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ORIGINAL PAPER

The small-world topology of Clovis lithic networks

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Abstract

North America was first settled in the late Pleistocene by Paleoindian peoples, Clovis is the best documented archeological complex associated with this settlement. Undoubtedly, Clovis groups faced adaptive challenges in the novel environments of a sparsely populated New World. In this paper, we ask whether Clovis had small-world networks to help them create and maintain connections across the vast landscape of western North America. Small worlds are properties of many real networks and are characterized by high clustering and short path lengths. To investigate this, we examined the topology of Clovis lithic networks in western North America. We employed two commonly used measures of network topology in our analyses of regional Clovis lithic networks and show that stone raw material was transported and exchanged with the characteristics of a small world. We also show that caching and the long-distance movement of stone was an important part of creating small worlds. Clovis small-world lithic networks may have mapped onto Clovis social networks or may have been independent of other networks, but either way, lithic exchange networks were far from random and served an important role in connecting local populations.

Keywords Clovis · Lithic network · Small world · Caches

Introduction

The Americas were initially settled by foragers during the final stages of the Pleistocene. This process likely started with small numbers of people, perhaps at the leading edge of a larger population diffusion, or as one of multiple pulses of population movements into the uninhabited landscape of the Americas. Archeological evidence of the first widespread culture in the Americas appears by about 13,500 calBP (calendar years before present) in western North America and lasts until approximately 12,500 calBP in eastern North America (Haynes et al. 1984; Haynes et al. 2007; Prasciunas and Surovell 2015; Sanchez et al. 2014; Waters and Stafford 2007, 2014). This culture, known as Clovis, represents the best documented evidence of the settlement and adaptive processes of the first peoples in North America (Ellis 2008; Eren and Buchanan 2016; Hamilton and Buchanan 2010; Kelly and Todd 1988; Meltzer 2004, 2009; Miller et al. 2013; Smallwood and Jennings 2015).

A problem faced by the first groups of hunter-gatherers in North America was maintaining a viable population (Anderson and Gillam 2001; Bocquet-Appel 1985; Meltzer 2002; Moore and Moseley 2001; Whallon 2006; Wobst 1974). The Clovis population needed to be robust enough to retain traditions, exchange mates and information, and endure an unpredictable environment. For small and scattered groups of people, this entailed exploring and learning new landscapes while keeping contact with dispersed peoples through networks. To approximate the structure of the Clovis social network, we use shared lithic materials among sites as a proxy for the interaction among Clovis groups. We show that within broad regions, local Clovis populations formed small worlds and suggest that aspects of the Clovis social network may have also been a small world that allowed Clovis people to solve the problem of having a dispersed population in an unknown land.

Small-world networks are ubiquitous in nature and have properties that are well-studied (Telesford et al. 2011;

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Newman 2010; Watts 1999; Watts and Strogatz 1998). Small worlds are commonly characterized by “six degrees of separation”, the phenomena of seemingly unlikely short paths linking clusters within networks (Watts 1999). Small-world networks are defined as having high clustering coefficients and short path lengths and lie in the network space between regular lattice networks with high clustering coefficients and long path lengths and random networks with low clustering coefficients and short path lengths. Small-world networks retain both dense clusters of nodes and short path lengths by having a few edges that connect clusters across the network and reducing the number of steps required to make those connections. These properties are beneficial for efficient flow across a network with clustering. For Clovis, a small-world social network would have helped maintain geographically dispersed populations via the exchange of mates, information, traditions, and materials across the vast landscape of North America during the late Pleistocene.

In this paper, we focus on Clovis in western North America. Western North America was the first region settled by populations migrating from western Eurasia (Rasmussen et al. 2014) entering the contiguous USA either along the western coastal margin or through the ice-free corridor in the interior. The western USA, from the west coast to the Great Plains, covers approximately 4.8 million square kilometers of land and contains diverse environmental regions from deserts to rainforests and plains to mountains. Small and dispersed colonizing Clovis groups would have had to maintain contact over long distances and unfamiliar terrain as their population numbers grew as they learned the landscape (Meltzer 2002, 2004). We show here that Clovis groups made occasional long-distance movements across the landscape and that these movements created small worlds. Archeologically, we can track these long-distance movements by the presence of distinctive lithic materials in Clovis assemblages. The overwhelming majority of the toolstone used by Clovis knappers was fine-grained materials, primarily cherts from various sources, which are found in discrete geological outcrops throughout the west (Buchanan et al. 2016). It is from these raw materials recovered at Clovis sites that we constructed a lithic network to evaluate the movement and interaction of people.

Here, we examine the structure of the western Clovis lithic network that we recently expanded with new data (see Buchanan et al. 2016, 2019) and ask if it has the properties of a small-world network. To answer this question, we quantify the path lengths and clustering of the Clovis network using two previously defined measures of small worldness. Our results show that local Clovis networks were small world while the global Clovis network is a lattice. We partitioned the network into northern and southern components and analyzed these separately. The results indicate that both northern and southern components are small-world networks. We follow this analysis with an examination of two possible mechanisms that helped create the small worlds. The first is long distance transport of raw materials and the second is the caching of raw materials at strategic places on the landscape. Lastly, we discuss these results in terms of what they imply about Clovis social life and interactions.

The western Clovis lithic network

In previous studies, we used lithic raw material data from western Clovis assemblages associated with discrete Clovis occupations in our network analyses (Buchanan et al. 2016, 2019). In this study, we define western Clovis as west of the Mississippi River. Following the previous analyses, we used three criteria for inclusion of a Clovis assemblage into our analyses (see Buchanan et al. 2016, 2019). First, the assemblage had to be reliably dated to the Clovis period, meaning that it was either associated with radiometric dates in the ca. 13,350–12,800 calBP range in western North America (Haynes Jr et al. 1984; Haynes et al. 2007; Holliday 2000; Sanchez et al. 2014; Waters and Stafford Jr 2007, 2014) or contained diagnostic artifacts that are radiometrically dated to these age ranges at another site. Second, the assemblage could not be significantly mixed with later materials. Third, an assemblage had to be available for study or information concerning raw material types and sources represented in the assemblage had to be published and accessible. Based on these criteria, we recorded lithic raw material information from 38 western Clovis assemblages (see Supplementary Materials Table S1).

