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# Procurement and Distribution of Pre-Hispanic Mesoamerican Obsidian 900 BC–AD 1520: a Social Network Analysis

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**Abstract** Ancient economies have been characterized by many researchers as localized, highly controlled by political actors, and static over long periods of time. In Mesoamerica, recent research has cast doubt on these views, with the recognition of early market place exchange, production by households for exchange, and the wide-ranging integration of communities into regional trade networks. Here, we expand on an earlier network analysis of obsidian assemblages from the Maya region during the Classic and Postclassic periods to incorporate data for all of Mesoamerica between 900 BC and AD 1520. Using both visual graphical representations and formal network metrics, we find that the Mesoamerican economy was dynamic and generally not highly centralized over time. The topology of this interactive network underwent significant changes over time. In particular, trends towards decreasing network hierarchy and size culminated in the highly commercialized "international" economy of Late Postclassic period as noted in previous studies. Based on this analysis, we make the case that the ancient Mesoamerican economy was neither predominantly top-down nor static, and so does not conform with oft-held presumptions regarding preindustrial economies.

**Keywords** Mesoamerica · Obsidian · Network analysis · Exchange · Ancient economy

## Introduction

Debates over the character and vibrancy of preindustrial economies are reaching a tipping point. For decades, discussions of precapitalist economic systems, including

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those in pre-Hispanic Mesoamerica, have been dominated by conceptually framed interpretations that emphasize top-down political control, self-sufficiency, the predominance of local production, and relative stasis even over lengthy periods of time (e.g., Finley 1999; Hopkins 2005; Lucas 2004; Polanyi *et al.* 1957; Wittfogel 1957). Of late, these views have come under assault with new indications of household production targeted towards marketplace exchange, lessened evidence for top-down control by command, the increasing importance of long-distance networks, and indications of significant shifts in the volume and connectivity of flows over time (e.g., Berdan 1989; Blanton *et al.* 2005; Feinman and Garraty 2010; Masson and Freidel 2012; Morris 2005; Oka and Kusimba 2008; Smith 2004). Nowhere has the advent and integration of new sources of data, through domestic excavations, compositional studies, new analytical perspectives such as social network analysis, along with new conceptual frames, had a more dramatic effect on long-standing theoretical views than in our vantage on the economies of pre-Hispanic Mesoamerica (e.g., Feinman and Nicholas 2012; Garraty and Stark 2010; Hirth 1996, 2013). For example, Hirth (2013, pp. 85) recently noted “Mesoamerica provides an intriguing case in the study of ancient economic structure because it contradicts how preindustrial economies are assumed to operate.”

Traditional perspectives on the pre-Hispanic Mesoamerican economy emphasize a self-sufficient reliance on local agrarian output, both at the level of the household but also as the near-exclusive economic foundation for large cities and polities. For instance, in an oft-cited review, Sanders and Webster (1988, pp. 542–543) stated that “most Mesoamerican cities fall into the regal-ritual category and had minor economic functions apart from administering the surpluses produced by the attached rural farmers. It is on the regal-ritual level that we find the least differentiation between urban and rural communities. The sizes of regal-ritual cities were governed primarily by the sizes of the states that they served and the productive potential of the hinterlands they dominated.” Clark (1986) similarly argued that obsidian production at the major pre-Hispanic city of Teotihuacan was largely geared towards local consumption and that trade—principally between elites—constituted a relatively minor component of the pre-Hispanic economy.

Alternatively, some researchers have focused on the role of pre-Hispanic trade and exchange, but have argued that production and distribution were rigidly monitored by elites at major urban centers through sponsorship of attached specialists and workshops, and tight control and regulation of distribution via trade enclaves or direct relationships with elites at other urban centers (e.g., Michels 1979; Sanders and Santley 1983; Santley 1983, 1984). Clark’s interpretation of obsidian production at Teotihuacan was in large part a criticism of earlier work by Santley, who argued that Teotihuacan, the major political and urban center for much of the later Formative to Middle-to-Late Classic in Central Mexico (~250 BC–AD 600), emerged largely through the control of obsidian production and distribution inside its political boundaries, and profited from supplying much of Mesoamerica with this obsidian (Santley 1983, 1984; Santley *et al.* 1986). From this perspective, the role of production for exchange and commerce has thus been largely downplayed (Clark 1986; Mallory 1986), with household production presumed to be targeted mostly towards local consumption and the payment of tribute (Carrasco 2001). Other models of the Mesoamerican economy emphasized least-cost considerations and predicted geographically determined patterns of commodity movement over time that were largely mediated by central political authorities through modes such as redistribution (e.g., Sanders 1956; Sanders and Santley 1983; cf. Zeitlan 1982). Until recently, this rather static and "top-down" view of pre-Hispanic Mesoamerican production and distribution has been widely influential (e.g., Sanders and Price 1968; Steward 1949). Generally, only for the Late Postclassic period (AD 1200–1520) has it been recognized that local political control of production and consumption was relaxed as mercantile activity, the capitalization of some labor and goods, and market exchange became prominent components of the Mesoamerican economy (e.g., Berdan *et al.* 2003).

