Transformation of social networks in the late pre-Hispanic US Southwest

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The late pre-Hispanic period in the US Southwest (A.D. 1200–1450) was characterized by large-scale demographic changes, including long-distance migration and population aggregation. To reconstruct how these processes reshaped social networks, we compiled a comprehensive artifact database from major sites dating to this interval in the western Southwest. We combine social network analysis with geographic information systems approaches to reconstruct network dynamics over 250 y. We show how social networks were transformed across the region at previously undocumented spatial, temporal, and social scales. Using well-dated decorated ceramics, we track changes in network topology at 50-y intervals to show a dramatic shift in network density and settlement centrality from the northern to the southern Southwest after A.D. 1300. Both obsidian sourcing and ceramic data demonstrate that long-distance network relationships also shifted from north to south after migration. Surprisingly, social distance does not always correlate with spatial distance because of the presence of network relationships spanning long geographic distances. Our research shows how a large network in the southern Southwest grew and then collapsed, whereas networks became more fragmented in the northern Southwest but persisted. The study also illustrates how formal social network analysis may be applied to large-scale databases of material culture to illustrate multigenerational changes in network structure.

archaeology | North American Southwest | spatial analysis | network visualization | regional interaction

The late pre-Hispanic period (A.D. 1200–1450) in the US Southwest was a time of widespread social and demographic upheaval (1). The interval from A.D. 1275 to 1325 was a pivotal period characterized by long-distance migration and the coalescence of populations into large villages (2–4). These changes have been the subject of detailed material cultural studies focused primarily at the scale of individual settlements or clusters of sites, as well as regional-scale studies based primarily on settlement size and location data. In this study, we combine settlement and artifact data across the US Southwest west of the Continental Divide (hereafter the western Southwest) to formally explore how networks of interaction changed during this period of transformation.

Our analyses use formal methods from social network analysis (SNA) (5–7) and geographic information systems (GIS) (8) on a comprehensive archaeological database of ceramics and obsidian for the period of A.D. 1200–1450 from the western Southwest (*SI Materials and Methods*). The database we compiled contains information on more than 4.3 million ceramic artifacts from more than 700 archaeological sites and more than 4,800 obsidian artifacts from 140 sites in a 334,000 km^2 area of the western Southwest. Formal network analysis has recently become more widely used in archaeology (9), especially as large-scale databases amenable to network approaches such as ours, are being developed. Network analyses emphasize the relationships among nodes (e.g., individuals, households, settlements), rather than the nodal attributes traditionally studied by archaeologists such as status, function, or size. They are particularly compatible with regional archaeological analyses with settlements treated as nodes (10). Concepts from SNA that have been used by archaeologists include centrality and its relationship to nodal properties such as social status or persistence, and long-term network dynamics (11–13). By combining SNA with GIS, archaeologists are also able to test the degree to which spatial distance correlates with or diverges from social relationships. We draw on these concepts to look at how network topology changed during a particularly dynamic period in the Southwest. We also look at the degree to which spatial proximity predicts social connectedness based on material culture from archaeological settlements.

Results and Discussion

Ceramic Networks. Ceramic networks are defined using the more than 800,000 decorated (painted) ceramics in the database, grouped into distinctive technological and stylistic categories or wares (14, 15). Decorated ceramics were used in a variety of social contexts, including feasting and religious ceremonies, and to convey messages about ideology and group identity (16, 17). Past studies focused on ceramics suggest that similarities in archaeological assemblages are generated through a number of different processes including local transmission of production practices, exchange, emulation, population movement, participation in shared ideologies, and active signaling of social boundaries (18, 19). At the vast spatial and analytical scale addressed here, similarities in the consumption of decorated ceramics capture the effects of one or more of these processes and provide a general indication of some of the most important and frequently activated social relationships among settlements, communities, or larger social entities. At the macroregional scale, Southwest archaeologists have used wares to look at interregional interaction as they include both technological and stylistic information, especially for the period we address here (20–23). This method does not measure direct interaction of individuals between every settlement, but indicates shared practices including those of production, distribution, and consumption. Several large-scale ceramic compositional studies suggest that similarities in ware frequencies tend to correspond

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Data deposition: The Southwest Social Networks database is available through Archaeology Southwest (a nonprofit organization) by application. The database contains sensitive locational information for archaeological sites and is available upon request.