The western Clovis lithic raw material type and source identifications have almost exclusively been made by visual inspection (however, see Huckell et al. 2011). Unfortunately, there is some subjectivity in this approach. Other methods, such as trace element analyses, can provide quantifiable data on lithic sources that contain diagnostic trace elements, but currently the best results from these types of analyses come from destroying specimens and are costly. Given this limitation, we recognize that some of the source attributions used in this study may change in the future with more objective analyses.

To build the networks, nodes are designated as assemblages and edges are shared raw materials among nodes. We identified five discrete components of the network. Three of the components (East Wenatchee in Washington, Kincaid Rockshelter in Texas, and Lange-Ferguson in North Dakota) are isolated assemblages. One component consists of only two assemblages that share raw materials (CW in Colorado and Eckles in Kansas). The fifth component has the remaining 33 assemblages. This large component is the focus of the present study (Fig. 1).

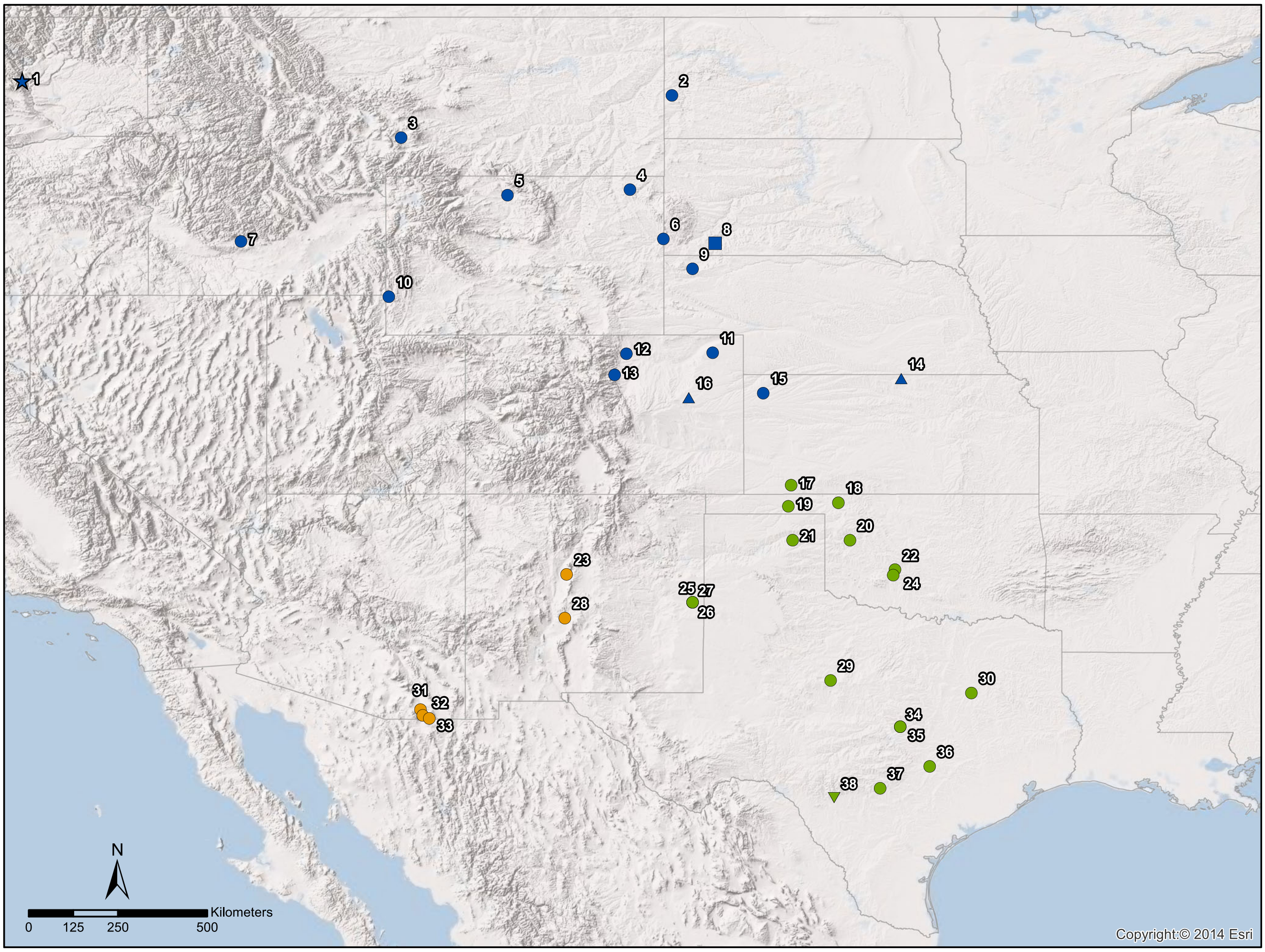

Fig. 1 Map of western North America with Clovis sites used in the analyses colored by region (Southwest = orange, Southern Plains = green, and the Northern and Central Plains = blue) and shape indicating network component (circles = component 1; triangles = component 2; square = component 3; star = component 4) (Key: 1, East Wenatchee; 2, Beach; 3, Anzick; 4, Crook County; 5, Colby; 6, Sheaman; 7, Simon; 8, Lange-Ferguson; 9, Franey; 10, Fenn; 11, Drake; 12, Watts; 13, Mahaffy; 14, Eckles; 15, Busse; 16, CW; 17, Sailor-Helton; 18, Jake Bluff; 19, JS; 20, Calvin Graybill #1; 21, Miami; 22, Anadarko; 23, Demolition Road; 24, Domebo; 25, Blackwater Draw; 26, Dickenson; 27, Green; 28, Mockingbird Gap; 29, Yellow Hawk; 30, Keven Davis; 31, Murray Springs; 32, Lehner; 33, Naco; 34, de Graffenreid; 35, Gault; 36, Hogeye; 37, Pavo Real; 38, Kincaid)

Is the Clovis lithic network a small world?

