otherwise direct or
tapered necks of the HE and Smithport Plain bottles. Given that the use of
sliding semilandmarks could potentially influence the results of this analysis by
adding a component of morphology to specimens where it does not exist, they
170 were abandoned.

2.3. Analysis

Landmarks and equidistant semilandmarks were exported as x,y and z co-
ordinate data from Dx. Those data were aligned to a global coordinate system
(Kendall, 1981, 1984; Slice, 2001), achieved through generalised Procrustes su-
175 perimposition (Rohlf & Slice, 1990) performed in R 3.4.4 (R Core Development
Team., 2017) using the *geomorph* library v.3.0.5 (Adams et al., 2017; Adams &
Otárola-Castillo, 2013). Procrustes superimposition translates, scales, and ro-
tates the coordinate data to allow for comparisons among objects (Gower, 1975;
Rohlf & Slice, 1990). The *geomorph* package uses a partial Procrustes superim-
180 position that projects the aligned specimens into tangent space subsequent to
alignment in preparation for the use of multivariate methods that assume linear

space (Rohlf, 1999; Slice, 2001).

Principal components analysis (Jolliffe, 2002) was used as an exploratory means of visualising shape variation among the bottles. The shape changes
185 described by each principal axis are commonly visualised using thin-plate spline warping of a reference 3D mesh (Klingenberg, 2013; Sherratt et al., 2014). A residual randomisation permutation procedure (RRPP; $n=1000$ permutations) was used for all Procrustes ANOVAs (Adams & Collyer, 2015), which has higher statistical power and a greater ability to identify patterns in the data should
190 they be present (Anderson & Ter Braak, 2003). To assess whether shape differs by site, Procrustes ANOVAs (Goodall, 1991) were run that also enlist effect-sizes (z-scores) computed as standard deviates of the generated sampling distributions (Collyer et al., 2015).

A Procrustes ANOVA and pairwise test was used to identify sites where
195 bottle shapes and forms differ. The pairwise test is conceptually similar to trajectory analysis (Adams & Collyer, 2007, 2009; Collyer & Adams, 2007, 2013) in that pairwise statistics are vector lengths between vectors, but differs since a factorial model is not explicitly needed to contrast vectors between point factor levels nested within group factor levels (Adams et al., 2017). Procrustes
200 variance was used to discriminate between groups and compare the amount of shape variation (morphological disparity) across communities (Zelditch et al., 2004), which is estimated as the Procrustes variance using residuals of linear model fit (Adams et al., 2017).

Morphological integration was assessed for the sample of HE vessels. Inte-
205 gration between pairs of traits was tested using a two-block partial least-squares (2B-PLS) analysis to evaluate relationships for two blocks of variables collected from the same specimens (Bookstein et al., 2003; Rohlf & Corti, 2000; Wold, 1966), using shape coordinates in all blocks of variables (Bastir & Rosas, 2006; Bookstein et al., 2003; Gunz & Harvati, 2007). To assess whether the different
210 modules (RIM_{neck} , $NECK_{body}$, and $BODY_{base}$ in particular) are integrated, a two-sample test using effect sizes calculated as standard deviates in sampling distributions from the 2B-PLS analyses were used to determine the significance

and strength of integration between the modules (Adams & Collyer, 2016).

Following analysis of the HE bottle sample, those data were added to the
215 aggregated sample to identify and expound upon global trends. Procrustes
ANOVAs were used to identify bottle types that might be said to differ sig-
nificantly. Morphological disparity was used to test whether specific types of
Caddo bottles occupy a significantly smaller range of morphospace than others,
providing evidence for morphological standardisation through time. An addi-
220 tional test of morphological disparity for Caddo bottles was subsequently run
by temporal period.

3. Results

The mean consensus configuration and Procrustes residuals were calculated
using a generalised Procrustes analysis (GPA) for the aggregated sample (Mit-
225 teroecker & Gunz, 2009, Figure 3) (Figure 4). This initial view of the data
demonstrates the degree of variability in HE bottles that occurs across the sam-
ple. As an exploratory measure, GM methods—to include GPA—aid in clari-
fying shape differences, and in the production of novel *a posteriori* hypotheses
(Mitteroecker & Gunz, 2009).