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to the actual volume of ceramics circulating among sites and regions, in particular during the period after A.D. 1300 (20, 24).

To summarize the strongest relations among settlements across our study area based on ceramic similarity, we constructed network graphs for each of four 50-y intervals (Fig. 1). We treat individual settlements as nodes in a network, with a tie between two sites defined by strong similarities in decorated ceramic assemblages. In graphic representations we present binary networks with ties defined as present or absent based on an absolute threshold of 75% decorated ceramic similarity, but most of our analyses, including centrality measures, are based on the continuous similarity scores among sites (*SI Materials and Methods*).

During the A.D. 1250–1300 interval, the majority of sites (~79%) fall within one of five major network components or clusters with the largest network components limited to the northern Southwest. The sites in these five network components are characterized by many overlapping internal connections with only a few external connections to sites in other network clusters. The last decades of the 1200s coincide with a well-documented period of depopulation out of the northeastern portion of the study area and a period of drought, although Southwest archaeologists do not attribute all depopulation to this environmental factor (1). There is greater agreement that depopulation involved immigration into the central and southern Southwest and aggregation into larger settlements (4, 25–29). During the following three intervals, regional network topology changed dramatically. The mean strength of ceramic similarities among settlements in the southern Southwest increased markedly through time after A.D. 1300, whereas in the north there was a brief decline after A.D. 1300, followed by a return to pre–A.D. 1300 levels (Table 1). The increased similarity shows that the southern river valleys became increasingly connected.

One way to examine archaeological social networks (as defined by decorated ceramic similarity) is through node or settlement centrality (30). In Fig. 1, node size is proportional to each settlement's eigenvector centrality based on weighted ceramic similarity scores among settlements. Eigenvector centrality is a robust measure that takes into account not only a node's immediate connections, but also those of the nodes to which it is connected throughout the network, with less weight placed on nodes with higher degrees of separation (*SI Materials and Methods*) (30). Between A.D. 1250 and 1300, the settlements with the highest eigenvector centralities were located in the largest network component (called the largest connected component, or the LCC, in SNA) in the top center of the graph, which is composed of settlements lying in both the northern and southern parts of the region. Two subregions were partially or fully depopulated by the next period: the Chuska/Chaco and Kayenta/Tusayan areas. These subregions were clearly separated from the largest network component in the north and generally have low centrality scores, suggesting that their isolation may have contributed to this depopulation. By contrast, each valley or basin in the southern Southwest was largely disconnected from other areas, all with low centrality scores.

After A.D. 1300, a new network subgroup emerged in the south that tied together settlements from multiple valleys. During the A.D. 1300–1350 period, when population coalesced across the western Southwest, eigenvector centrality of sites in the southern component increased. Common to all sites in this network component were shared high frequencies of decorated Salado polychrome pottery, a widespread ceramic tradition first made by small groups generally attributed to Kayenta immigrants and their descendants who moved from northeastern Arizona into central Arizona in the A.D. 1280s (16, 31). In the 1300s, this ware became