The western Clovis sites in the largest component range from Texas in the south to North Dakota in the north and are primarily found in the Great Plains, Rocky Mountains, and Southwest regions (Fig. 1). Figure 2 shows this component as a circular network with nodes (assemblages) colored by region.

The circular network shows that nodes from different regions are connected by edges (Fig. 2). For example, the JS cache assemblage located on the Southern Plains in Oklahoma shares raw materials with assemblages found on the Northern Plains. The Demolition Road and Mockingbird Gap assemblages in New Mexico share raw materials with sites located on the Southern Plains. The Drake cache in Colorado includes chert from the Southern Plains.

Next, we quantified the topological structure of the western Clovis lithic network by examining the clustering coefficients and the average path lengths, both independently and then together, using two measures of small worldness. First, we tested whether the clustering coefficient of the western Clovis network was significantly different from a sample of equivalently sized random networks. The clustering coefficient is a measure of clustering within the network. This measure divides the number of closed triplets of nodes (node triplets connected by three edges) divided by the total number of triplets in the network that are both open (node triplets connected by two edges) and closed (Newman 2010). For this test, we created 100 Erdős–Rényi random networks (where all networks with a given number of nodes and edges are equally likely) with the same number of nodes ($n = 33$) and density (0.288) as the observed western Clovis network and

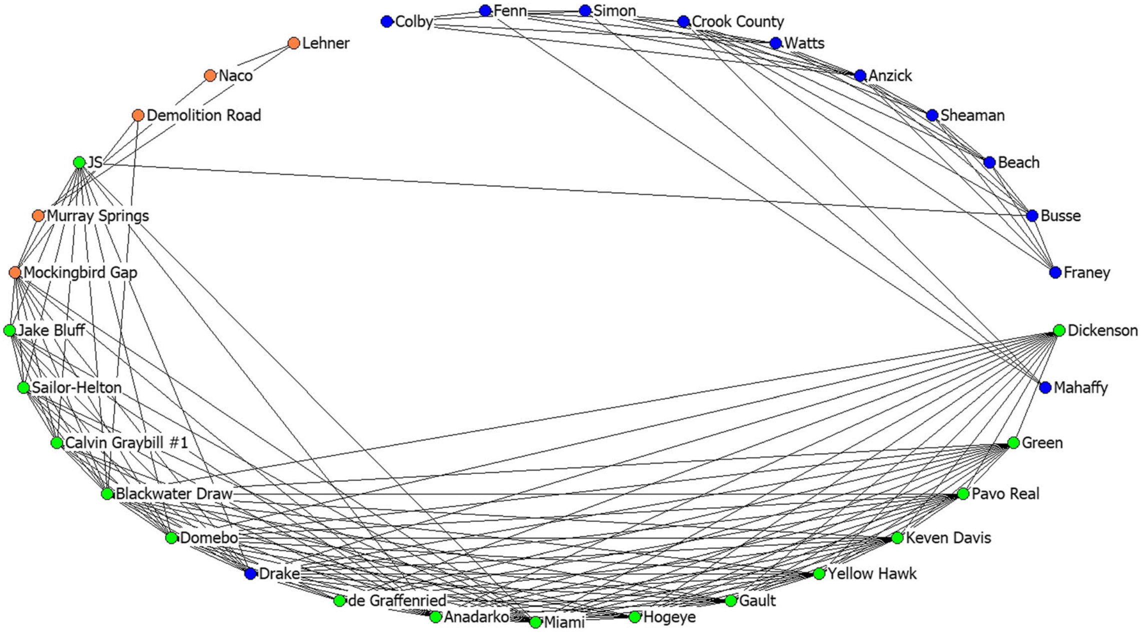

Fig. 2 Circular network of the western Clovis lithic data with edges connecting nodes sharing raw materials. Nodes are colored by region (Southwest = orange, Southern Plains = green, and the Northern and Central Plains = blue)

then compared the clustering coefficients of the random networks to the clustering coefficient of the observed Clovis network.

Our results demonstrate that the western Clovis lithic network with a clustering coefficient of 0.835 is significantly larger than the clustering coefficients for the random networks (Fig. 3). The mean clustering coefficient for the random networks is 0.29 with confidence limits of 0.286 to 0.294 and a standard deviation of 0.02. Therefore, the western Clovis lithic network has a clustering coefficient that is more than 20 standard deviations larger than the mean for random networks of the same size and density. This result indicates that the western Clovis network has one of the properties of a small-world network, a high clustering coefficient.

We then evaluated the average path length for the observed western Clovis network. The average path length is the sum of all the shortest distances between all pairs of nodes in a network divided by the number of those pairs. The observed average path length for the western Clovis network is 2.72 and is considerably longer than the corresponding average measure of 1.78 (bootstrapped confidence limits 1.768 to 1.785 with a standard deviation of 0.04) for 100 Erdős–Rényi random networks. This difference between the observed network and the random networks is not unexpected as random networks typically have shorter path lengths than real networks.

Second, we used two metrics to determine whether the Clovis lithic network is a small world. The first measure was developed by Watts and Strogatz (1998). Their measure, σ, is the ratio of the observed clustering coefficient to the clustering coefficient for an equivalent random network divided by the ratio of the observed average path length to the average path length for an equivalent random network:

$$\sigma = \frac{C/Crand}{L/Lrand}$$

The resulting value of σ is the small-world coefficient. Watts and Strogatz (1998) suggest that networks with $\sigma > 1$ have small-world properties. The second small-world measure, ω, derived by Telesford et al. (2011) takes the ratio of the observed average path length, L, of a given network to the same measure from an equivalent random network, L_{rand}, and then subtracts this ratio from the ratio of the clustering coefficient, C, of a given network to the same measure from an equivalent lattice network, C_{latt}. Such that:

$$\omega = \frac{Lrand}{L} - \frac{C}{Clatt}$$

The resulting values of ω are restricted to the interval -1 to 1 and are not dependent on network size. Values of ω that are close to -1 are more lattice-like with high degrees of clustering, whereas values of ω closer to 1 are comparable to random networks with short path lengths. Telesford et al. (2011) suggest that small-world networks typically can be found to have ω values between -0.5 and 0.5.