Select studies have considered the broader role of trade and exchange as a means to understand long-term change in pre-Hispanic Mesoamerica (e.g., Blanton and Fargher 2012; Blanton and Feinman 1984; Blanton *et al.* 1996, 2005; Hirth 1978, 1996, 2013; Rathje 1973; Turner and Sabloff 2012; Webb 1973). For example, scholars working from a world-systems perspective have focused on the role of long-distance exchange, production, and consumption in creating and reinforcing sociopolitical relations across this pre-Hispanic macroregion (Blanton and Fargher 2012; Blanton *et al.* 2005; Kepecs *et al.* 1994). Yet, even these perspectives have tended to impose a somewhat top-down or centrally focused vantage on economic practice. More recently, scholars have challenged long-standing elite-driven perspectives on pre-Hispanic Mesoamerican economies (e.g., Feinman and Nicholas 2012; Hirth 2013). There is an increasing recognition that many households produced in part for exchange prior to the Late Postclassic period (Feinman 1999; Feinman and Nicholas 2012; Hirth 2009), and that marketplaces (and the exchange of goods and services through them) were a basic component of economic activities in Mesoamerica well before Aztec times (e.g., Dahlin *et al* 2007; Feinman and Garraty 2010; Feinman and Nicholas 2010; Hirth 2013; Masson and Freidel 2012; Shaw 2012; Smith 2004).

More broadly, researchers (e.g., Chase-Dunn and Willard 1993; He and Deem 2010) applying world-systems perspectives also have emphasized the dynamic nature of both modern and ancient (Frank 1993) economic systems, noting both relatively short (decades) and long (centuries) periods of change during which certain economic shifts appear synchronous over broad spatial landscapes. Cyclical patterns of economic development, political centralization, demographic increase, and urbanization have been defined in places as geographically distant from one another as Europe and China for much of the last several millennia (Chase-Dunn and Willard 1993; Turchin and Hall 2003). Recently, scholars interested in studying the structure and diachronic dynamics of the modern world economy have increasingly turned to network analysis to understand how patterns of connection between cities or nations are structured, how that structure changes over time, and what impact shifting network structures have on the long-term political, demographic, and economic outcomes of particular localities and network actors (Alderson and Beckfield 2004; Fagiolo *et al.* 2010). In a previous paper (Golitko *et al.* 2012), we examined the role of changing network structure in the Maya area of eastern Mesoamerica using sourced obsidian assemblages. Through this diachronic analysis, we documented the increasing importance of maritime (relative to inland riverine) transport routes, a shift that contributed to the decline of inland Classic period Maya centers and subsequent fluorescence of coastally oriented cities in Belize and the northern Yucatan Peninsula during the Late Classic (~AD 600–800) and Terminal Classic (~AD 800–1000) periods.

In this paper, we expand on our previous analysis by conducting diachronic network analysis of sourced obsidian assemblages spanning Mesoamerica from the Middle Preclassic/Formative period (~900 BC) to the Late Postclassic (AD 1200–1520) period. We evaluate several assumptions that have long been held regarding both the pre-Hispanic Mesoamerican and other ancient economies. First, we evaluate the role of important pre-Hispanic urban and political centers in ancient trade networks—do major centers such as the city of Teotihuacan occupy central positions in network structure (e.g., Sanders and Santley 1983; Santley 1984) that might imply a highly controlled system of production and distribution, or are network connections more evenly dispersed among ancient communities? Second, we examine whether flows of obsidian were geographically determined largely by least-cost expectations, or if they display significant changes over time, including cyclical increases and decreases in their patterns of circulation. In network terms, we examine changes in network density, size, and hierarchy as measures of how integrated the regional obsidian distribution system was over time, and the degree to which particular places or political centers were able to exercise control over network structure and flow.

Based on the empirical analysis undertaken, we illustrate that long-distance networks across this macroregion do not conform either to the expectations of least-cost geographical models or state-dominated monopolies, and they certainly were anything but static over time. Instead, the topology of these pre-Hispanic Mesoamerican networks varied dramatically, with the major connections between eastern and western Mesoamerica shifting between coastal and inland routes, and between the Gulf and Pacific coasts. While our analysis confirms the "international" and commercialized nature of the Late Postclassic economy, we suggest that this was the outcome of long-term processes by which transport networks and the Mesoamerican economic world became increasingly more interconnected ("smaller" in network terms—see Watts 1999) over a 1,500-year period. Through network analysis, we present the ancient Mesoamerican economy as a dynamic counter-example to static models of premodern agrarian economies put forward by prehistorians, economists, and economic historians.

## Materials and Methods

### Mesoamerican Obsidian Assemblages

The ancient Mesoamerican economy was based on agrarian output as well as the production and transport of a wide variety of craft goods, specialty consumables, and raw materials including ceramics, feathers, salt, cacao, copal, tobacco, textiles, marine shell, jade, and during later time periods, metals such as gold, copper, and bronze (Blanton and Fargher 2012; Hirth 2013; Smith 2003a). Obsidian was another widely transferred good that served as one of the primary raw materials for making sharp-edged tools for thousands of years prior to the European introduction of steel. Obsidian in Mesoamerica serves as a valuable portal for the study of trade and exchange networks because of the large number of potential sources located in both central Mexico and the Guatemalan/Honduran highlands that were exploited, and because the characteristics of these sources have been intensively studied for decades via both geochemical and visual means (Braswell *et al.* 2000; Cobean 2002; Glascock 2002;

Glascock *et al.* 1998). Consequently, there is a large suite of archaeological assemblages throughout Mesoamerica from which samples of obsidian have been identified in a consistent and comparable manner to their source quarries. The large number of obsidian sources that were available to pre-Hispanic consumers (Fig. 1) provides a potential basis for the documentation of intersite and diachronic variation that then can be analyzed to infer and examine transport routes (e.g., Braswell 2003; Hammond 1972; Nelson 1985).