230 Principal components analysis (PCA) was conducted on scaled, translated,
and rotated landmarks, and demonstrate that the first two PCs account for
roughly 71.5 (PC1) and 13.6 (PC2) percent of the variation in bottle shape
(Table 3 and Figure 5). Together, PC1 and PC2 account for 85.1 percent of
shape variation in HE bottles, with each remaining PC representing less than
235 seven percent of the variation (Table 3). The first two PCs are plotted in Figure
5, where warp grids represent the shape changes along PC1. This plot indicates
that shape changes associated with PC1 articulate most readily with neck and
body shape. Those shape changes associated with PC2 are also dominated by
differences in bottle neck and body shape.

240 A Procrustes ANOVA was used to test for a significant difference in HE
bottle shape by site, and indicates a significant difference in HE bottle shape by

Figure 4: Results of generalised Procrustes analysis for the HE sample. Mean consensus configuration shown in black; samples in gray.

site ($RRPP = 1000$; $Rs_q = 0.77985$; $Pr(>F) = 0.007$). A Procrustes ANOVA and pairwise comparison was then used to identify which sites differ significantly in shape, and whether that difference is in magnitude, direction, or both (Table 4). Those sites with samples found to differ significantly include Gahagan Mound and Belcher Mound, Gahagan Mound and Crenshaw Mound, Gahagan Mound and Haley Place, Gahagan Mound and Paul Mitchell, Gahagan Mound and the Pohler Collection, Smithport Landing and Paul Mitchell, and Smithport Landing and the Pohler Collection.

A 2B-PLS analysis was used to test for morphological integration between combinations of the components (rim, neck, body, and base). Results indicate significant integration between the rim and neck (1000 random permutations, $r_{PLS} = 0.974$, $P\text{-value} = 0.001$), rim and body (1000 random permutations, $r_{PLS} = 0.966$, $P\text{-value} = 0.001$), rim and base (1000 random permutations, $r_{PLS} = 0.839$, $P\text{-value} = 0.001$), neck and body (1000 random permutations, $r_{PLS} = 0.965$, $P\text{-value} = 0.001$), neck and base (1000 random permutations, $r_{PLS} = 0.934$, $P\text{-value} = 0.001$), and body and base (1000 random permutations, r_{PLS}

Table 3: Results of principal components analysis for first 10 PCs (> 99 percent of total variance explained).

	SD	PVE	CVE
PC1	0.09488	0.71506	0.71506
PC2	0.04138	0.13598	0.85104
PC3	0.02928	0.06812	0.91916
PC4	0.02382	0.04507	0.96423
PC5	0.01203	0.01150	0.97573
PC6	0.01001	0.00796	0.98370
PC7	0.008698	0.006010	0.989710
PC8	0.006896	0.003780	0.993480
PC9	0.00507	0.00204	0.99552
PC10	0.004659	0.001720	0.997250

SD - standard deviation; PVE - percentage variance explained; CVE - cumulative variance explained.

Figure 5: Results of PCA summarising shape variation in the HE sample.

Table 4: P-values, effect sizes, and least-squares means distance matrix for advanced Procrustes ANOVA and pairwise test (RRPP = 1000) of HE bottle shape by site.

	Allen	Belcher	Crenshaw	FNF	Gahagan	GCD	Haley	Hatchell	Mitchell	MCM	Pohler	Smithport
Allen	1.0000 <i>0.0000000</i> (0.00000000)											
Belcher		1.0000 <i>0.3180215</i> (0.16516413)										
Crenshaw			1.0000 <i>0.2695194</i> (0.16112756)									
FNF				1.0000 <i>0.8955</i> (0.12180959)								
Gahagan					1.000 <i>0.0490</i> (0.0969601)							
GCD						1.000 <i>0.3780</i> (0.1547562)						
Haley							1.000 <i>0.2920</i> (0.13440033)					
Hatchell								1.0000 <i>0.6530</i> (0.11689981)				
Mitchell									1.000 <i>0.8970307</i> (0.16184198)			
MCM										1.0000 <i>0.6560</i> (0.14459067)		
Pohler											1.000 <i>0.0920</i> (0.11576771)	
Smithport												1.000 <i>1.4388538</i> (0.20151407)
												<i>0.0000000</i> <i>0.9210</i> (0.18838326)
												<i>0.0000000</i> <i>1.1654711</i> (0.06292918)

Significant differences in bold; effect sizes (z) in italics; LS means distance matrix in parentheses; FNF = Frank Norris Farm; GCD = George C. Davis; MCM = Mustang Creek Mound.