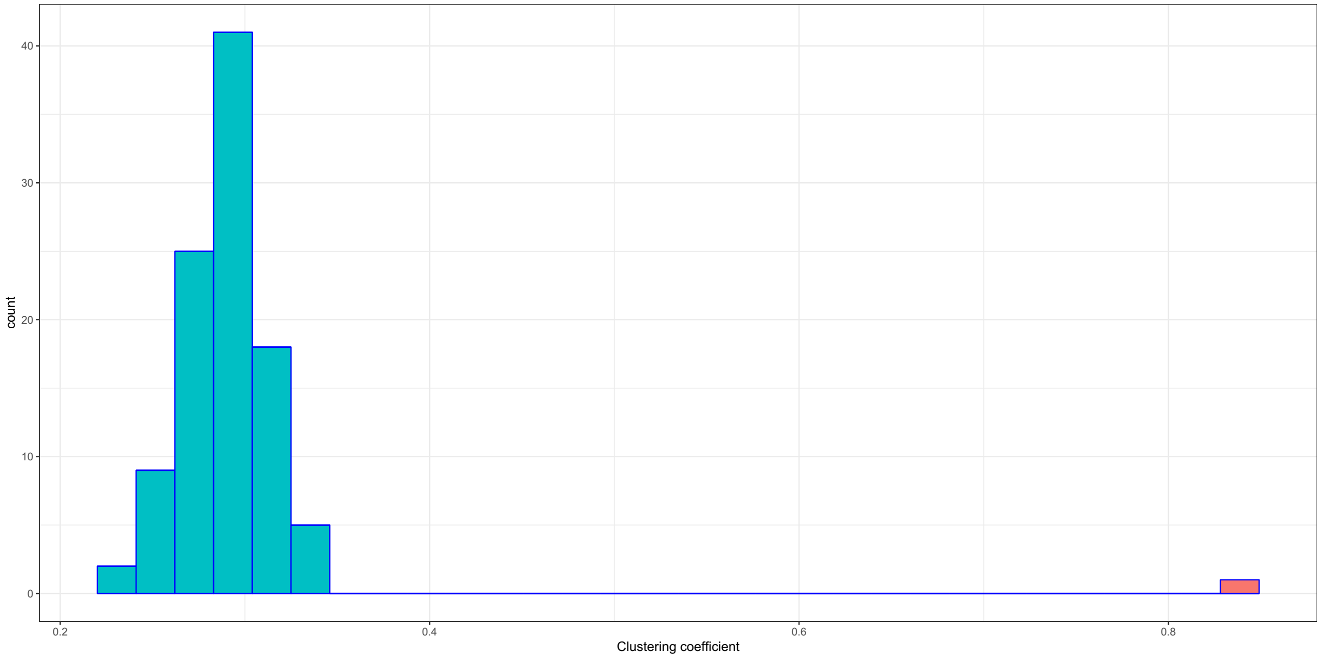

Fig. 3 Histogram of clustering coefficients (cc) for 100 random networks with 33 nodes (turquoise colored bars) and the observed clustering coefficient for the western Clovis lithic network (red bar)

We used Social Network Visualizer version 2.4 (Kalamaras 2018) to construct lattice and random networks. From these, we calculated average path lengths and clustering coefficients. Using Social Network Visualizer, we calculated the average path lengths and clustering coefficients from 100 Erdős–Rényi random networks that were equivalent to the Clovis network (with 33 nodes and 152 edges) and used the overall averages of these values in the ratios. Similarly, we constructed lattice networks with 33 nodes and an average degree of nine[1] to find the equivalent clustering coefficient for a lattice network. Example random and lattice networks are shown in Fig. 4.

Results show that Clovis raw material networks are non-random. For the western Clovis lithic network, $\sigma = 1.89$, and is consistent with a small world (i.e., $\sigma > 1$), whereas, $\omega = -0.62$ is consistent with a more lattice-like network (i.e., $\omega < -0.5$; Table 1).

Given the discrepancy between σ and ω values and the apparent modularity of densely clustered components in the overall network (the right and left clusters in Fig. 5b), we examined the substructure of the western Clovis lithic network. We conducted a Girvan-Newman (2002) partition analysis on the overall network and found support for the separation of the overall network into two components. The first component consists of 22 nodes and includes assemblages from the Southern Plains and Southwest (and one assemblage, Drake from Colorado with raw materials from the Southern Plains) that we labeled the southern component (Fig. 5a), and the second component with 11 nodes includes assemblages from the Northern and Central Plains, which we term the northern component (Fig. 5b). Results show (Table 1) that both northern and southern components are small worlds, as in both cases $\sigma > 1$ and $\omega > -0.5 < 0.5$.

How did Clovis begin to transform their lithic network into a small world?

The majority of lithic raw materials used by Clovis people in western North America during the late Pleistocene are distinctive and come from spatially discrete geological outcrops (Buchanan et al. 2016). As many archeologists have noted previously, finding artifacts made of particular lithic materials that were deposited far from their geological source provides a measure of how far that material has moved in the hands of people (examples for the Paleoindian period include: Ellis 2008; Frison and Bradley 1999; Goodyear 1989; Haynes 2002; Kelly and Todd 1988; Meltzer 2009). We were able to determine the geological source in 78 cases, for 36 different raw materials in the 33 assemblages (see Supplementary Materials Table S1), that range in distance from 0 to 955 km source-to-site with a mean distance of 227 km (95% C.I.: 183–269 km). Half of the source-to-site distances are 200 km or more and several of these cases traverse subregions (Fig. 6). For example, the Drake cache on the Central Plains of

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[1] Because the Social Network Visualizer (Kalamaras 2018) software creates random lattice networks using only even numbered average node degrees we interpolated the clustering coefficient for a lattice network with an average degree of 9 (the same average degree as the observed western Clovis network) by constructing lattice networks with average degrees of 8 and 10.