In our earlier study of the Maya area (Golitko *et al.* 2012), we compiled data from 121 pre-Hispanic sites spanning the period between AD 300–1520. We temporally segregated this sample into the Classic, Terminal Classic, Early Postclassic, and Late Postclassic periods. Our sample was chosen to encompass the region in which obsidian from the Guatemalan highlands—the most common sources present at Maya sites—was distributed and utilized. In the present analysis, we aim to comprehensively compile published obsidian source frequencies for all sites south of 22° north latitude and north of the Panamanian Isthmus, the region generally considered to encompass pre-Hispanic Mesoamerica (Fig. 2). We omit sourced assemblages from Zacatecas for which there is insufficient chronological information to assign the sampled pieces to a particular time period (Darling 1998). Our data were drawn from both prior summaries of obsidian provenience data (Braswell 2003; Nelson 1985; Dreiss and Brown 1989) and from primary publications including recent major sourcing projects at Tikal (Moholy-Nagy *et al.* 2013) and in the Valley of Oaxaca (Feinman *et al.* 2013) carried

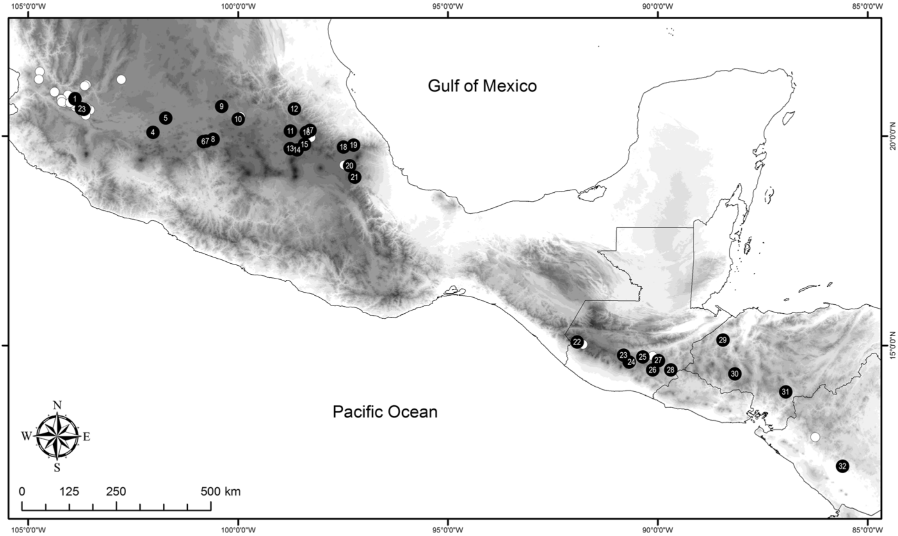

**Fig. 1** Location of obsidian sources in Mesoamerica. Sources that were identified at archaeological sites included in this study are indicated by *black circles with numerical labels*, while *white circles* indicate other known geochemically distinct sources. Digital elevation data were obtained from the USGS GMTED2010 dataset (Danielson and Gesch 2011). Sources are as follows: *1* Tequila, *2* Huaxtla, *3* La Primavera, *4* Cerro Varal, *5* Penjamo, *6* Zinapécuaro, *7* Cruz Negra, *8* Ucareo, *9* El Paraiso, *10* Fuentezuelas, *11* Sierra de Pachuca, *12* Zacualtipan, *13* Otumba, *14* Malpais, *15* Paredon, *16* Tulancingo, *17* Tepalzingo, *18* Zaragoza, *19* Altotonga, *20* Guadalupe Victoria, *21* Pico de Orizaba, *22* Tajumulco, *23* San Martin Jilotepeque, *24* San Bartolome Milpas Altas, *25* El Chayal, *26* Media Cuesta, *27* Jalapa, *28* Ixtepeque, *29* San Luis, *30* La Esperanza, *31* Güinope, *32* Nic-2

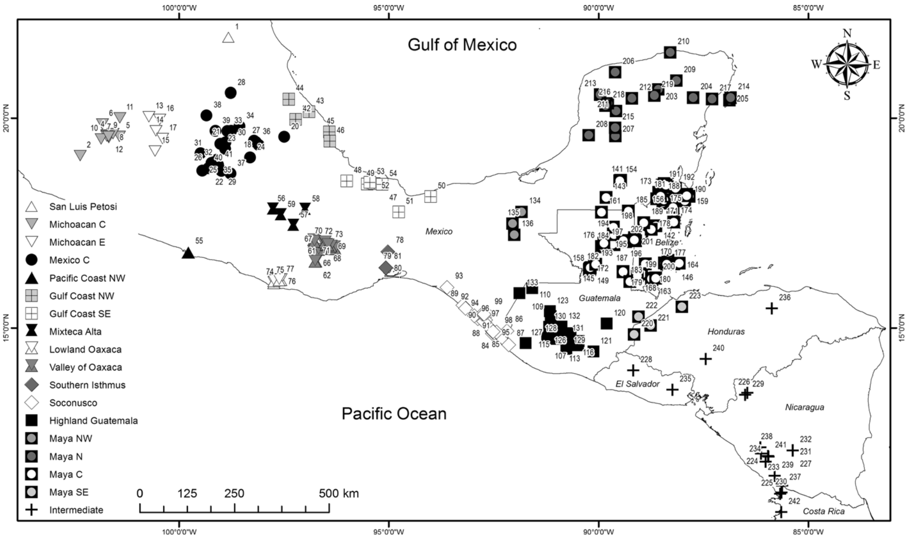

**Fig. 2** Sites with sourced obsidian in Mesoamerica. Sites are coded by region for comparison to network graphs. A complete listing of all obsidian assemblages included in the study can be found in the included online supplement

out by the authors. These data from Mesoamerica in our analysis include obsidian sourced by both chemical (INAA, PIXE-PIGME, XRF, LA-ICP-MS) and visual means. In total, we assembled an empirical record from 242 sites, which span the period from 900 BC to the end of the pre-Hispanic era (see Online Supplemental Tables).

