

Perdiz arrow points from Caddo burial contexts aid in defining discrete behavioral regions

Robert Z. Selden 1 · John E. Dockall 2 ·

Received: date / Accepted: date

Abstract Recent research in the ancestral Caddo area has yielded evidence for distinct *behavioral regions*, across which material culture from Caddo burials—bottles and Gahagan bifaces—has been found to express significant morphological differences. This inquiry assesses whether Perdiz arrow points from Caddo burials, assumed to reflect design intent, may differ across the same geography, and extend the pattern of shape differences to a third category of Caddo material culture. Perdiz arrow points collected from the geographies of the northern and southern Caddo *behavioral regions* defined in a recent social network analysis were employed to test the hypothesis that morphological attributes differ, and are predictable, between the two communities. Results indicate significant between-community differences in maximum length, width, stem length, and stem width, but not thickness. Using the same traditional metrics combined with the tools of machine learning, a predictive model—support vector machine—was designed to assess the degree to which community differences could be predicted, achieving a receiver operator curve score of 97 percent, and an accuracy score of 94 percent. The subsequent geometric morphometric analysis identified significant differences in Perdiz arrow point shape, size, and

Components of the analytical workflow used in this manuscript were developed and funded by a Preservation Technology and Training grant (P14AP00138) to RZS from the National Center for Preservation Technology and Training, as well as grants to RZS from the Caddo Nation of Oklahoma, National Forests and Grasslands in Texas (15-PA-11081300-033) and the United States Forest Service (20-PA-11081300-074).

Robert Z. Selden 1
Heritage Research Center, Stephen F. Austin State University; Department of Biology,
Stephen F. Austin State University; and Cultural Heritage Department, Jean Monnet University

E-mail: zselden@sfasu.edu

John E. Dockall 2
Cox|McClain Environmental Consultants, Inc.
E-mail: johnd@coxmcclain.com

allometry, coupled with significant results for modularity and morphological integration. These findings bolster recent arguments that established two discrete *behavioral regions* in the ancestral Caddo area defined on the basis of discernible morphological differences across three categories of Caddo material culture.

Keywords American Southeast · Caddo · Texas · archaeoinformatics · computational archaeology · machine learning · museum studies · digital humanities · STEM ·

1 Introduction

Perdiz arrow points generally follow two distinct manufacturing trajectories; one that enlists flakes, and the other, blade flakes [1,2,3,4]. Lithic tool stone in the Caddo area of northeast Texas is relatively sparse, consists primarily of chert, quartzite, and silicified wood characteristic of the local geological formations, which may contribute to local variation in shape and size [4,5]. It has been demonstrated elsewhere that Perdiz arrow points from northeast Texas vary significantly by time, raw material, and burial context [4]. In outline, Perdiz arrow points possess a:

[t]riangular blade with edges usually quite straight but sometimes slightly convex or concave. Shoulders sometimes at right angles to stem but usually well barbed. Stem contracted, often quite sharp at base, but may be somewhat rounded. Occasionally, specimen may be worked on one face only or mainly on one face . . . [w]orkmanship generally good, sometimes exceedingly fine with minutely serrated blade edges [6, 504].

A social network analysis of diagnostic artifacts from Historic Caddo (post-CE 1680) sites in northeast Texas demonstrated two spatially distinct *behavioral regions* [7] (Fig. 1). The network analysis was limited to Historic Caddo types; however, Formative Early Caddo (CE 800 – 1200) Gahagan bifaces and Caddo bottle types have been found to express significantly different morphologies between the same two areas [8,9,10,11], extending the prehistoric longevity of distinct *behavioral regions*. Gahagan bifaces from the ancestral Caddo area also differ significantly in shape, size, and form compared with those recovered from central Texas sites [12], suggesting a second *shape boundary* between the ancestral Caddo area and central Texas.

The goal of this exploratory endeavor was to assess whether traditional metrics collected for Perdiz arrow points support the *shape boundary* posited in recent social network and geometric morphometric analyses, to determine whether linear metrics might be useful predictors of regional membership, and—if so—to identify those morphological features that articulate with each *behavioral region* using geometric morphometrics. It is assumed that complete Perdiz arrow points included as offerings in Caddo burials represent the *design intent* of the maker. Should the analysis yield significant results, it would



Fig. 1 Historic Caddo network generated using ceramic and lithic types, which include Perdiz arrow points (DOI 10.17605/OSF.IO/WD2ZT), illustrating the two (north [blue] and south [red]) Caddo behavioral regions. The regions were identified using a modularity statistic to identify those nodes more densely connected to one another than to the rest of the network.

bolster the argument for at least two discrete Caddo *behavioral regions* in northeast Texas; each empirically defined by discernible morphological differences across three discrete categories of Caddo material culture.