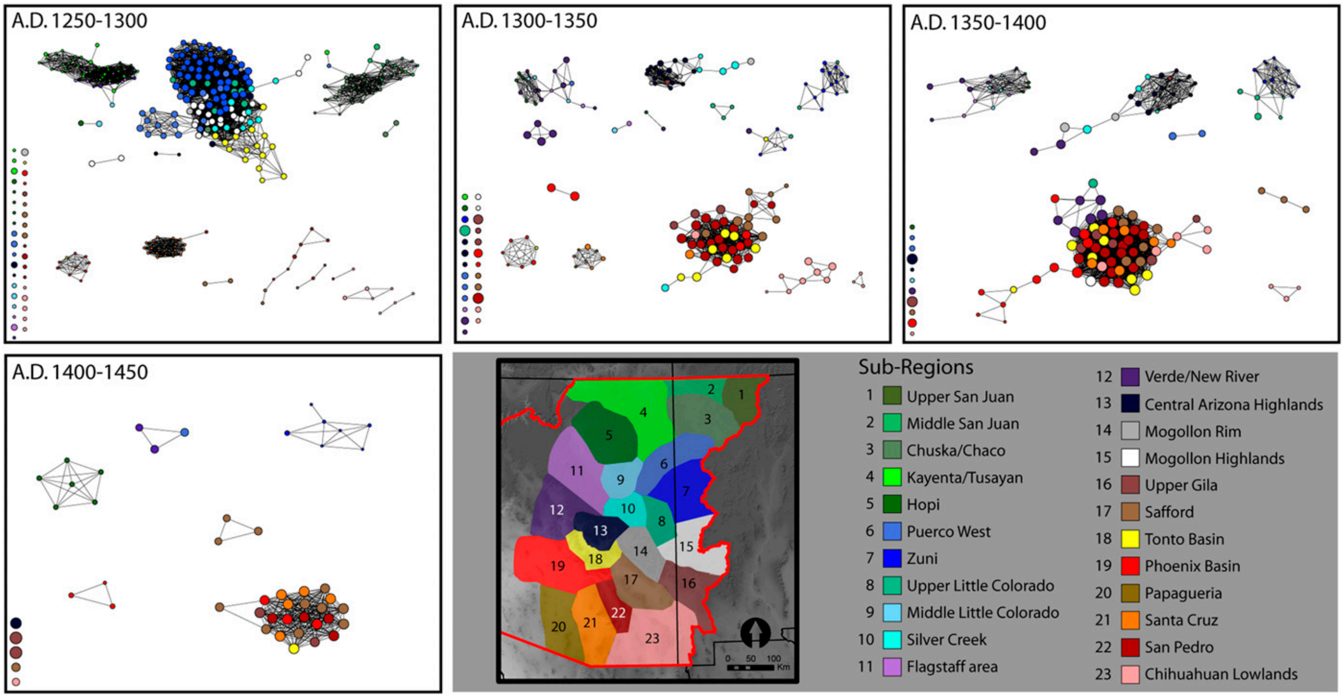

Fig. 1. Networks of ceramic similarity through time, color coded by archaeological subregion. Network graphs display all sites for which ceramic data are available as nodes with ties defined as ceramic similarity scores ≥75% of possible similarity. The relative sizes of nodes represent relative eigenvector centrality scores for each site. Although a binary network is shown here, centrality scores were calculated based on the raw similarities among all sites in the sample. Sites with no ties as defined by the 75% similarity threshold are shown in the bottom left of each plot. These graphs show a strong and consistent division between sites in the southern (warmer colors) and northern Southwest (cooler colors). During the interval of major migration (A.D. 1250–1300), networks in the southern Southwest consist of several distinct network components with low centrality scores. Through time, networks in the southern Southwest become increasingly central and well connected, whereas networks in the northern Southwest are increasingly regionalized and less central.

Table 1. Mean weighted (i.e., nonbinarized) degree centrality for the northern and southern Southwest by time period

	Mean standardized degree centrality				
Location	1200–1250	1250–1300	1300–1350	1350–1400	1400–1450
Northern Southwest	0.206	0.212	0.159	0.221	0.237
Southern Southwest	0.120	0.105	0.180	0.362	0.497

Scores were standardized by dividing by the total number of sites in each period.

widespread in the southern Southwest, especially at sites identified as migrant enclaves (25–29). The shifting topology of the network from the north to the south after A.D. 1300 is shown in the location of the LCC for each period and accompanying statistics (Table 2). Besides the spatial shift, the LCC includes an increasingly larger proportion of all of the settlement nodes in the full network increasing from 25% to 51%. The A.D. 1300–1350 period was clearly a transitional interval with the lowest average degree settlement centrality of all other periods.

The large southern network component persisted into the 15th century, but the densely occupied Phoenix Basin became increasingly isolated as regional population declined (4). In the northern part of the study region, ceramic networks fragmented with the strongest ties confined to major river valleys. Through time, the structure of the ceramic network in the northern part of the region increasingly resembled the structure of the southern Southwest before A.D. 1300. By A.D. 1450, the northern and southern Southwest areas were maximally disconnected. This period was when settlements in the southern Southwest became highly dispersed and has been referred to as a “collapse” or “decline” (4, 32). Settlements in the Hopi and Zuni regions persisted in the northern part of our study area, represented by two isolated settlement clusters each having distinctive ceramic assemblages.