We have pooled the assemblages included in this investigation into eight chronological time blocks, which we label periods 1–8 (Table 1). These periods roughly correspond with commonly utilized chronological phases for Mesoamerica, and generally span the Early Formative/Preclassic (periods 1–2), Middle Formative/Preclassic (period 3), Late-Terminal Formative/Preclassic (period 4), Early-Middle Classic (period 5), Late Classic-Terminal/Epi-Classic (period 6), Early Postclassic (period 7), and Late Postclassic (period 8). Although this set of data includes material dating as far

**Table 1** Compiled obsidian assemblages from Mesoamerican archaeological sites by time period. In this paper, we focus on periods 3–8

| Period | Dates | Phase(s) | Sites | >10 sourced samples |
|---|---|---|---|---|
| 1 | Pre-1200 BC | Formative | 17 | 16 |
| 2 | 1200-850 BC | Early Preclassic/Formative | 18 | 15 |
| 3 | 900-300 BC | Middle Preclassic/Formative | 40 | 28 |
| 4 | 250 BC-AD 250 | Late-Terminal Preclassic/Formative | 33 | 20 |
| 5 | AD 300-600 | Early-Middle Classic | 64 | 44 |
| 6 | AD 600-900 | Late Classic-Terminal/Epiclassic | 99 | 68 |
| 7 | AD 900-1200 | Early Postclassic | 50 | 28 |
| 8 | AD 1200-1520 | Late Postclassic | 87 | 61 |

back as ~3000 BC, the geographical coverage and sample sizes for the assemblages predating 900 BC were not sufficiently robust to merit inclusion in this analysis and interpretation. Consequently, we limit this discussion to periods 3–8. Periods 5–8 each span 300 years, while periods 3 and 4 aggregate longer temporal contexts, in each case 600 years. For these Preclassic/Formative assemblages, we opted to pool longer units of time in order to expand the number of sites included in each time block and improve the regional representation. Without question, we would prefer to have all the examined temporal blocks cover equivalent units of time, and be shorter in duration than the periods examined here. In the best-case archaeological scenario, time blocks of ~50 years have been utilized (Mills *et al.* 2013a), while other studies have pooled archaeological materials that may span up to a millennium of human settlement and activity (e.g., Coward 2013). For obsidian assemblages whose specified contexts overlap our temporal blocks, we placed the materials into the periods to which the majority of each specific occupation or context dates. As in our earlier study, we have omitted from this investigation all obsidian assemblages with fewer than ten sourced pieces. Such contexts (with small samples and so a high probability of distorted frequencies) have the potential to skew more meaningful and representative patterns. In some cases, when insufficient sample sizes characterize all available site assemblages for an entire region during a particular time block, we combined these site assemblages into a single pooled set of frequencies for the region as a whole.

## Network Analysis

Network analysis, including applications in archaeology, has been synthesized in a number of recent publications (Barabási 2003; Brughmans 2013; Knappett 2011; Knoke and Yang 2008; Wasserman and Faust 1994). For that reason, only a brief overview of our analytical frame will be outlined here, and we refer readers to these aforementioned overviews. A network consists of a set of actors ("nodes") and the connections ("edges") between them. Connections may be assigned between nodes based on virtually any index of similarity or contact, while nodes may represent almost any scale from an individual neuron in the brain up to major multinational corporations, specific settlements, or even nation-states. For instance, recent network studies of the modern world economy have utilized measures including the volume of imports and exports between nations (Bhattacharya *et al.* 2008; Fagiolo *et al.* 2010; Kali *et al.* 2007; Kali and Reyes 2007; Kick and Davis 2001; Mahutga 2002; Sacks *et al.* 2001), the location and sizes of corporate branch offices in different cities (Alderson and Beckfield 2004), as well as the volume of bank loans across international boundaries (Oatley *et al.* 2013). For Mesoamerica, network analysis has been previously applied to the study of intercommunity interactions in Formative period Oaxaca using shared pottery styles (Plog 1976), Aztec political and economic organization using roadway maps (Santley 1986), Maya political relations between contemporaneous cities based on epigraphic evidence of political relationships (Munson and Macri 2009; Scholnick *et al.* 2013), and architectural and material similarity to evaluate site stratigraphy (Munson 2013).