1.1 Caddo behavioral regions

In a June 18, 1937 Works Progress Administration interview with Lillian Cassaway, Sadie Bedoka—a Caddo-Delaware woman raised with the Caddo—stated that:

Each [Caddo] clan had its own shape to make its pottery. One clan never thought of making anything the same pattern of another clan.
You could tell who made the pottery by the shape [13, 395].

General differences in Caddo ceramic forms have been noted elsewhere [14, 15]; however, the study of the Clarence H. Webb collection was the first to illustrate a significant north-south geographic shape difference among Hickory Engraved and Smithport Plain Caddo bottle types [10]. That preliminary observation was later confirmed using more robust samples of Hickory Engraved

and Smithport Plain bottles [8,9], then expanded to include a greater variety of Caddo bottle types across a larger spatial and temporal extent [11].

The co-presence of diagnostic artifact and attribute types has been used to define Caddo phases and periods, which serve as a heuristic tool aiding archaeologists in explaining the local cultural landscape, as well as regional differences between local landscapes. The Historic Caddo network expands those efforts, augmenting the previously defined phases and periods, and emphasizing the dynamic and manifold relational connections that reinforce and transcend the currently-defined categories [7]. This was achieved by enlisting a multi-scalar methodological approach [16,17], where northern and southern communities were parsed into constituent groups using diagnostic types paired with a modularity statistic [18,19]. A number of the constituent groups identified in the network analysis were found to articulate with known Caddo polities, while others were not [7].

A subsequent analysis of Gahagan bifaces confirmed that a second category of Caddo material culture expressed significant morphological differences across the same geography as the Hickory Engraved and Smithport Plain bottles [20]. The morphology of Gahagan bifaces from sites in central Texas was later found to differ significantly when compared with those recovered from the Caddo region [12]. That Gahagan bifaces were found to differ across two *spatial boundaries* was noteworthy, particularly since it has regularly been assumed that these large bifaces were manufactured in central Texas and arrived in the ancestral Caddo area as products of trade and/or exchange [12, 20]. Further, that Gahagan bifaces were found to differ across the same geography as those communities posited in the Historic Caddo network analysis suggested that the temporal range of the *shape boundary* might extend to the Formative/Early Caddo period (CE 800 - 1250); a hypothesis that was later confirmed in a more comprehensive analysis of Caddo bottles [11].

2 Methods and results

Sixty seven intact Perdiz arrow points recovered from Caddo burial contexts in Camp, Nacogdoches, and Shelby counties were used for this study (supplementary materials). A standard suite of linear metrics was collected for each specimen, including maximum length, width, thickness, stem length, and stem width. Following collection, data were imported to R 4.1.1 [21] (supplementary materials), where boxplots were produced, along with a Principal Components Analysis (PCA) followed by analyses of variance (ANOVA) to test whether the morphology of Perdiz arrow points differs across the shape boundary (Fig.2).

Boxplots illustrate the distribution and mean for each of the five variables (Fig. 2a-e), and the PCA (Fig. 2f) illustrates over 92 percent of the variation in the sample among PC1 (84.65 percent) and PC2 (11.71 percent). The ANOVAs demonstrate significant differences in Perdiz arrow point morphology among four of the five variables (maximum length, width, stem length, and stem width) (supplementary materials). Maximum thickness does not dif-

fer significantly between the northern and southern communities, which led to the decision to conduct the subsequent geometric morphometric analysis as a two dimensional, rather than a three-dimensional, study (supplementary materials).

2.1 Predictive model

The utility of support vector machines to classify archaeological materials has increased greatly with the rise of big data [22,23,24,25]. All linear data were imported to Python and modeled using the `scikit-learn` package [26, 27] (supplementary materials). Data were subsequently split into training (75 percent) and testing (25 percent) subsets. A *standard scaler* was used to decrease the sensitivity of the algorithm to outliers by standardizing features, and a *nested cross validation* of the training set was used to achieve unbiased estimates of model performance, resulting in a mean cross validation score of 86 percent (supplementary materials). The model was subsequently fit on the training set, yielding a receiver operator curve score of 97 percent, and an accuracy score of 94 percent (supplementary materials).

2.2 Geometric morphometrics

Each of the arrow points was imaged using a flatbed scanner (HP Scanjet G4050) at 600 dpi. The landmarking protocol developed for this study (supplementary materials) includes six landmarks and 24 equidistant semilandmarks to characterize Perdiz arrow point shape, and were applied using the `StereoMorph` package in R [28]. The characteristic points and tangents used in the landmarking protocol were inspired by the work of Birkhoff [29].