Social and Spatial Connectivity. The same network dynamics are displayed geographically by showing differences in ceramic similarity tie strength between settlements (Fig. 2). In the 13th century, there were more long-distance ties in the northern Southwest than the south. Some of the longest distance connections tied sites in east-central Arizona to those in west-central New Mexico and those in northern Arizona to central Arizona. Through time, the relative proportion of strong similarities among distant sites increased, but in contrast to the pre–A.D.

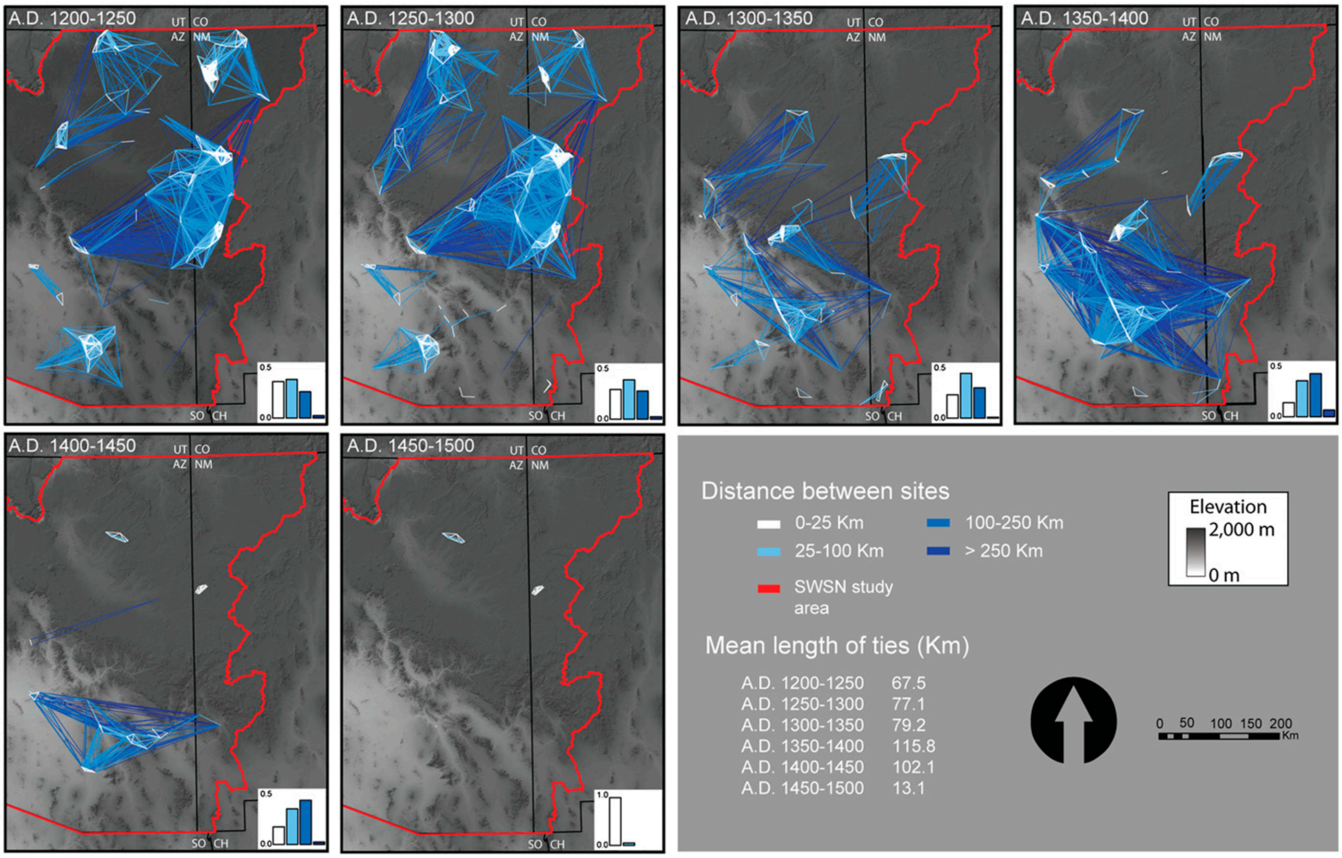

Fig. 2. Regional scale networks of ceramic similarity through time. These maps summarize the strongest patterns of potential connectivity across the study area by displaying ties among all settlements with ≥75% of possible ceramic similarity, color coded by the linear distance between settlements. Bar plots associated with each map show the relative proportions of connections of varying distance. The proportion of strong similarities among distant sites increases dramatically between the A.D. 1300–1350 and 1350–1400 intervals, in particular for areas below the Mogollon Rim. This shift shows that, by about one to two generations after the arrival of northern migrants in the southern Southwest, the spatial scale of connectivity among settlements had dramatically increased.