In contrast with many other investigatory approaches employed by archaeologists and other social scientists, network analysis does not assign explanatory primacy to the attributes of archaeological sites, actors, or cultures. Network analysis instead focuses primarily on the relations between actors. For instance, network positioning may place structural constraints on individual network actors. Nodes occupying advantageous positions—either because they have many connections, are connected primarily to other well-connected actors, or serve as important bridges between other network actors—are perceived as having a structural advantage that can be converted into long-term socioeconomic resilience or success, while those in disadvantageous positions may conversely have lesser opportunities (for prehistoric and ancient cases, see Menze and Ur 2012; Mizoguchi 2009; Padgett and Ansell 1993; Peregrine 1991; Pitts 1978/1979, for the modern world economy, see Fagiolo *et al.* 2010; Kali and Reyes 2007; Kick and Davis 2001; Sacks *et al.* 2001). Critically, network analysis does not require a priori definition of cores, peripheries, or other analytical constructs beyond the level of the individual nodes (e.g., Smith and Berdan 2003) in order to interpret the structures of particular economic or social systems (Terrell 2013). In consequence, network approaches can simultaneously incorporate multiple scales of analysis into a single global analytical construct or graph.

Our approach, in accord with those employed by other researchers (e.g., Coward 2013; Mills *et al.* 2013b; Mizoguchi 2009; Sindbæk 2007) treats shared material culture—in this case, obsidian from numerous sources in central Mexico and the highlands of Guatemala and Honduras—as a proxy measure for the degree or strength of connectedness between ancient settlements. Nodes represent sourced and temporally contextualized obsidian assemblages for whole archaeological sites, presumed to reflect spatially discrete pre-Hispanic settlements during one of the specified time spans. In the future, it may be possible to treat variability at a finer grain, for instance at the level of the site sector or even household. Yet such distinctions are possible only where very large datasets are available (for instance, Feinman *et al.* 2013 or Moholy-Nagy *et al.* 2013), which is not the case for the majority of analyses reported in the literature.

We rely on the Brainerd-Robinson (BR) coefficient—which ranges from 0 (complete dissimilarity) to 200 (complete similarity)—as a measure of edge weight between the sites in this analysis (Golitko *et al.* 2012; Mills *et al.* 2013b). This measure is calculated on source frequencies, not numbers of sourced pieces. The use of this approach generates weighted (edges are valued rather than treated as simply present or absent), undirected (connections do not indicate flow in a particular direction between nodes) networks (e.g., Hanneman and Riddle 2005). Analyses of both social networks in general (Garlaschelli and Loffredo 2004) and the modern world trade network in specific (Fagiolo *et al.* 2010; Garlaschelli and Loffredo 2005) indicate that networks can often be simplified to undirected approximations without the loss of key structural information.

### Network Visualization

We visually display the analytical graphs (or networks) produced in two different ways to emphasize distinct aspects of each network's structure. The first of these is the same approach we applied to constructing the graphs employed in our earlier study, which has been termed the "mini-max" approach (Cochrane and Lipo 2010). A link-weight cutoff is set at the value at (or above) which all nodes so connected are considered to be linked to one another. Nodes are then positioned relative to each other using spring embedding (DeJordy *et al.* 2007), a form of multidimensional scaling that treats nodes and edges as a physical system of springs—nodes are positioned so that the total level of energy in the system is minimized. This approach prevents nodes from overlapping while still preserving a large amount of the overall structure of the network in a two-dimensional display. This analytical tack allows for a concise visual display of the network proximity between nodes. Nodes are coded by region (see Fig. 2), but these regions are not used as formal analytical constructs, do not necessarily represent culture-historical or political boundaries, and are only displayed to allow for the easy recognition of geographical placement relative to network positioning on mini-max graphs.

We also include graphs with each node positioned geographically. Rather than displaying all links equivalently, we dichotomize between those we label "weak" links (BR values of less than 94) and those we label "strong" links (BR coefficients of greater or equal to 94). These values were chosen as they represent the respective highest and lowest mini-max thresholds needed to completely link the six networks we analyze. In principal, these values are entirely arbitrary, however, this approach does allow for the rapid visual inspection and comparison of the distinct patterns of strong and weak links that characterize each of the time periods. When we refer to stronger or weaker ties between nodes in the network, we refer only to this dichotomization of ties by these link weights, and not to the more formal definition of weak ties as used by Granovetter (1973) and other authors, referring to weaker ties bridging densely connected network clusters via nodes referred to as brokers (Burt 2005; Peeples and Haas 2013). We return to the question of brokerage and weak ties in the more formal sense in our discussion of results. All network visualization and plotting was performed using the NetDraw module associated with the UCINET software package.

## Interpreting Archaeological Similarity Networks as Distribution Networks

Economies can be modeled as consisting of three primary components—production, distribution, and consumption. In the present analysis, we draw on the end result of consumption patterns for obsidian to model distribution networks. By adopting this approach, we largely omit production from the analysis to focus on patterns of linkage between Mesoamerican settlements. We examine and compare key structural aspects of a sequence of distribution systems in ways that can be formally expressed using network terminology and a set of relevant metrics. Except where noted, all formal network measures were calculated on unbinarized matrices of BR or normalized (BR/200) BR scores (Peeples and Roberts 2013), employing measures developed for analysis of weighted networks (e.g., Opsahl *et al.* 2010). Network measures were calculated using the *igraph* and *tnet* packages in R.