Landmark data were aligned to a global coordinate system [30,31,32], achieved through generalized Procrustes superimposition [33] performed in R 4.1.1 [21] using the `geomorph` package v4.0.0 [34]. Procrustes superimposition translates, scales, and rotates the coordinate data allowing for comparisons among objects [35,33]. The `geomorph` package uses a partial Procrustes superimposition that projects the aligned specimens into tangent space subsequent to alignment in preparation for the use of multivariate methods that assume linear space [36,32] (Fig.3).

Principal components analysis [37] was used to visualize shape variation among the arrow points (Fig. 4). The shape changes described by each principal axis are commonly visualized using thin-plate spline warping of a reference image or 3D mesh [38,39]. A residual randomization permutation procedure (RRPP; $n = 10,000$ permutations) was used for all Procrustes ANOVAs [40, 41], which has higher statistical power and a greater ability to identify patterns in the data should they be present [42]. To assess whether shape changes with size (allometry), and differs by group (region), Procrustes ANOVAs [43] were also run that enlist effect-sizes (z-scores) computed as standard deviates



Fig. 2 Boxplots for a, maximum length; b, maximum width; c, maximum thickness; d, stem length; e, stem width, and f, PCA for linear metrics associated with the Perdiz arrow points. Additional information related to the analysis, including data and code needed to reproduce these results, can be found in the supplemental materials at <https://seldenlab.github.io/perdiz3/>.

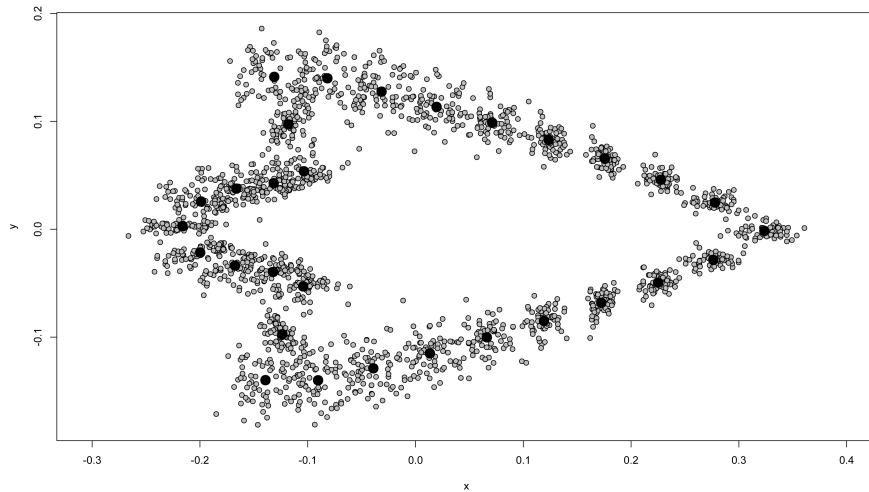


Fig. 3 Results of generalized Procrustes analysis, illustrating mean shape (black) and all specimens in the sample (gray). Additional information related to the GPA, including those data and code needed to reproduce these results, can be found in the supplemental materials at <https://seldenlab.github.io/perdiz3/>.

of the generated sampling distributions [44]. Procrustes variance was used to discriminate between regions and compare the amount of shape variation (morphological disparity) [45], estimated as the Procrustes variance using residuals of linear model fit [46]. A pairwise comparison of morphological integration was used to test the strength of integration between blade and basal morphology using a z-score [47].

The analysis of modularity, which compares within-module covariation of landmarks against between-module covariation was significant (Fig. 4 and supplementary materials), demonstrated that Perdiz arrow point blades and bases are, in fact, modular. The test for morphological integration was also significant (Fig. 4 and supplementary materials), indicating that the blades and bases of Perdiz arrow points are integrated. These results demonstrate that blade and base shapes for Perdiz arrow points are predictable; a finding that would have great utility in studies of Perdiz arrow point morphology that incorporate fragmentary specimens.

A Procrustes ANOVA was used to test whether a significant difference exists in Perdiz arrow point (centroid) size, and results were significant difference ($RRPP = 10,000$; $Rsq = 0.30681$; $Pr(>F) = 1e-04$). A second Procrustes ANOVA was used to test whether a significant difference exists in arrow point shape by region (northern vs. southern communities) ($RRPP = 10,000$; $Rsq = 0.0536$; $Pr(>F) = 0.0161$). A comparison of mean consensus configurations was used to characterize intraspecific shape variation of Perdiz arrow points from the northern and southern *behavioral regions*. Differential morphology