= 0.933, P-value = 0.001) for bottles in the sample (Figure 6). A pairwise test of morphological integration was used to identify suites of traits that can be said to covary (Table 5). The pairwise test of morphological integration for the HE sample reveals that no combination of the suites of traits used in the manufacture of HE bottles can be said to vary in a coordinated manner. Thus, while pairs of HE bottle attributes can be said to be morphologically integrated, the suites of HE bottle components are not.

Table 5: P-values and effect sizes for morphological integration of trait suites. All results based on 1000 random permutations.

	RIM _{neck}	RIM _{body}	RIM _{base}	NECK _{body}	NECK _{base}	BODY _{base}
RIM _{neck}	1.0000000 (0.0000000)					
RIM _{body}	0.2982163 (0.5295376)	1.0000000 (0.0000000)				
RIM _{base}	0.1501732 (1.0356908)	0.3012915 (0.52068968)	1.0000000 (0.0000000)			
NECK _{body}	0.2812790 (0.5790463)	0.4820211 (0.04508159)	0.3152516 (0.4810187)	1.0000000 (0.0000000)		
NECK _{base}	0.3174451 (0.4748551)	0.4836780 (0.04092468)	0.2919756 (0.5476225)	0.4660765 (0.08513646)	1.0000000 (0.0000000)	
BODY _{base}	0.1675077 (0.9640607)	0.3321982 (0.43385131)	0.4603731 (0.0994939)	0.3473903 (0.39237570)	0.3215232 (0.46344371)	1.0000000 (0.0000000)

Pairwise differences in PLS effect size in parentheses.

3.1. Synthesis of HE bottles with aggregated sample

The mean consensus configuration and Procrustes residuals were calculated using a GPA for the aggregated sample (Figure 7). PCA was conducted on scaled, translated, and rotated landmarks, and demonstrate that the first two PCs account for roughly 59 (PC1) and 20.3 (PC2) percent of the variation in bottle shape (Table 6 and Figure 8). Together, PC1 and PC2 account for 79.4 percent of shape variation in the aggregated sample, with each remaining PC representing less than eleven percent of the variation (Table 6). The first two

Figure 6: Results of 2B-PLS analyses for pairs of morphological components; (a) rim and neck, (b) rim and body, (c) rim and base, (d) neck and body, (e) neck and base, and (f) body and base.

PCs are plotted in Figure 8, where warp grids represent the shape changes along PC1. This plot indicates that shape changes associated with PC1 articulate
 275 most readily with rim, neck, and body shape. Those shape changes associated with PC2 are also dominated by differences in rim, neck, and body shape.

Figure 7: Results of GPA for the aggregated sample. Mean consensus configuration shown in black; samples in gray.

A Procrustes ANOVA was used to test for a significant difference in Caddo bottle shape by size (RRPP = 1000; Rsq = 0.19971; $\Pr(>F) = 0.001$). A second Procrustes ANOVA was used to test for a significant difference in Caddo bottle
 280 shape by type (RRPP = 1000; Rsq = 0.41129; $\Pr(>F) = 0.001$), which was followed by a Procrustes ANOVA and pairwise comparison used to identify which types differ significantly in shape, and whether that difference is in magnitude, direction, or both (Table 7).

A test of morphological disparity indicates that Hickory Engraved and Smith-
 285 port Plain bottles display a greater range of shape variation among individuals relative to other groups, and differ significantly from the Belcher Engraved and Taylor Engraved bottles (Table 8). In a subsequent test, the Formative-Early Caddo bottles (Hickory Engraved and Smithport Plain) were found to encom-

Table 6: Results of PCA for the first 10 PCs (> 99 percent of total variance explained).