Table 2. Topological properties of ceramic networks through time

Period	LCC (%)	L	k	p	D	LCC location
A.D. 1200–1250	109 (39)	1,985	46.84	2.27	9	North
A.D. 1250–1300	125 (40)	2,085	41.25	2.34	8	North
A.D. 1300–1350	44 (25)	410	18.05	2.00	8	South
A.D. 1350–1400	65 (45)	1,173	42.22	2.00	8	South
A.D. 1400–1450	23 (51)	233	22.67	1.10	3	South

Location is whether the LCC is geographically in the north or south. D, diameter of the LCC (maximum distance between two nodes); k, mean degree for the total network; L, number of connections within the LCC; LCC, largest connected component within the binarized networks with the percentage of all nodes in this component in parentheses; p, average path length for the total network.

1300 network, most long distance ties (>100 km) were among sites in the southern rather than the northern Southwest, especially after A.D. 1350.

To explore how much the spatial distribution and density of settlements explains the degree of social connectivity, we need to compare variables characterizing social connectivity and potential spatial connectivity at the site level. Following common assumptions (33, 34) that most social interaction took place within a day's round trip walk of home, or ∼18 km, we anticipated that sites would have had stronger social connections to proximate sites considering that virtually all travel and movement of goods was pedestrian. Our first observation quantifies what is graphically shown in Fig. 2: that the mean distances among sites with strong social connections are surprisingly high, ranging between 70 and 120 km in all but the final period of our analyses.

We also examined the relationship between potential connectivity as a function of spatial proximity (taking terrain into account) and actual social connectivity as a function of material culture (here ceramic) similarities. Again following the assumption that social connectivity should be a function of spatial proximity, we calculated Pearson's *r* coefficients for all sites between this measure of potential connectivity and degree centrality. The *r* values never exceeded 0.34 for the study area as a whole, again casting doubt on the strength of the correlation between spatial proximity and connectivity (Fig. 3). These findings suggest that physical distance did not structure social relations as strongly as has been claimed (35), even in a context where pedestrian travel was the only means of transportation.

An interesting pattern becomes apparent, however, when we separate the study area into the northern and southern zones. Sites in the north show a considerably stronger positive correlation between spatial concentration and degree centrality, whereas sites in the south exhibit much weaker correlations that are even negative for some intervals (Fig. 3). Following widespread social upheaval in the north during the late A.D. 1200s, we see decline in this positive relationship in the north, although it remains consistently stronger than in the south, indicating the importance of long-distance contacts. By the last period for which we have comparable data from the two areas, in the A.D. 1400–1450 interval, we see the correlation begin to rise slightly in the north, whereas declining sharply in the south. This contrast suggests to us that by the end of our time range, social connections began to reorient themselves in each area as population declined across the region as a whole.

Obsidian Circulation and Ceramic Social Networks. The circulation of obsidian provides further insight into the relationship between spatial and social distance. Obsidian procurement and exchange patterns were constructed based on X-ray fluorescence (XRF) analysis of more than 4,800 obsidian artifacts from 140 archaeological sites throughout the study area (36). Obsidian, or volcanic glass, was an important raw material valued for its sharper-than-steel cutting edge and striking visual properties that has made it an object of symbolic value among many cultures. Importantly, obsidian can be traced to its geographic origin based on trace elements present in the raw material. If geographic proximity was the primary consideration in procurement and exchange, a site-to-source distance decay model should predict the relative proportions of obsidian sources represented in site assemblages. Substantial deviation from this null model would suggest that geography was not the only factor driving obsidian circulation. An alternative explanation, which we test against the ceramic data, would be that social connections among communities effectively reduced the procurement costs of otherwise distant materials, or the value of maintaining social relations outweighed procurement costs. In this analysis, simulated obsidian assemblages were generated with the expected proportion of each nonlocal source calculated using a gravity model based on the terrain-cost adjusted source-to-site distances (*SI Materials and Methods*).