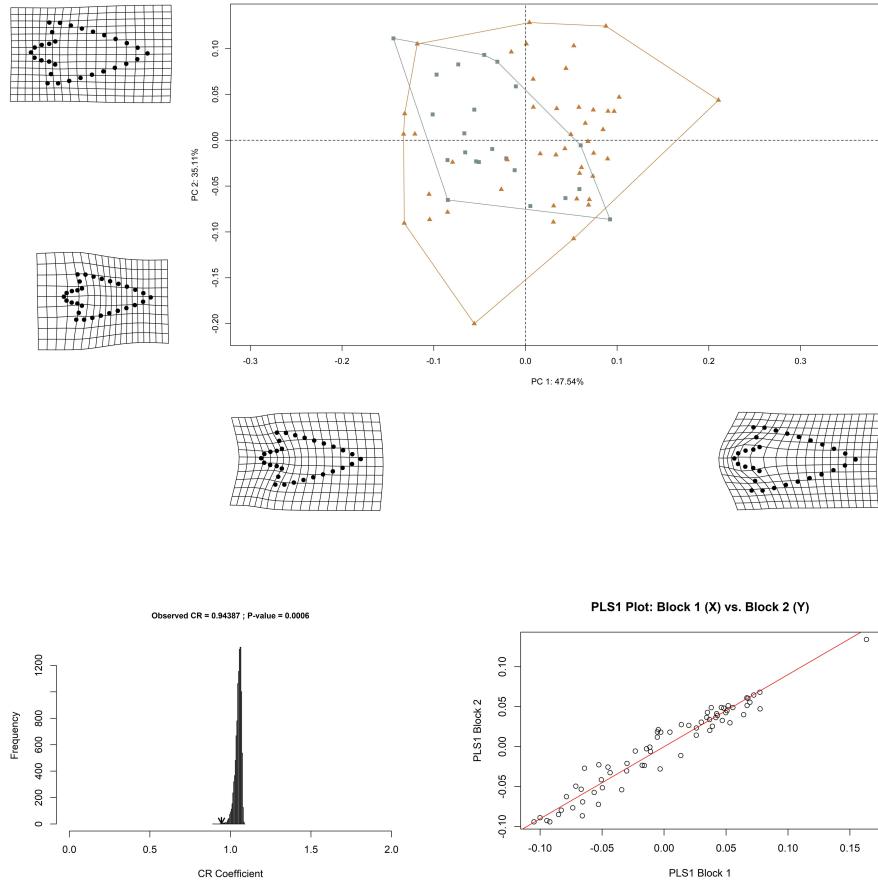


Fig. 4 Principal components analysis plot (PC1/PC2) for Perdiz arrow points by behavioral region/community (top; gray squares, north; orange triangles, south), and results of modularity (bottom left) and blade/base morphological integration (bottom right) analyses. Additional information related to the PCA, including the full listing of results and those data and code needed to reproduce these results, can be found in the supplemental materials at <https://seldenlab.github.io/perdiz/>.

occurs primarily in the basal area, where the angle between the shoulder and base is more acute, with a base that is generally shorter and narrower in the southern *behavioral region* than it is in the north (Fig. 5 and supplementary materials).

3 Discussion

The *shape boundary* empirically delineates two discrete *behavioral regions* in the ancestral Caddo area. That the Perdiz arrow points recovered from Caddo



Fig. 5 Mean shapes for Perdiz arrow points from the northern (left), and southern (center) behavioral region. In the comparison of the two (right), the northern behavioral region is represented by gray circles, and the southern, by black. Additional information related to the mean shapes, including those data and code needed to reproduce these results, can be found in the supplemental materials at <https://seldenlab.github.io/perdiz3/>.

burials north and south of the *shape boundary* were found to differ significantly, expands the scope of the *behavioral regions* to include three classes of artifacts (Caddo bottles, bifaces, and—now—arrow points) [8,9,10,11,12, 20]. This study clearly illustrates that those morphological differences among Perdiz arrow points found in the northern and southern *behavioral regions* are predictable (supplementary materials), and can be identified using the standard suite of linear metrics regularly collected in the context of cultural resource management endeavors.

The geometric morphometric analysis demonstrated significant morphological differences for Perdiz arrow points recovered north and south of the *shape boundary*, where the most pronounced difference occurs in basal morphology (see Fig. 5). Allometry was also found to be significant, demonstrating that the shape of Perdiz arrow points differs with size. Those arrow points used in this study are considered to represent *design intent*, and are not thought to exhibit retouch or resharpening. This finding provides evidence in support of the argument that Perdiz arrow point morphology is labile [4].

The blades and bases of the arrow points were found to be modular, as well as integrated. This indicates that each module functions independently, and that base shape is a predictor of blade shape, and vice-versa. Further work is warranted to assess whether Perdiz arrow points from those constituent groups within the northern and southern *behavioral regions* may express unique morphologies, aiding in delimiting local boundaries associated with constituent Caddo groups. Whether, and to what extent, it may be possible to identify specific groups of makers using unmodified arrow points from similar contexts remains unknown. Additional complexity is introduced when considering that Perdiz arrow points included in Caddo burials may have been manufactured

and transported to the ancestral Caddo territory, and (potentially) placed in burials by members of non-Caddo groups. This challenges the concept that all cultural material recovered from Caddo burials were manufactured by, and placed with the deceased, *only* by members of a specific Caddo family, group, or polity.