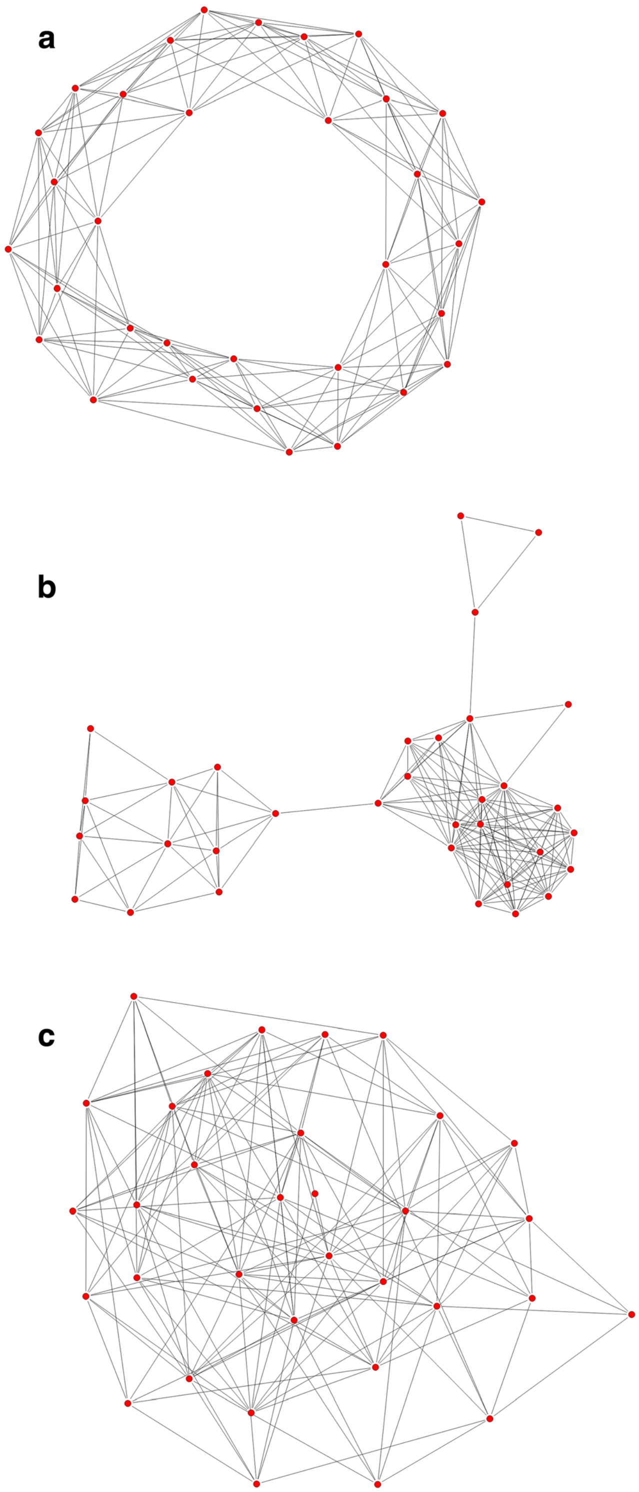


Fig. 4 Comparison of the western Clovis lithic network to examples of equivalent ring lattice and random networks. All networks have 33 nodes and are constructed using the Kamada–Kawai algorithm. The three panels are: **a** ring lattice network, **b** western Clovis lithic network, and **c** random network

Table 1 Network properties (nodes, edges, average path length [Avg. Path], and clustering coefficient [CC]) and σ and ω values for the overall western Clovis lithic network (the largest component) and subsets of this network (the northern component and the southern component)

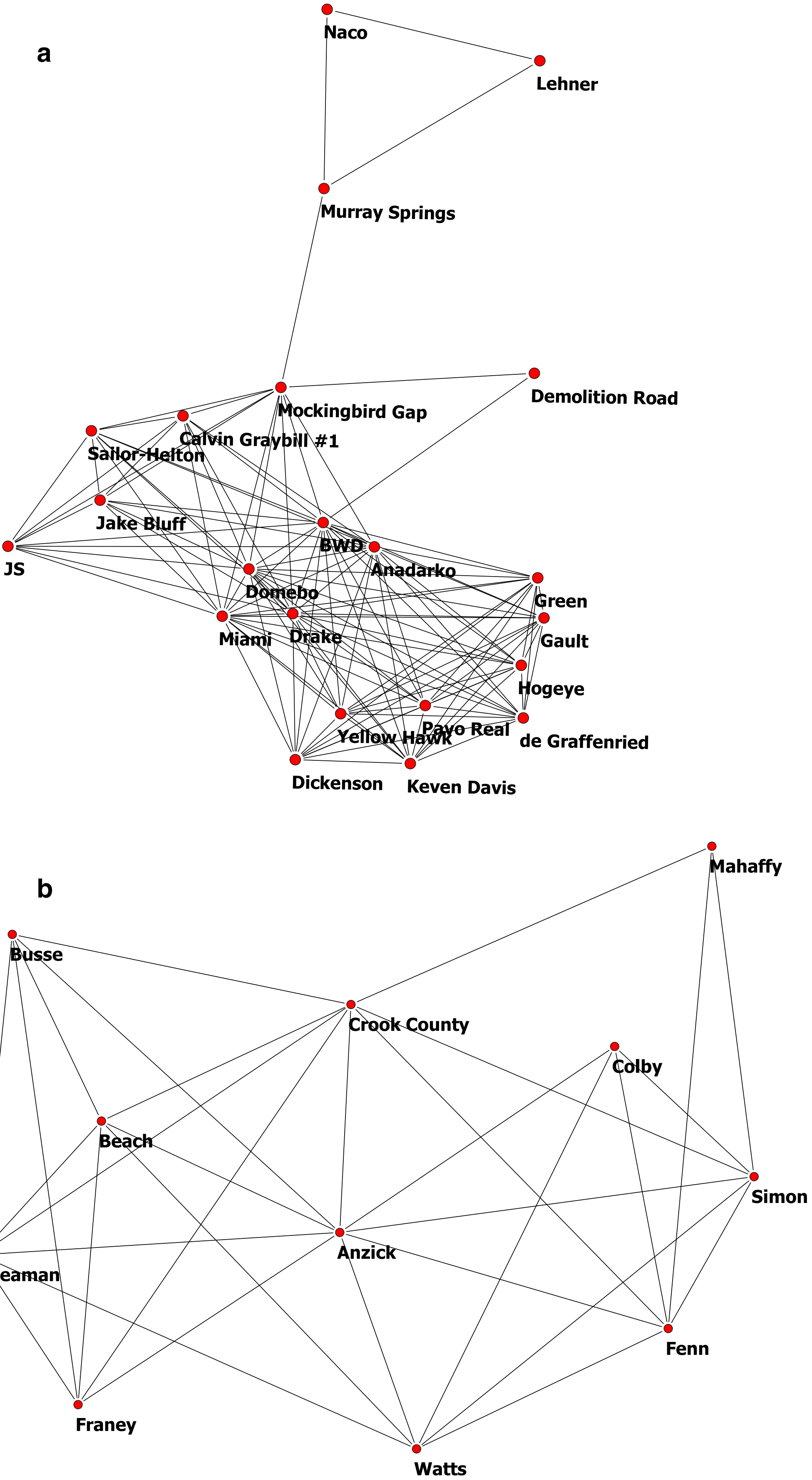
	Nodes	Edges	Avg. Path	CC	σ	ω
Largest component	33	152	2.72	0.84	1.89	− 0.62
Equivalent random	33	152	1.78	0.29		
Equivalent lattice	33	152	2.31	0.66		
Northern component	11	32	1.42	0.78	1.31	− 0.31
Equivalent random	11	32	1.42	0.57		
Equivalent lattice	11	32	1.40	0.60		
Southern component	22	119	1.74	0.89	1.12	− 0.46
Equivalent random	22	119	1.49	0.48		
Equivalent lattice	22	119	1.51	0.67		