	SD	PVE	CVE
PC1	0.09246	0.59053	0.59053
PC2	0.05433	0.20389	0.79442
PC3	0.03994	0.11020	0.90463
PC4	0.02350	0.03814	0.94276
PC5	0.01773	0.02172	0.96449
PC6	0.01305	0.01176	0.97624
PC7	0.009666	0.006450	0.982700
PC8	0.008099	0.004530	0.987230
PC9	0.006923	0.003310	0.990540
PC10	0.006142	0.002610	0.993140

SD - standard deviation; PVE - percentage variance explained; CVE - cumulative variance explained.

Table 7: P-values, effect sizes, and least-squares means distance matrix for for advanced Procrustes ANOVA and pairwise test (RRPP = 1000) of shape by type.

	Belcher Eng	Hickory Eng	Keno Tr	Smithport Pl	Taylor Eng
Belcher Eng	1.000 <i>0.0000000</i> (0.00000000)				
Hickory Eng	0.001 <i>4.3918490</i> (0.11446991)	1.000 <i>0.0000000</i> (0.00000000)			
Keno Tr	0.031 <i>2.3403817</i> (0.17142455)	0.001 <i>3.974456</i> (0.22630873)	1.000 <i>0.0000000</i> (0.00000000)		
Smithport Pl	0.001 <i>3.6675308</i> (0.21608391)	0.045 <i>2.017590</i> (0.15298269)	0.006 <i>3.141604</i> (0.2706105)	1.000 <i>0.0000000</i> (0.00000000)	
Taylor Eng	0.717 <i>-0.6707131</i> (0.04607309)	0.155 <i>1.039303</i> (0.08509648)	0.046 <i>1.936829</i> (0.1758952)	0.041 <i>1.980969</i> (0.1774856)	1.000 <i>0.0000000</i> (0.00000000)

Significant differences in bold; effect sizes (z) in italics, LS means distance matrix in parentheses.

Figure 8: Results of PCA summarising shape variation in the aggregated sample, where red = Hickory Engraved, dark blue = Smithport Plain, green = Keno Trailed, light blue = Taylor Engraved, and black = Belcher Engraved.

pass a significantly greater range of morphological variability than the Late-
 290 Historic Caddo bottles (Belcher Engraved, Keno Trailed, and Taylor Engraved)
 in the aggregated sample (Table 9).

4. Discussion

Three dimensional meshes were used as the basis for a GM analysis of HE
 bottle shapes from 10 sites and one collection. This study builds upon results
 295 from a previous GM study of the Webb collection, confirms that the posited dif-
 ferences in HE bottle shape identified between the Belcher Mound and Gahagan
 Mound, Smithport Landing, and Allen Plantation sites are more widespread,
 highlighting site-specific and (north-south; above/below the confluence of Cy-
 press Bayou and the Red River) geographic variability for the type (Table 4 and
 300 Figure 9). The pairwise test of morphological integration was not significant
 (Table 5), thus the hypothesis that Caddo potters adhered to a template of

Table 8: P-values and pairwise absolute differences between variances for a test of morphological disparity by type (RRPP = 1000).

	Belcher Eng	Hickory Eng	Keno Tr	Smithport Pl	Taylor Eng
Belcher Eng	1.000 (0.0000000000)				
Hickory Eng	0.002 (0.0089995247)	1.000 (0.0000000000)			
Keno Tr	0.900 (0.0009174212)	0.072 (0.009916946)	1.000 (0.0000000000)		
Smithport Pl	0.021 (0.0134728788)	0.495 (0.004473354)	0.087 (0.0143903000)	1.000 (0.0000000000)	
Taylor Eng	0.796 (0.0012076110)	0.049 (0.007791914)	0.732 (0.0021250322)	0.070 (0.012265268)	1.000 (0.0000000000)

Significant results in bold; pairwise absolute differences between variances in parentheses.

Table 9: P-values and pairwise absolute differences between variances for a test of morphological disparity by period (RRPP = 1000).

	Formative-Early	Late-Historic
Formative-Early	1.00 (0.000000)	
Late-Historic	0.016 (0.007825053)	1.00 (0.000000)

Significant results in bold; pairwise absolute differences between variances in parentheses.

vessel shape associated with specific decorative motifs must be rejected for this sample.