3.1 Morphologically-distinct behavioral regions

In considering the role(s) of artifacts as aspects of *social identity*, it is important not to lose sight of the fact that people and artifacts are active agents in the production and maintenance of *social identity(ies)*. Both categories of artifacts (bottles and bifaces) contribute to local and regional *communities of identity* and *communities of practice* [48]. Generally, this concept may be more easily applied to bottles since they were manufactured and used by individuals sharing collective *Caddo identities*. Bifaces (Perdiz arrow points and Gahagan bifaces) potentially represent multiple *identities*—those being the Caddo, as users; and non-Caddo, as producers—at least with regard to chipped stone tools incorporated in mortuary contexts. This idea lends defensible credence to the concept of morphologically-distinct *behavioral regions* among the Caddo, while integrating the possibility of understanding interactions between Caddo and non-Caddo groups, to include the movement of material culture between Caddo *behavioral regions*.

Three categories of Caddo material culture differ north and south of the *shape boundary*, indicating regionally-distinct perspectives related to production (bottles), and/or aesthetic choice/cultural interaction (bifaces). These differing perspectives incorporate group decisions that include shape, size, form, and decorative expression, which likely represent the culmination of generational perspectives [49]. Simply stated, such perspectives are representative of tradition. Eckert and colleagues [48] indicate that provenance, the origin or source of an item, is a significant component of understanding the interrelatedness of *communities of identity* and *communities of practice*. Perdiz arrow points and Gahagan bifaces recovered north and south of the *shape boundary* are morphologically distinct. A second *shape boundary* demonstrates that Gahagan bifaces differ significantly between the ancestral Caddo region and central Texas, where they are currently thought to have been manufactured. This suggests that those *communities of practice* that articulate with the production of chipped stone artifacts recovered from Caddo internments, are not Caddo.

It is entirely possible that there are no *communities of practice* at all for chipped stone artifacts recovered from Caddo mortuary contexts. However, there do appear to have been *communities of practice* associated with Perdiz arrow points recovered from non-mortuary contexts in the ancestral Caddo area, which may more readily reflect the distinct retouch/resharpening approaches employed by Caddo knappers [4]. Similar interpretations can be applied to Gahagan bifaces, as few have been reported outside of Caddo mortuary

contexts. It may be more fitting to perceive of Perdiz arrow points and Gaha-gan bifaces as indicative of *communities of identity* rather than *communities of practice*, due to the contextual discrepancy evinced through mortuary and non-mortuary settings. The provenance of bifaces from Caddo mortuary contexts can most assuredly be considered non-local, or produced outside of the ancestral Caddo region, based on multiple factors that include raw material, workmanship, morphology, and context.

4 Conclusion

general:

- morphological attributes are representative of *intentional attributes* (Costin 2005) related to morphological characteristics
- dimensional standardization has utility in identifying the range of variation and overlap of product morphology in and between communities (Arnold 1991)
- relative dimensional standardization may imply a smaller number of production units (Costin 1991) contrasted with larger production units
- might there have been limits of technological/aesthetic social tolerance within/between the *behavioral regions*?

bottles:

- bottles as a complete system; stone tools as partial/components
- similarities/differences in bottle shapes transcend type assignments
- bottles from the northern *behavioral region* express a significantly greater diversity in size; potential (size) standardization in the southern *behavioral region*
- production activities more likely to be localized than exchange systems, and assumed to leave a clearer signature (Costin 1991)

bifaces:

- bifaces from the Caddo area express a significantly greater diversity in size when compared to central Texas

This study enlisted a combined analytical approach that incorporated social network analysis, linear metrics, machine learning, and geometric morphometrics, which expanded support for two discrete Caddo behavioral regions to include a third category of Caddo material culture. While evidence from one category—Caddo bottles—supports discussions of production, the other two—bifaces—more readily articulate with production activities outside of the ancestral Caddo area. Further work is warranted to expand the scope of this research program to include analyses of differential production within the two *behavioral regions* outlined in this study using a greater diversity of diagnostic artifact types.

Acknowledgments

We express our gratitude to the Caddo Nation of Oklahoma and the Anthropology and Archaeology Laboratory at Stephen F. Austin State University for the requisite permissions and access to the NAGPRA objects from the Washington Square Mound site and Turner collections, and to Tom A. Middlebrook for brokering access to the Perdiz arrow points from burials at the Morse Mound site. Thanks also to the editors and reviewers for their useful comments and constructive criticisms, which further improved this manuscript.