Our analysis focuses on two primary topological properties of pre-Hispanic obsidian distribution networks—integration and hierarchy—and how they change over time. We recognize that in the social sciences, integration is often a relatively ill-defined and somewhat vague concept, so we utilize multiple network metrics to examine different aspects of regional connections. Specifically, we measure network density (the ratio of present connections to potential connections given the number of nodes for a particular time period) and network size (Hanneman and Riddle 2005; Watts 1999). We assess network size using two measures, diameter (the longest path between any two nodes) and average path length. Additionally, we calculate the standard deviation of path lengths (expressed as a relative standard deviation to eliminate correlation with average path length) as one measure of how evenly distributed links are between nodes. For network size, weighted versions of measures were utilized, treating higher link weights as less “costly” to traverse (Opsahl *et al.* 2010). Generally speaking, a highly integrated network should have some combination of high density, relatively evenly distributed ties, as well as small diameter and path length, but these multiple measures of integration also allow us to assess different topological (structural) possibilities for network integration rather than a simple statement of whether one particular network is more or less integrated than another.

Network hierarchy typically is assessed by examining degree distribution (rank-ordered degree centrality values either by percentage of nodes included in particular ranges of degree values or by rank ordering degree) and measuring network assortativity (whether nodes tend to connect to other similar nodes or whether poorly connected nodes tend to primarily link to well-connected nodes) via degree correlations or by using methods such as block modeling (e.g., Kali *et al.* 2007; Mahutga 2002; Kim and Shin 2002). Here, we calculate degree, eigenvector, and betweenness centrality values (Freeman 1977; Hanneman and Riddle 2005; Wasserman and Faust 1994) for each site during each time period, again using measures developed for analysis of weighted networks, which treat higher link weights as less costly to traverse (Opsahl *et al.* 2010). These three measures are then used to calculate network level centralization indices (Freeman 1979; Peeples and Roberts 2013; Wasserman and Faust 1994), which express the distribution of centralization measures across all network nodes. In an extremely hierarchical network, a handful of nodes will have far higher levels of centrality than other network nodes, resulting in high centralization indices. In a nonhierarchical network, the distribution of centrality scores will be relatively flat, and centralization indices correspondingly low. Note that our use of hierarchy here is expressed in network terms and also refers specifically to the distribution of obsidian, not necessarily its production or the volume transported through a given node. Minc (2006) presents several metrics for examining hierarchy using more traditional archaeological approaches to assemblage diversity and trade volume that might in the future be productively combined with formal network analysis to better estimate network hierarchy.

In economic analyses of modern economies, this suite of metrics is typically applied to direct measures of commodity flow to assess network positioning—how many imports (in tonnage, value, or some other measure) and/or exports moved between two nations or cities in a given year. These measures directly incorporate data on both volume and directionality of flow to assess how individual network actors are positioned; the measures may then be synthesized to describe network topology. Using archaeological data in the manner we do—with similarity coefficients as a proxy measure for connection strength—introduces another level of interpretive complexity to our analysis. We are not directly measuring the volume of flow between nodes, but rather inferring the path by which flow traversed the network, and interpreting stronger network links as indicative of heavier volumes of flow.

It is appropriate here to stress also that we are not reconstructing ancient trade networks in the geographical sense of a literal mapping of how obsidian physically moved across the landscape. Our approach instead examines the end product of a temporally defined sequence of obsidian exchanges through diverse transport routes.

Based on the resultant distributions of obsidian, we infer the relative strength of the connections between all places included in the analytical sample for each time block. We treat the underlying geographical features that constrain and facilitate transport—for instance, the routes recently reconstructed by White and Barber (2012)—as less variable over time.

A simple thought experiment serves to illustrate that the approach adopted here does not generate a physical representation of transport corridors. Imagine two distribution systems, one a classic "down-the-line" system and the other a classic "redistributive" system (Renfrew 1977), each with obsidian fed in from one direction. This input of obsidian consists of specified frequencies of available sources obtained from more distant network links. In the first case, obsidian is transported from one settlement to the next in line, and unless there is some particular preference for one kind of obsidian over another, each site in the chain will end up with approximately the same relative frequencies of different sources. In the redistributive system, obsidian is first transported to a single central node, than redistributed out to surrounding settlements. Again, unless there is a preference for a particular source material, each settlement will obtain approximately the same relative frequencies. A network constructed from a similarity matrix of relationships between each site will in both cases map out as a complete network (one in which all possible ties are present) with about equal strengths of connection between each node. Of course, other researchers beyond scholars of formal network analysis have long noted the issue of equifinality of outcomes (e.g., Hodder and Orton 1976). There are other topological possibilities for underlying transport networks besides the two we present (e.g., Minc 2006), all of which might hypothetically also result in the same reconstructed similarity network. The introduction of obsidian input from multiple directions will result in variant frequencies and more interesting and informative network topology, but not necessarily an exact mapping of the physical path of transport.

Consequently, it is clear that network mapping based on assemblage similarities measures generalized strengths of interconnection rather than the exact topology of the underlying transport links between sites. This thought experiment should also make clear that calculating the exact degree or betweenness of a node is not achievable using our approach—in both the down-the-line system and distributive system, there is variability in both these measures for different nodes, yet all nodes in the resulting similarity network have identical node-level properties. If one introduces multiple directions of flow, node-level measures may move progressively closer to their actual values in the underlying distribution network.

Metaphorically, we envision an archaeological network constructed from assemblage similarity measures as akin to photographing the flow of obsidian through a latent transport network (consisting of terrestrial and aquatic paths between settlements) for a set period, closing the shutter, then opening it again for another set interval, producing a series of cumulative "snapshots" of network activity. The strength of a tie between two settlements (think of a path growing darker on the photo as more traffic moves along it) reflects a combination of the volume of transport between nodes, the path length traversed to connect those nodes, and the duration or regularity of flow along a connection between two nodes. Consequently, we interpret tie strength in the weighted networks as indicative of the probability that that tie was present, operational, and significant in the past. Although formal network measures may not entirely reflect accurate network positioning for each individual node, patterns of connectivity and other global network patterns—particularly as they vary between time periods—still have analytical utility and allow us to make general statements about features of network topology such as centralization, density, and other measures (e.g., Mills *et al.* 2013a).