Figure 9: Comparison of mean shapes for sites where HE assemblages were found to differ significantly; a, Gahagan Mound (gray) and Belcher Mound; b, Gahagan Mound (gray) and Crenshaw Mound; c, Gahagan Mound (gray) and Haley Place; d, Gahagan Mound (gray) and Paul Mitchell; e, Gahagan Mound (gray) and Pohler Collection; f, Smithport Landing (gray) and Paul Mitchell; and g, Smithport Landing (gray) and Pohler Collection. These differences in HE bottle shapes articulate with the northern (Belcher Mound, Crenshaw Mound, Haley Place, Paul Mitchell, and Pohler Collection) and southern (Gahagan Mound and Smithport Landing) communities of practice.

Results suggest that the shape of HE bottles may be protean, indicating that
 305 variability in Caddo bottle shape was not prescribed, but labile. Spatial differences
 apparent in HE bottle morphology indicate a possible cultural integument
 for which the etiology remains unclear. The extent to which this division in bottle
 shape may be supported by other types and categories of Caddo material
 culture is unknown; although, results from the previous study of the Webb Col-
 310 lection indicate that Smithport Plain bottle shapes articulate with a similar
 shift in morphology across the same geographic area. The spatial differences

may articulate with differences in HE bottle production; however, the contribution of time remains ill-understood and the putative origin and temporal range for the HE type is not well defined due to a lack of chronometric dates from
315 residues found in HE bottles or contexts from which they were recovered. It is possible that one of the HE bottle shapes represents an earlier manifestation of the type and the other is subsequent; though it is also entirely possible that these two industries were in operation simultaneously.

Efforts to broaden this study through the addition of more samples may aid
320 in further clarifying nuances associated with the variability demonstrated here, which highlight significant differences in the manufacture of HE bottle shape that are dominated largely by geography. The most noticeable differences occur between the bottle bodies and necks of the north-south sample, which generally present as round or pear-shaped in the northern sites and sub-globular in the
325 south, with the juncture of the body and neck evidenced by a more obtuse angle in the north, a (relatively) thinner base of the bottle neck at the neck-body juncture that reduces the amount that HE bottle necks contract toward the rim, and a shorter neck (Figure 9).

4.1. Synthesis with the aggregated sample

330 In coadunating the HE sample with data from the Webb collection (Selden Jr., 2018b), a broader analysis of Caddo bottle shapes can be considered. The aggregated sample is representative of two periods; one Formative-Early (HE and Smithport Plain), and the other Late-Historic (Belcher Engraved, Keno Trailed, and Taylor Engraved). The advanced Procrustes ANOVA and pairwise
335 test demonstrates some significant differences between the types (Table 7). Through the addition of 14 HE bottles, the Formative-Early bottle types in the sample were found to differ significantly in shape, demonstrating the utility of continued iterative improvements to interpretation (Figure 10). These results can be contrasted with those from the previous analysis of the Webb collection, where the Formative-Early bottles were not found to differ significantly
340 in shape (Selden Jr., 2018b, Table 5). Additionally, it was found that a Late-

Historic type, Taylor Engraved, does not differ significantly from HE but does differ significantly from Smithport Plain, representing an about-face from the previous analysis (Selden Jr., 2018b, Table 5) (Table 7 and Figure 10).

Figure 10: Comparison of mean bottle shapes by type for those types found to differ significantly (Table 7); (a) Belcher Engraved (gray) and Hickory Engraved, (b) Belcher Engraved (gray) and Keno Trailed, (c) Belcher Engraved (gray) and Smithport Plain, (d) Hickory Engraved (gray) and Keno Trailed, (e) Hickory Engraved (gray) and Smithport Plain, (f) Keno Trailed (gray) and Smithport Plain, (g) Keno Trailed (gray) and Taylor Engraved, and (h) Smithport Plain (gray) and Taylor Engraved.