Data Management

The data and analysis code associated with this project can be accessed through the GitHub repository (<https://github.com/seldenlab/perdiz3>) or the supplementary materials (<https://seldenlab.github.io/perdiz3/>); which are digitally curated on the Open Science Framework at DOI: 10.17605/OSF.IO/UK9ZD.

References

1. J.E. Dockall, R.C. Fields, K.W. Kibler, C.J. Broehm, J. Budd, E.F. Gadus, K.M. Gardner, Testing and Data Recovery Excavations at the Jayroe Site (41HM51), Hamilton County, Texas (Waco District, CSJ No. 0909-29-030 (Part I)). Tech. rep., Reports of Investigations No. 187. Prewitt and Associates, Inc., Austin Texas. Archeological Studies Program, Report No. 184. Texas Department of Transportation, Environmental Affairs Division, Archeological Studies Branch, Austin Texas (2020)
2. L. Johnson, The Life and Times of Toyah-Culture Folk: The Buckhollow Encampment Site 41KM16, Kimble County, Texas. Report, Texas Department of Transportation and Office of the State Archeologist Report 38. Austin, Texas (1994)
3. R.A. Ricklis, *Toyah Components: Evidence for Occupation in the Project Area during the Latter Part of the Late Prehistoric Period* (Studies in Archeology 19. Vol. 1, Texas Archeological Research Laboratory, University of Texas, Austin, Texas, 1994), pp. 207–316
4. R.Z. Selden Jr., J.E. Dockall, C.B. Bousman, T.K. Perttula, Shape as a function of time + raw material + burial context? An exploratory analysis of Perdiz arrow points from the ancestral Caddo area of the American Southeast, Journal of Archaeological Science: Reports **37** (2021). DOI 10.1016/j.jasrep.2021.102916
5. L.D. Banks, *From Mountain Peaks to Alligator Stomachs: A Review of Lithic Sources in the Trans-Mississippi South, The Southern Plains*. Memoir No. 4 (Oklahoma Anthropological Society, Norman, 1990)
6. D.A. Suhm, A.D. Krieger, E.B. Jelks, An Introductory Handbook of Texas Archeology, Bulletin of the Texas Archeological Society **25**, 1 (1954)
7. R.Z. Selden Jr., in *Ancestral Caddo Ceramic Traditions*, ed. by D.P. McKinnon, T.K. Perttula, J.S. Girard (LSU Press, Baton Rouge, 2021), pp. 240–257
8. R.Z. Selden Jr., A Preliminary Study of Smithport Plain Bottle Morphology in the Southern Caddo Area, Bulletin of the Texas Archeological Society **89**, 63 (2018). URL <https://scholarworks.sfasu.edu/crhr/283/>
9. R.Z. Selden Jr., Ceramic Morphological Organisation in the Southern Caddo Area: Quiddity of Shape for Hickory Engraved Bottles, Journal of Archaeological Science: Reports **21**, 884 (2018). DOI 10.1016/j.jasrep.2018.08.045