### Impact of Sampling

Incomplete sampling is a near certainty in network analysis, and this issue has been extensively examined in the literature (e.g., Borgatti *et al.* 2006; Knoke and Yang 2008; Kossinets 2006). Prior studies examining sampling effects have found that while many node-level measures such as degree centrality may be heavily impacted by sampling, network metrics such as betweenness, centrality, and diameter are robust to node removal (Wey *et al.* 2008).

In archaeology, it is difficult, perhaps often impossible, to estimate how many sites form the "complete" ancient network that is being examined and sampled from. For instance, the ~20–60 archaeological sites in our reconstructed networks likely represent far less than 1 % of all settlements and centers that may have existed in Mesoamerica during any one of our analytical time blocks. However, using a dissimilarity measure to generate links from frequency data adds a level of robustness against incomplete sampling—archaeological sites in close spatial proximity to one another are likely to have similar obsidian assemblages, so that a small sample of sites with good regional representation may preserve many formal aspects of network structure, as Mills, Clark, and colleagues (2013, supplemental information) demonstrate for their Southwestern US dataset using bootstrap analysis. In particular, while individual scores for nodes may fluctuate depending on sampling, network level summary statistics such as centralization tend to remain fairly constant.

There are further spatial concerns in regards to using source similarity data. Sites that are situated near to only a few obsidian sources (for instance, in eastern Mesoamerica) may as a result have higher average link weights between them than sites located in an area of higher source diversity (for instance, in western Mesoamerica). We do not view this as a particular problem—geography and source distribution will naturally constrain economic network structure, and as a result this effect is simply one other factor that generates network topology along with transportation technology, political factors, and numerous other variables. We are in any case particularly interested in examining deviations from that expected geographical patterning. However, in the case of settlements located in the immediate vicinity of an obsidian source (what Renfrew (1977) called the "supply zone"), residents might be far less likely to obtain obsidian from elsewhere (although if that source was exported in any significant quantity, connections will still be evident), and consequently that site might appear less connected into local networks than was actually the case. This is a problem with our approach that might be addressed in the future by expanding to examine other classes of material culture.

## Visual Interpretation of Network Graphs

In visually examining the networks we construct, we make note of several key structural components that may potentially change over time. First, because obsidian sources in Mesoamerica are geographically localized in two major areas—central Mexico and the Guatemalan-Honduran Highlands—we might anticipate that network clustering will mimic this pattern—resulting in bipartite graphs with weak east-west linkage—particularly if static least-cost models of the Mesoamerican economy hold true. It is of particular interest to examine both how strongly this geographical patterning holds, but also where the prime links between these two major areas (which we refer to as "western" and "eastern" Mesoamerica) are positioned. In other words, do the major transport links between eastern and western Mesoamerica shift over time? Second, we visually examine how particular central localities or places were positioned relative to network structure over time. Do certain large/key centers play important bridging roles between different regions of Mesoamerica, or in the extreme, dominate network topology? Finally, we examine the geographical distribution of links to examine whether density and link strength fluctuate within particular parts of the graph or geographic regions over time.

## Period 3 (900–300 BC)

Based on visual inspection of the mini-max plot constructed for period 3 (Fig. 3), we see that network structure conforms to the expectation that the geographical positioning of obsidian sources should generate a roughly bipartite division between eastern and western sites, and that the two Gulf Coast centers for which we have data had key bridging roles between eastern and western Mesoamerica during this period (Fig. 3). In formal network terminology, these Gulf Coast centers appear to serve the role of brokers (e.g., Burt 2005; Peeples and Haas 2013), linking more densely connected

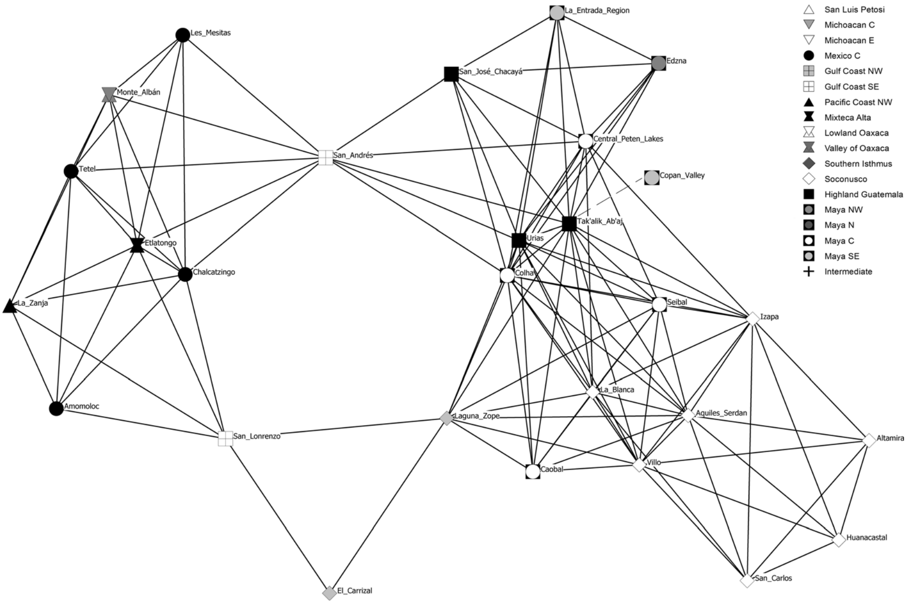

**Fig. 3** Spring-embedded network graph of period 3 (900–300 BC) obsidian assemblages with edges drawn at a threshold value of ≥57, the minimum value at which all nodes with the exception of the Copan Valley connect into the network. The *dashed line* represents a connection at BR=11. Nodes are coded by region as in Fig. 1