Colorado has lithic material (Alibates and Edwards) from the Southern Plains, The JS cache in Oklahoma has lithic material from the Central Plains (Niobrara), and Mockingbird Gap and Demolition Road in the Southwest has lithic material from the Southern Plains. Thus, the lithic materials recovered in Clovis assemblages across the west show that Clovis people were transporting materials widely.

Many of the longest movements of lithic materials represented in our sample come from Clovis caches. Caches are primarily deposits of lithic materials that sometimes contain other bone or ivory artifacts and are interpreted as single activity locales that involve the deposition of artifacts for functional or ritual reasons (Kilby 2008, 2014, 2015; Kilby and Huckell 2013). Twenty of the top 23 long-distance movements of lithic materials from sources to sites are from caches. Overall, the lithic material in caches ($n = 40$) moved significantly farther than lithics found at other site types ($n = 38$) (both samples are skewed with long tails, therefore we used a Mann-Whitney test: $U = 403$, $z = -3.56$, $p = 0.0004$). Caches may have been deposited on long-distance forays (Kilby 2015), during interactions of people from different regions, or as central place load exchange locations (Kilby 2008, 2014, 2015). A separation of the sites into northern and southern components shows that the caches in the north have longer site-to-source distances than caches in the south where transport distances are similar to other site types (Fig. 7). Given these differences, we speculate that in the north, caches may have been used during exploration or to move greater distances because the higher latitude environment and lower biomass required longer forays, whereas in the south, caches may have been more often used as deposits to reduce the distances between sources and activity locations.

To further examine the contribution of caches to making the Clovis network into a small world, we removed the cache assemblages from the southern component and recalculated the network statistics and σ and ω values. We could not do this for the northern component because most of the assemblages (9 of the 11) are caches. For the southern component, we removed eight cache assemblages and examined the network

Fig. 5 The southern and northern components of the western Clovis lithic network using the Kamada–Kawai layout algorithm. **a** The southern component with 22 nodes and 119 edges, **b** the northern component with 11 nodes and 32 edges