We compared simulated obsidian source assemblages with the observed assemblages to identify sites that conformed to or deviated from the distance decay or gravity model (Fig. 4). For site-source ties that statistically deviated from distance decay, the specific over- and underrepresented obsidian sources were identified. Obsidian artifacts are not as well dated and can only be apportioned into two intervals (before and after A.D. 1300) using site occupation determined by ceramic cross-dating. During the A.D. 1200–1300 interval, nonlocal obsidian procurement was rare and limited largely to finished tools over debitage (31). Obsidian use in the majority of sites where data are available does not deviate from the distance decay model. The few exceptions are primarily sites in northwestern New Mexico where the Jemez source is overrepresented. These sites had ceramic assemblages that were more similar to each other than would be expected by chance, suggesting that this overrepresentation may be strongly influenced by the social networks responsible for the flow of decorated ceramics (*SI Materials and Methods*).

Dramatic changes occurred in obsidian procurement and exchange after A.D. 1300. Obsidian density increased more than 10-fold in many regions with the movement of raw material replacing that of finished tools (37, 38). The proportion of sites that deviated from distance decay differed significantly from the previous period, more than doubling (χ^2 = 10.4448, df = 1, *P*

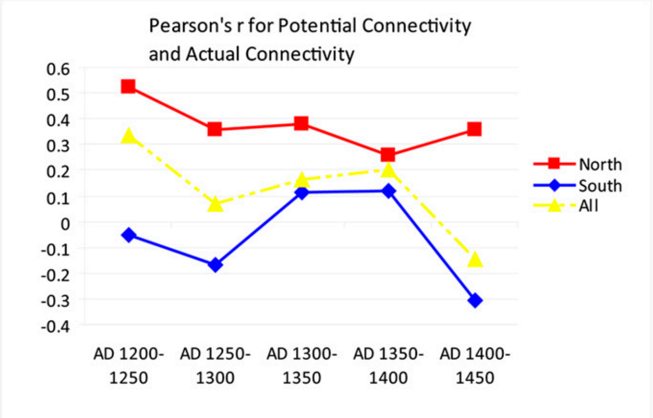

Fig. 3. Pearson's *r* between potential connectivity (based on distances modeled by friction surfaces shown in Fig. S2) and actual connectivity based on ceramic similarity scores. Relatively little social connectivity can be accounted for by spatial propinquity. The relationship is highest early on, and only for the north, illustrating how much long-distance ties make up the relationships among sites in both northern and southern networks.