Results from the test of morphological disparity also differ from the initial analysis; however, to a lesser degree (Table 8). In this analysis, the HE bottles occupy a significantly greater range of morphospace than the Taylor Engraved bottles, and the Smithport Plain bottles still occupy a greater range of morphospace than the Belcher Engraved bottles in following with the analysis of the Webb collection, but not the Keno Trailed or Taylor Engraved bottles (Selden Jr., 2018b, Table 6) (Table 8). However, the test of morphological disparity by period confirms that the Late-Historic Caddo bottles still occupy a (significantly) more restricted range of morphospace when compared to those

from the Formative-Early period.

355 4.2. Morphological standardisation

The morphological attributes employed in this analysis are interpreted to be representative of *intentional attributes* related to morphological characteristics of vessel function (Costin, 2005); the rim, neck, body, and base of Caddo bottles in this instance. The sample of bottles from the Late-Historic period warrants
360 expansion to further test whether—and to what extent—bottle morphology can be said to be restricted. Expansion of the HE sample, and the subsequent analysis of Smithport Plain bottle morphology (Selden Jr., 2018a), extends those findings from the initial study (Selden Jr., 2018b), shifting the interpretation from one of north-south production differences for HE and Smithport Plain
365 bottles to one of differential production for the two types. Additionally, through coadunating the HE bottles with the larger sample, a possible trend toward standardisation is posited that warrants further testing as sample sizes from the differing temporal periods are increased.

Standardisation is relative (Costin, 2001; Sinopoli, 1988), is seen as a cultural marker that may have utility in a variety of interpretations, and attempts
370 to measure standardisation have been made using a variety of variables (Junker, 1993). "Standardization refers to homogeneity in ceramic materials, vessel shape, and/or decoration" (Costin & Hagstrum, 1995, 622), while diversity "can be most generally considered as the opposite of standardization" (Rice,
375 1991, 273). Attributes associated with standardisation may prove dynamic, potentially indicating periods of standardised production as well as periods of creativity and innovation that more readily articulate with diversity (Kenoyer et al., 1991). In production contexts, standardisation may be seen as the result of minimised labour costs and improvements in efficiency (Sinopoli, 1988). Both
380 standardisation and diversity have utility in characterising tolerance, where a greater range of shapes may be indicative of a higher tolerance, and a lower tolerance by a decrease in variation (Erkins & Bettinger, 2001). However, the various functional types and size classes used by prehistoric societies can be a

substantive challenge to parse properly from the etic perspective of the archae-
ologist (Longacre et al., 1988).

Morphological disparity aided in clarifying a general trend toward standard-
isation for this sample of Caddo bottles, and morphological integration high-
lighted those components (i.e., rim, neck, body, and base) and suites of compo-
nents that covary. The iterative improvement of these results will articulate with
the continued development of a dynamic data-driven interpretation of Caddo
bottle shapes. Given the absence of direct evidence for ceramic production in
the archaeological record of the Caddo, analysts must leverage indirect evidence
as a means of generating testable hypotheses. Those hypotheses, if they are to
be successful, should not be limited to a single class of artefact, should enlist
data for specimens from similar spatial and temporal contexts, and should be
supported by analyses at variable scales (Figure 11).

Figure 11: Scans of incised sherds (left with surface texture applied, and removed at right) collected with a 3D optical profilometer are being used in a study of variable Caddo tool (tip/bit) morphologies used to apply the incisions.

5. Conclusion

As sample sizes continue to increase, through the addition of more collections and new discoveries, interpretations should remain dynamic, and demonstrate

400 the many iterative improvements achieved throughout the life cycle of a long-term research design. Systematic comparative studies for aggregated samples of Caddo ceramics are necessary to comprehend the vagaries of vessel morphology. The morphological similarities and differences discussed above have utility in a wide range of research domains, and those bottles used in this analysis can
405 also provide indirect evidence that might be leveraged in studies of Caddo ceramic manufacture and production in the absence of known production areas. A pairwise comparison of morphological integration yielded results that are not significant, thus the hypothesis that Caddo potters adhered to a template of vessel shape associated with specific decorative motifs must be rejected. How-
410 ever, the results of morphological disparity, while differing from those produced in the earlier analysis of the Webb collection, still demonstrate a gradual trend toward standardisation from the Formative-Early to the Late-Historic Caddo periods.

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