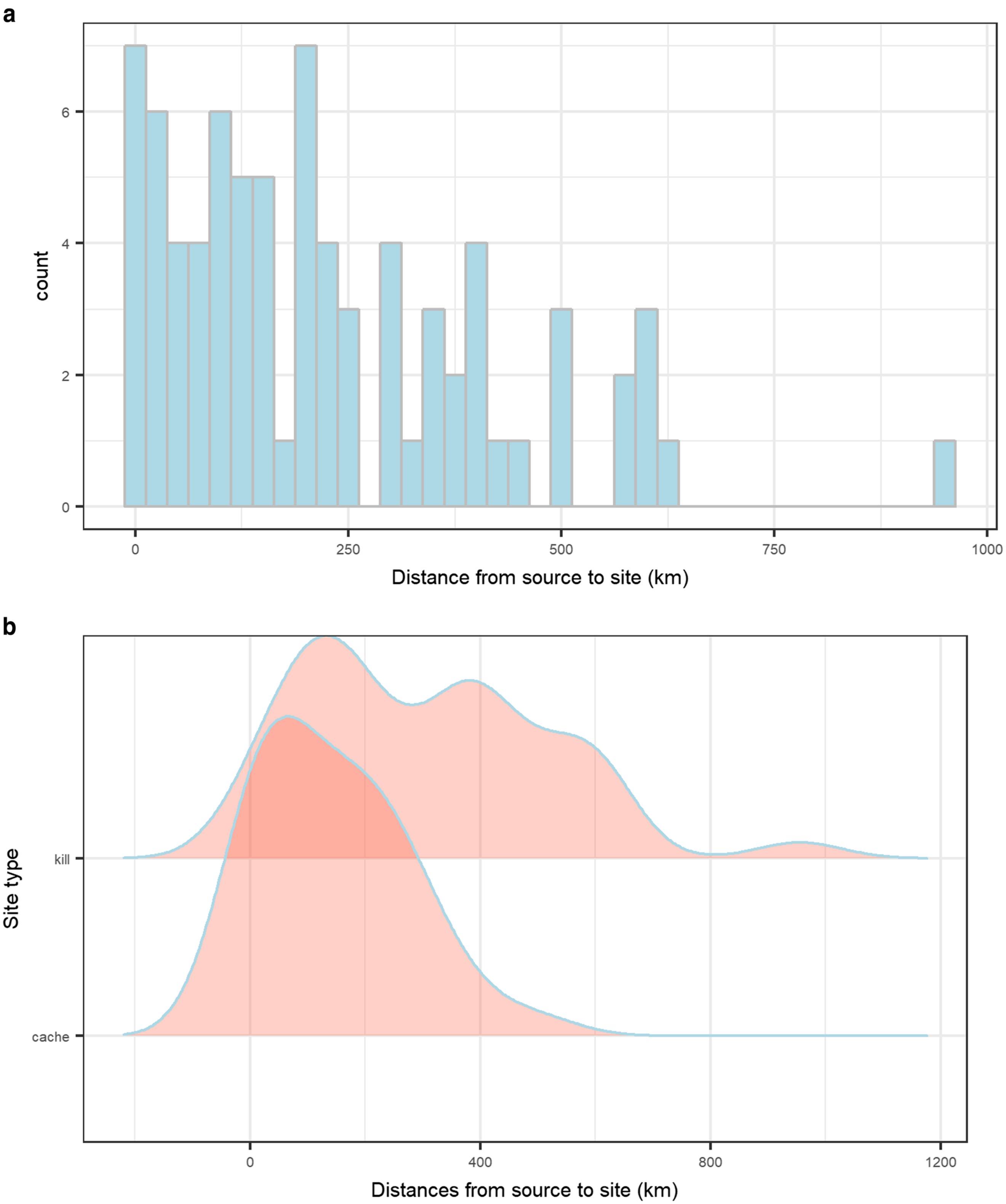


Fig. 6 Plots of the distances in kilometers from geological sources to western Clovis site locations. **a** Histogram of all 78 cases of lithic raw material transport, **b** density plots of lithic raw material transport distinguished by site type

properties of the remaining 14 assemblages. The average path length increases and the clustering coefficient decreases for the southern component when the cache assemblages are removed and the ω value indicates that the network becomes more lattice-like (Table 2). This evidence suggests that caches played an important role in creating a small world.

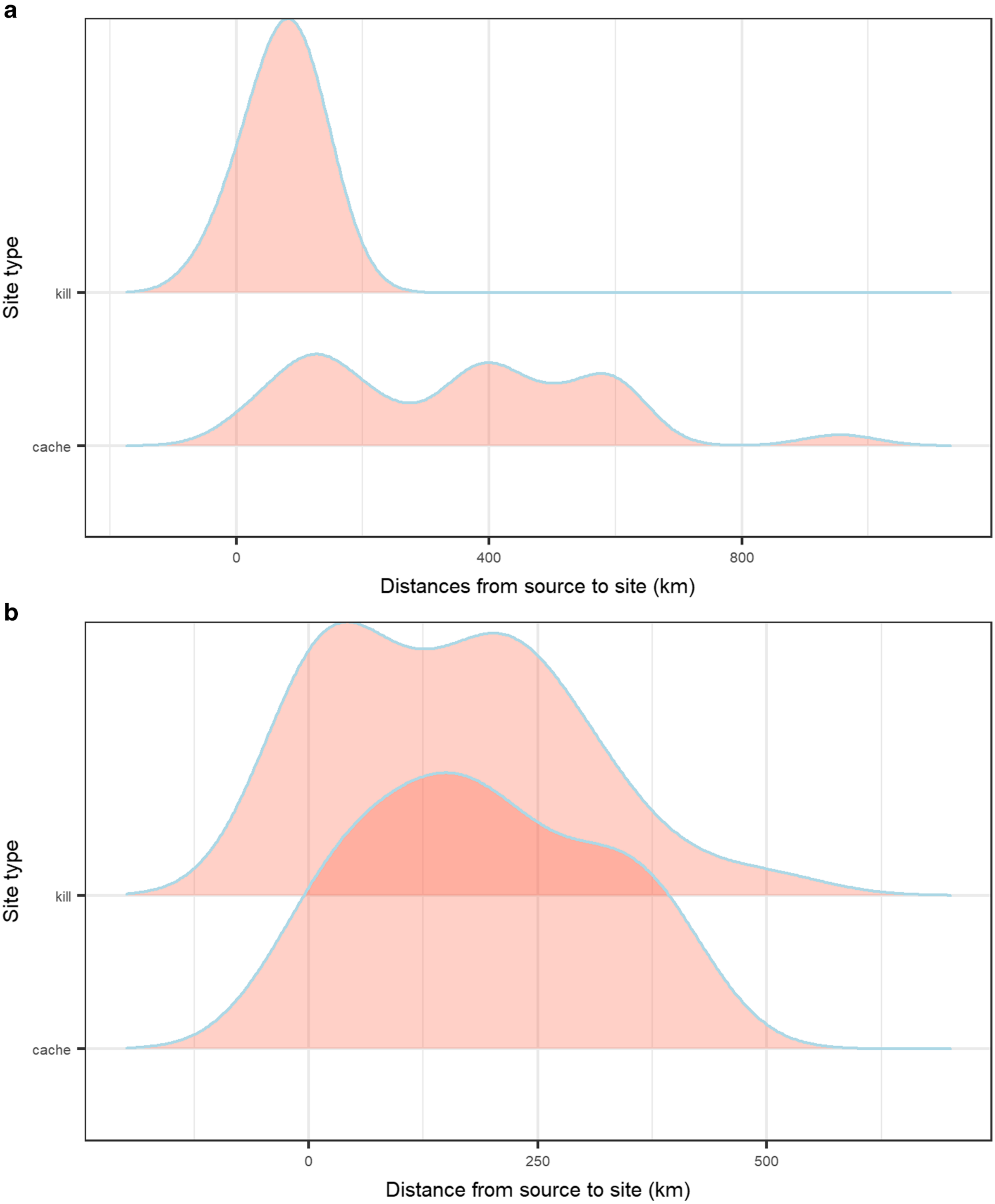


Fig. 7 Density plots of the distances in kilometers from geological sources to western Clovis sites in **a** the northern component and **b** the southern component. In both figures, the upper distribution are kill site assemblages and the lower distribution are cache assemblages

In addition to examining source-to-site distances that lithic materials were moved by Clovis people, we examined the importance of sites in the network in terms of connecting parts of the network. To do this, we calculated betweenness

Table 2 Network properties (nodes, edges, average path length [Avg. Path], and clustering coefficient [CC]) and σ and ω values for the southern component of the western Clovis lithic network (the largest component) with cache assemblages removed from the network