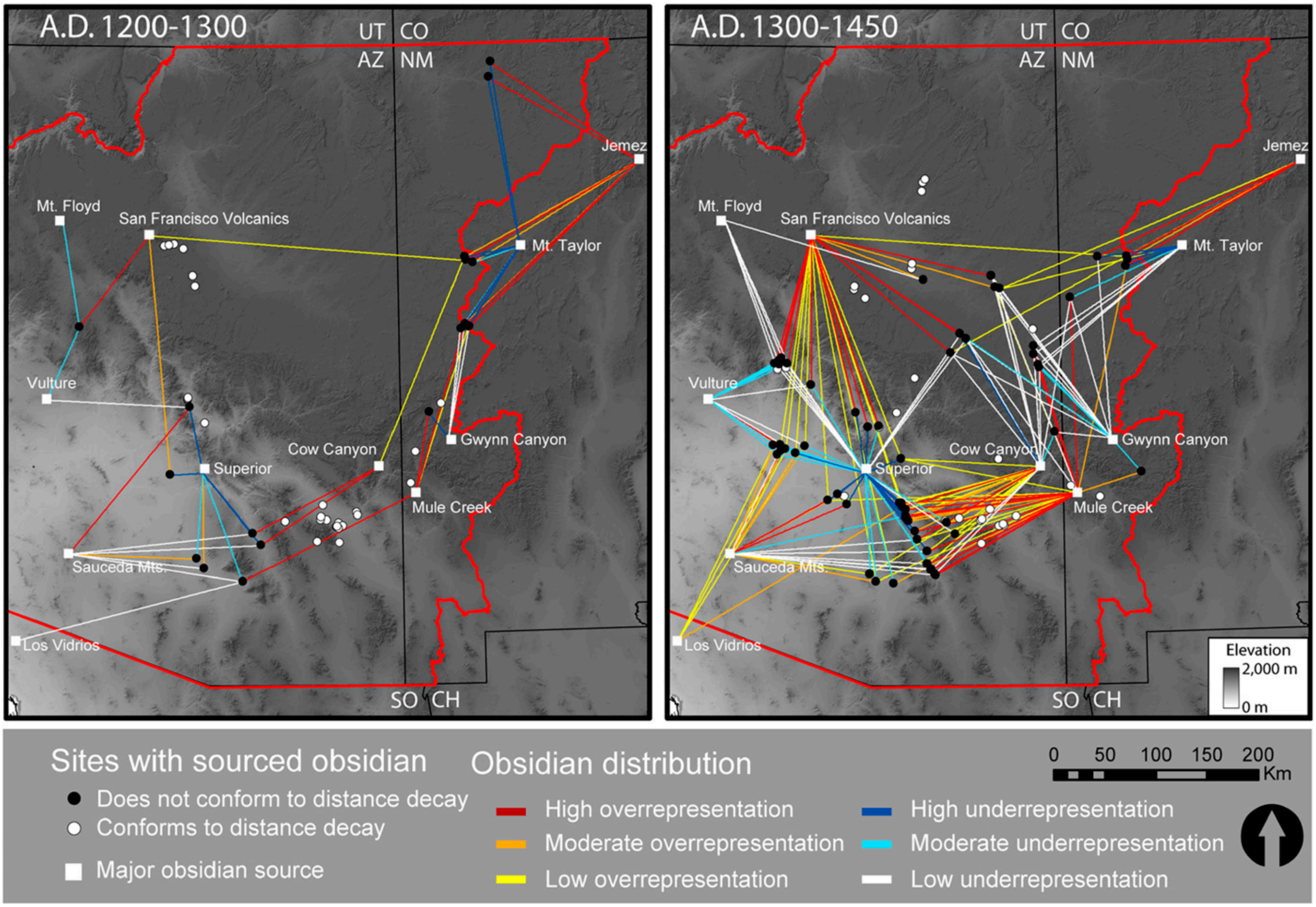

Fig. 4. Maps showing sites that do or do not deviate from expected patterns of obsidian procurement based on a gravity distance decay model before (A.D. 1200–1300) and after (A.D. 1300–1450) the major period of migration. Lines connecting known obsidian sources to deviating sites are color coded to indicate varying degrees of source over- or underrepresentation with respect to expected obsidian frequencies (*SI Materials and Methods*).

value = 0.001). Coincident with the southward shift in ceramic network centrality discussed above, the majority of sites that deviated from distance decay after A.D. 1300 were located in southern and central Arizona. With the exception of the San Francisco Volcanic source, which crossed ceramic boundaries, sites in which a specific source is overrepresented have significantly higher ceramic similarity scores. In particular, sites in which Mule Creek and Cow Canyon sources were overrepresented were also dominated by Salado polychromes, suggesting a strong relationship between obsidian circulation and ceramic networks in this particular case.

Conclusions

Our analyses show how dramatically social networks changed in the Southwest over a 250-y period. They reveal the complexity of interactions that occurred at an unprecedented spatial and temporal scale. One surprising result is the number of strong similarities in ceramic assemblages that exceeded 250 km in a context in which movement was exclusively on foot. These long-distance connections were highest in the century following a period of massive demographic change, including depopulation, migration, and settlement coalescence. Another result was the separation of networks in the northern and southern networks and the relative connectivity of networks in each area. The trajectories of both regions diverged after A.D. 1300 as the southern network continued to grow while the northern network contracted and became more fragmented. The southern Southwest became increasingly connected from a network perspective. However, many archaeologists believe that these were diverse, even multiethnic communities (4, 16, 27, 39), suggesting that participation in the network may have promoted integration. As population decreased in the 14th through 15th centuries (4), this network grew but, ultimately, proved unstable and disintegrated in the A.D. 1400–1450 period.