10. R.Z. Selden Jr., Ceramic Morphological Organisation in the Southern Caddo Area: The Clarence H. Webb Collections, *Journal of Cultural Heritage* **35**, 41 (2019). DOI 10.1016/j.culher.2018.07.002. URL <https://www.sciencedirect.com/science/article/abs/pii/S1296207418301912?via%3Dihub>
11. R.Z. Selden Jr., in *Ancestral Caddo Ceramic Traditions*, ed. by D.P. McKinnon, J.S. Girard, T.K. Perttula (LSU Press, Baton Rouge, 2021), pp. 258–276
12. R.Z. Selden Jr., J.E. Dockall, M. Dubied, A quantitative assessment of intraspecific morphological variation in Gahagan bifaces from the southern Caddo area and central Texas, *Southeastern Archaeology* **39**(2), 125 (2020). DOI 10.1080/0734578x.2020.1744416
13. L. Cassaway. Indian-Pioneer History Project for Oklahoma: Sadie Bedoka (1937)
14. A.D. Krieger, *Culture Complexes and Chronology in Northern Texas, with Extensions of Puebloan Datings to the Mississippi Valley*, vol. Publication No. 4640 (The University of Texas, Austin, 1946)
15. R.Z. Selden Jr., T.K. Perttula, M.J. O'Brien, Advances in Documentation, Digital Curation, Virtual Exhibition, and a Test of 3D Geometric Morphometrics: A Case Study of the Vanderpool Vessels from the Ancestral Caddo Territory, *Advances in Archaeological Practice* **2**(2), 1 (2014). DOI 10.7183/2326-3768.2.2.64
16. C. Knappett, *An Archaeology of Interaction: Network Perspectives on Material Culture & Society* (Oxford University Press, Oxford, 2011)
17. B.J. Mills, M.A. Peebles, W.R. Haas Jr., L. Borck, J.J. Clark, J.M. Roberts Jr., Multiscalar Perspectives on Social Networks in the Late Prehispanic Southwest, *American Antiquity* **80**(1), 3 (2015). DOI 10.7183/0002-7316.79.4.3. URL <https://www.cambridge.org/core/journals/american-antiquity/article/multiscalar-perspectives-on-social-networks-in-the-late-prehispanic-southwest/B40CF133F9E61102185B25AD4DF0FE30>
18. V.D. Blondel, J.L. Guillaume, R. Lambiotte, E. Lefebvre, Fast Unfolding of Communities in Large Networks, *Journal of Statistical Mechanics: Theory and Experiment* **2008**(10), P10008 (2008). DOI 10.1088/1742-5468/2008/10/p10008. URL <Go to ISI>://WOS:000260529900010https://iopscience.iop.org/article/10.1088/1742-5468/2008/10/P10008
19. R. Lambiotte, J.C. Delvenne, M. Barahona, Random Walks, Markov Processes and the Multiscale Modular Organization of Complex Networks, *IEEE Transactions on Network Science and Engineering* **1**(2), 76 (2014). DOI 10.1109/tnse.2015.2391998. URL <https://ieeexplore.ieee.org/document/7010026/>
20. R.Z. Selden Jr., J.E. Dockall, H.J. Shafer, Lithic Morphological Organisation: Gahagan Bifaces from the Southern Caddo Area, *Digital Applications in Archaeology and Cultural Heritage* **10**, e00080 (2018). DOI 10.1016/j.daach.2018.e00080
21. R.C.D. Team, *R: A Language and Environment for Statistical Computing. Electronic resource*, (R Foundation for Statistical Computing, Vienna, Austria, 2021). URL <http://www.R-project.org>
22. M. S. Bhatt, T. P. Patalia, Indian Monuments Classification using Support Vector Machine, *International Journal of Electrical and Computer Engineering* **7**(4) (2017). DOI 10.11591/ijece.v7i4.pp1952-1963
23. F. Monna, J. Magail, T. Rolland, N. Navarro, J. Wilczek, J.O. Gantulga, Y. Esin, L. Granjon, A.C. Allard, C. Chateau-Smith, Machine learning for rapid mapping of archaeological structures made of dry stones - example of burial monuments from the khirgisur culture, mongolia -, *Journal of Cultural Heritage* **43**, 118 (2020). DOI 10.1016/j.culher.2020.01.002
24. H.K. Febriawan, O. Moefti, D. Haryanto, T. Wiguna, Detection and characterization of an archaeological wreck site in Sunda Strait, Indonesia, *Forum geografic* **XIX**(1), 60 (2020). DOI 10.5775/fg.2020.054.i
25. I. Kadhim, F. Abed, The Potential of LiDAR and UAV-Photogrammetric Data Analysis to Interpret Archaeological Sites: A Case Study of Chun Castle in South-West England, *ISPRS International Journal of Geo-Information* **10**(1) (2021). DOI 10.3390/ijgi10010041
26. F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel, M. Blondel, P. Prettenhofer, R. Weiss, V. Dubourg, J. Vanderplas, A. Passos, D. Cournapeau, M. Brucher, M. Perrot, E. Duchesnay, Scikit-learn: Machine Learning in Python, *Journal of Machine Learning Research* **12**, 2825 (2011)