	Nodes	Edges	Avg. Path	CC	σ	ω
Southern component without caches	14	42	1.86	0.84	1.19	− 0.56
Equivalent random	14	42	1.57	0.47		
Equivalent lattice	14	42	1.62	0.60		

centrality measures for each of the nodes in the network and ranked them. Betweenness centrality calculates the number of shortest paths that travel through each of the nodes. For the northern component, the Crook County and Anzick assemblages have the highest betweenness centrality values that are more than two times the next betweenness centrality value (Table 3). Of the seven assemblages with non-zero betweenness centrality values, six are caches, which again indicates the importance of caches in the north. For the southern component, the Mockingbird Gap assemblage has the highest betweenness centrality. This site is located in New Mexico and links sites in Arizona to sites in New Mexico and the Southern Plains (Table 4). Only two of the seven assemblages in the southern component with non-zero betweenness centrality values are caches suggesting that caches are not as critical to creating a small world as they are in the north.

Discussion

Our results show that the western Clovis lithic network has a high degree of clustering that reflects the focused use of a few particular lithic sources within each region. The lithic network also has evidence of short cuts between clusters that reflect the long-distance movement of distinctive raw materials. These long-distance movements reduce the average path length of the network. We also show that caches are usually associated with stone that was moved long distances. Together, the clustering and the connections among regions suggests that the Clovis word was a small world. However, the two commonly used measures of network topology we used to measure small worldness gave conflicting results, one indicating that the western Clovis lithic network was small world-like and the other that it was lattice-like. Given these results, we partitioned the network into northern and southern components, the resulting measures of network topology then indicated that both components were small worlds.

What does it mean that the Clovis lithic networks were small worlds? Certainly, the high clustering within the overall network must partially be a function of the fixed location of the geological sources of the lithic raw materials. However, the location of geological sources does not set unalterable constraints on the eventual distribution of lithic materials in space; Clovis people regularly moved toolstone long distances and across regions. Therefore, the spatial distribution of the lithic materials is influenced both by the original source location of raw materials and the transport decisions made by Clovis individuals. With this in mind, the separation of the northern and southern components may have been the product of some sort of boundary. Both regions have sites that share many of the same lithic raw materials. The particular lithic materials found at these sites could have been transported by people acquiring raw materials directly from sources, or through exchange. In either case, the shared use of particular lithic materials indicates overlap in range and the lithic materials themselves may have been markers of territorial boundaries or identity. Thus, the north-south separation suggests that most movement of lithics was constrained within these regions and we can assume that this also limited social interactions,

Table 3 Betweenness centrality (BC) and standardized betweenness centrality (BC′) measures for the northern component identified by site type. Seven of the 11 assemblages in the northern component of the western Clovis lithic network are shown, the remaining four assemblages have betweenness values of zero

Assemblage	Site type	BC	BC′
Crook County	Cache	7.667	0.170
Anzick	Cache	7.533	0.167
Watts	Cache	2.333	0.052
Fenn	Cache	1.867	0.041
Simon	Cache	1.867	0.041
Sheaman	Camp	0.867	0.019
Beach	Cache	0.867	0.019

Table 4 Betweenness centrality (BC) and standardized betweenness centrality (BC′) measures for the southern component identified by site type. Seven of the 22 assemblages in the southern component of the western Clovis lithic network are shown, the remaining 15 assemblages have betweenness centrality values of zero

Assemblage	Site type	BC	BC′
Mockingbird Gap	Camp	58.00	0.276
Murray Springs	Camp/kill	38.00	0.181
Blackwater Draw	Camp/kill	24.80	0.118
Drake	Cache	12.80	0.061
Miami	Kill	12.80	0.061
Anadarko	Cache	12.80	0.061
Domebo	Kill	12.80	0.061

or at the least, the development of home ranges across this boundary (Buchanan et al. 2016). Another possibility is that the northern region was occupied earlier than the southern region and that there was little overlap in time between the occupations of the two regions. If the two regions were occupied consecutively, interactions between the regions would be impossible. However, examination of the limited number of dates in the north and south suggests that there was some temporal overlap in the occupation of the north and south regions (Hamilton and Buchanan 2007; Prasciunas and Surovell 2015).

If we assume lithic raw materials moved through populations via established social networks among dispersed groups of Clovis hunter-gatherers, then this would suggest Clovis regional social networks were small worlds of locally connected groups with occasional longer-distance connections. Small worlds would have thus enabled dispersed groups of Clovis hunter-gatherers to exchange lithic raw materials and information about the landscape and prey across a wider network and would have facilitated maintaining a viable mating pool in a dispersed, decentralized, and low-density population. On the other hand, if lithic raw materials were exchanged through dedicated lithic exchange networks, independent of the topology of other social networks, this would suggest that lithic exchange played an important role in connecting local populations. In either case, the small-world topology of lithic material movement indicates that Clovis economic exchange networks were far from random.

The long-distance movement of distinctive lithic materials is critical to the construction of small-world lithic networks. This long-distance movement of lithic materials would have had an added benefit in the Clovis world when geographic information about source locations were shared. This type of geographic information may have helped make the small-world networks navigable. This is a problem with small worlds that was pointed out by Kleinberg (2000), while the small-world models described by Watts and Strogatz (1998; Watts 1999) are topologically configured like small worlds, they are not necessarily navigable. That is, the shortest path between any two nodes in a small-world network is not known. Navigating the Clovis physical and social worlds may have been made easier by the fact that the materials being transported or exchanged were mostly distinctive and had discrete spatial source locations. If we consider the Clovis lithic network as one type of network that exists with other social networks such as kin relationships, friendships, mate exchanges, etc. we can speculate that the location of certain geological outcrops in a region was necessary spatial information that was shared among various groups and that this spatial information with its material component, the stone, helped to make the Clovis network navigable. However, the extent to which the various networks that Clovis people were part of overlapped is an empirical question and will take additional analyses of other components of their material culture to determine. Recent analyses of the post-European contact ethnographic record of Great Plains tribes suggest that within-culture networks may not overlap (Lycett 2017). This finding reinforces the importance of future work directed toward describing other Clovis networks.

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