The process was very different in the northern part of the study area, where two distinct components emerged: one at Hopi and one at Zuni. The persistence of these two subregions when the southern network disintegrated in the 15th century suggests that the smaller networks may have been more sustainable in the long run—in fact they still exist today. The larger and denser southern network, on the other hand, could not be maintained, especially as population in the region decreased for reasons that are still hotly debated among archaeologists (4, 32, 40).

Network analyses, as presented here, can be applied to other areas and time periods to investigate how social and spatial networks changed, especially with known demographic changes. Archaeology has considerable advantages for understanding the dynamics of social networks because of the long temporal scale and a history of studying the interrelationship of spatial, social, and material variables. We expect that network analyses will become an increasingly attractive alternative to traditional artifact distribution approaches in understanding these relationships.

Materials and Methods

Ceramic Networks. Ceramic data were compiled from published and unpublished sources, reanalysis of museum collections, and infield archaeological analysis. Using the method described by Roberts et al. (41) (Fig. S1), ceramic assemblages for each site were apportioned into five 50-y intervals between A.D. 1200 and 1450 based on the estimated total population and occupation span of each site, as well as the cross-dated production spans for individual ceramic types recovered from that site. To construct network ties, we use an index of similarity based on the proportions of decorated ceramic wares among sites (Table S1) as a proxy for the strength of relations among the inhabitants of those sites (*SI Materials and Methods*). Emphasis is placed on the "strong ties" based on an absolute threshold of 75% decorated ceramic similarity rather than the "weak ties," which are based on those wares that are more rare (*SI Materials and Methods*) (42). Network graphs in Fig. 1 were generated in R based on binarized ties among sites with nodes positioned using the force-based Fruchterman-Reingold algorithm. Fig. 2 is also based on binarized ties among sites color coded by the geodesic distances between sites. Distances were calculated between sites in ArcGIS using projected Universal Transverse Mercator (UTM) coordinates (North American Datum 1927). Both artifact sample size and number of sites in the sample were tested through bootstrapped replicates to test robustness of centrality scores (Table S2).

Spatial Networks. To develop a measure of terrain cost-adjusted proximity among all sites, we created a friction surface (a surface indicating the relative energy costs associated with travel in any direction) around all sites occupied during each 50-y interval using ArcGIS. This procedure produces a continuous grid across the study area of terrain cost-adjusted distances from cell to cell. These grids were then divided into 10 concentric polygons of cost-adjusted radii (in 1-km intervals) around each settlement equivalent to the energy needed to traverse 1–10 km over flat terrain (Fig. S2). Because of variability in the terrain, the total spatial extent of each polygon at each radius differed across the study area. For each cost-adjusted distance (1–10 km), we defined each set of overlapping buffers as a single unit and counted the total number of sites within each set. For example, a site might have 2 sites within overlapping 1-km buffers, 6 sites within overlapping 2-km buffers, 10 sites within overlapping 3-km buffers, and so on. Fig. S3 shows the proportions of possible ties among sites within overlapping 9-km cost-adjusted buffers and among sites in different buffers by time period for the northern and southern Southwest. For each site, we then summed the counts across all 10 buffers into a single value, which we defined as our degree of spatial connectivity. This measure, which ranges from 10 and 1,350 in our dataset, provides a proxy of spatial connectedness across a range of local spatial scales. Sites that are closer (in cost-adjusted distances) to more sites over shorter cost-adjusted distances will have higher values. We then assessed the probability that sites within a common buffer had higher ceramic similarity scores than sites not in the same buffer (Table S3).

Obsidian Networks. Obsidian artifacts for this study were characterized using XRF and compared with the chemical compositional data from the 50 known geological obsidian sources in the Southwest (including northern Mexico) (36) (*SI Materials and Methods*). Eleven of these sources were determined to be present in our sample of 4,805 pieces of obsidian (Tables S4 and S5). Samples were analyzed using the Spectrace QuanX and Thermoscientific Quant'X energy dispersive spectrometers at the University of California at Berkeley's Archaeology Laboratories and the Thermoscientific Niton transportable energy dispersive spectrometer (EDXRF; http://www.swxrflab.net/anlysis.htm). Travel costs were estimated using the methods described in the previous section from each site with obsidian data to the perimeter of the 11 most intensively used obsidian sources.

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