27. L. Buitinck, G. Louppe, M. Blondel, F. Pedregosa, A. Mueller, O. Grisel, V. Niculae, P. Prettenhofer, A. Gramfort, J. Grobler, R. Layton, J. VanderPlas, A. Joly, B. Holt, G. Varoquaux, in *ECML PKDD Workshop: Languages for Data Mining and Machine Learning* (2013), pp. 108–122
28. A.M. Olsen, M.W. Westneat, Stereomorph: An r package for the collection of 3d landmarks and curves using a stereo camera set-up, *Methods in Ecology and Evolution* **6**(3), 351 (2015). DOI 10.1111/2041-210x.12326
29. G.D. Birkhoff, *Aesthetic Measure* (Harvard University Press, Cambridge, 1933)
30. D.G. Kendall, *The Statistics of Shape* (Wiley, New York, 1981), pp. 75–80
31. D.G. Kendall, Shape manifolds, procrustean metrics, and complex projective spaces, *Bulletin of the London Mathematical Society* **16**(2), 81 (1984). DOI 10.1112/blms/16.2.81. URL <http://onlinelibrary.wiley.com/doi/10.1112/blms/16.2.81>
32. D.E. Slice, Landmark Coordinates Aligned by Procrustes Analysis Do Not Lie in Kendall's Shape Space, *Systematic Biology* **50**(1), 141 (2001). DOI 10.1080/10635150119110
33. F.J. Rohlf, D.E. Slice, Extensions of the Procrustes Method for the Optimal Superimposition of Landmarks, *Systematic Zoology* **39**(1), 40 (1990). DOI 10.2307/2992207. URL <https://academic.oup.com/sysbio/article-abstract/39/1/40/1629843?redirectedFrom=fulltext>
34. D.C. Adams, E. Otarola-Castillo, geomorph: An R Package for the Collection and Analysis of Geometric Morphometric Shape Data, *Methods in Ecology and Evolution* **4**(4), 393 (2013). DOI 10.1111/2041-210x.12035. URL <https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/2041-210X.12035>
35. J.C. Gower, Generalized Procrustes Analysis, *Psychometrika* **40**(1), 33 (1975). DOI <https://doi.org/10.1007/BF02291478>. URL <https://link.springer.com/article/10.1007%2FBF02291478>
36. F.J. Rohlf, Shape Statistics: Procrustes Superimpositions and Tangent Spaces, *Journal of Classification* **16**(2), 197 (1999). DOI 10.1007/s003579900054. URL <https://link.springer.com/article/10.1007%2Fs003579900054>
37. I.T. Jolliffe, *Principal Component Analysis* (Springer, New York, 2002)
38. C.P. Klingenberg, Visualizations in Geometric Morphometrics: How to Read and How to Make Graphs Showing Shape Changes, *Hystrix* **24**, 15 (2013)
39. E. Sherratt, D.J. Gower, C.P. Klingenberg, M. Wilkinson, Evolution of Cranial Shape in Caecilians (Amphibia: Gymnophiona), *Evolutionary Biology* **41**, 528 (2014). DOI <https://doi.org/10.1007/s11692-014-9287-2>. URL <https://link.springer.com/article/10.1007%2Fs11692-014-9287-2>
40. D.C. Adams, M.L. Collyer, Permutation Tests for Phylogenetic Comparative Analyses of High-Dimensional Shape Data: What you Shuffle Matters, *Evolution* **69**(3), 823 (2015). DOI 10.1111/evo.12596. URL <http://www.ncbi.nlm.nih.gov/pubmed/25641367>
41. M.L. Collyer, D.C. Adams, RRPP: An R Package for Fitting Linear Models to High-Dimensional Data using Residual Randomization, *Methods in Ecology and Evolution* **9**(7), 1772 (2018). DOI <https://doi.org/10.1111/2041-210X.13029>. URL <https://besjournals.onlinelibrary.wiley.com/doi/pdf/10.1111/2041-210X.13029>
42. M.J. Anderson, C.J.F. Ter Braak, Permutation Tests for Multi-Factorial Analysis of Variance, *Journal of Statistical Computation and Simulation* **73**(2), 85 (2003). DOI 10.1080=0094965021000015558
43. C. Goodall, Procrustes Methods in the Statistical Analysis of Shape, *Journal of the Royal Statistical Society. Series B (Methodological)* **53**(2), 285 (1991)
44. M.L. Collyer, D.J. Sekora, D.C. Adams, A method for analysis of phenotypic change for phenotypes described by high-dimensional data, *Heredity (Edinb)* **115**(4), 357 (2015). DOI 10.1038/hdy.2014.75. URL <http://www.ncbi.nlm.nih.gov/pubmed/25204302>

45. M.L. Zelditch, D.L. Swiderski, H.D. Sheets, W.L. Fink, *Geometric Morphometrics for Biologists : A Primer* (Elsevier Science, Burlington, 2004). URL <http://ebookcentral.proquest.com/lib/tamucs/detail.action?docID=298308>
46. D.C. Adams, M.L. Collyer, A. Kaliantzopoulou, E. Sherratt, Package 'geomorph': Geometric Morphometric Analyses of 2D/3D Landmark Data. R package version 3.2.1 (March 1, 2020) (2018). URL <http://geomorphr.github.io/geomorph/>
47. D.C. Adams, M.L. Collyer, On the Comparison of the Strength of Morphological Integration across Morphometric Datasets, *Evolution* **70**(11), 2623 (2016). DOI 10.1111/evo.13045. URL <https://www.ncbi.nlm.nih.gov/pubmed/27592864> <https://onlinelibrary.wiley.com/doi/abs/10.1111/evo.13045>
48. S.L. Eckert, K.L. Schleher, W.D. James, Communities of Identity, Communities of Practice: Understanding Santa Fe Black-on-White Pottery in the Espanola Basin of New Mexico, *Journal of Archaeological Science* **63**, 1 (2015). DOI 10.1016/j.jas.2015.07.001. URL <https://www.sciencedirect.com/science/article/pii/S030544031500223X?via%3Dihub>
49. M.T. Stark, *Glaze Ware Technology, the Social Lives of Pots, and Communities of Practice in the Late Prehistoric Southwest* (University of Arizona Press, Tucson, 2006), pp. 17–33