network components (western and eastern Mesoamerica in this case) to one another through a series of relatively weaker ties. Yet these Gulf Coast centers San Andrés and San Lorenzo are not particularly tightly linked to one another, with both more closely connected to other sites in the graph. As has long been recognized (e.g., Pool 2009), the residents of Gulf Coast/Olmec settlements at this time were actively engaged in exchange and interaction networks that ranged widely in Mesoamerica (Flannery and Marcus 1994, pp. 385–390). Both Gulf Coast assemblages contain primarily central Mexican obsidians, but only at San Lorenzo are the more proximate sources in Puebla, such as Guadalupe Victoria or Zaragoza, also well represented. Based on these findings, we see little indication that these sources in Puebla were directly controlled during this period by settlements on the Gulf Coast (cf. Zeitlan 1982; see also Hirth and Pillsbury 2013).

The obsidian at both San Lorenzo and San Andrés was obtained mostly from more distant sources closer to the Basin of Mexico, principally Sierra de Pachuca, Ucareo, Otumba, and Paredon. San Andrés is more strongly connected to central Mexico in our network than is San Lorenzo. This may reflect a chronological change in network topology, however, as the material from San Lorenzo dates entirely to the first centuries of period 3, while the material from San Andrés spans nearly the entire period. These connections between the Gulf Coast and central Mexico appear to pass through the important center of Chalcatzingo, which in our reconstructed networks is well connected to the Gulf Coast and Oaxaca as well as to more proximate locations in central Mexico in conformance with Chalcatzingo's long-suspected role as a major center of pan-regional exchange and interaction during the first half of period 3 (Grove 1987, 1989; Hirth 1978).

Displayed as a geographically positioned network (Fig. 4), the location of the Gulf Coast settlements as bridges or brokers between the eastern and western Mesoamerica is less pronounced than on the mini-max network graph. The potential importance of

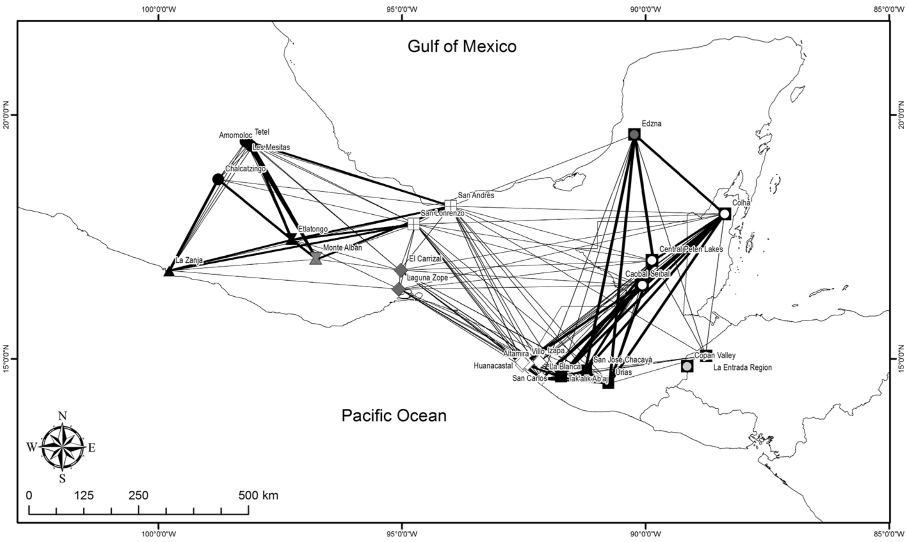

**Fig. 4** Period 3 (900–300 BC) network links with nodes positioned geographically. Edge thickness corresponds to link strength—*thin edges* represent links of 94≥BR≥30, while *thick edges* represent links of BR≥94

Pacific Coast links is evident here, particularly across the southern Isthmus region; so the Gulf Coast region did not exclusively control or dominate the web of connections for obsidian transport. In particular, known important Pacific coastal centers at Laguna Zope and La Blanca (Love 2007) also served bridging roles, linking the central Maya lowlands to western Mesoamerica and Soconusco respectively. Although it appears that several routes of transport may have connected to the Isthmus of Tehuantepec during period 3, none of these links from east to west exceed our "strong" link threshold of 94.

The core of the period 3 network links together at a BR value of 57, a higher degree of connectivity than found for the two subsequent time blocks. An exception to this level of connectedness is the Copan Valley in Honduras. The assemblage there consists almost entirely of the local Ixtepeque source, which while important throughout the Maya area later in the pre-Hispanic period, appears to have had a more localized distribution between 900 and 300 BC. The Copan Valley links weakly back to the Guatemalan Highlands (BR=11), but the presence of small percentages of Ixtepeque obsidian further north in the Maya lowlands seems to indicate that this region was already weakly connected to the Maya core area. The presence of a small percentage of La Esperanza obsidian (Honduras) in the Copan Valley serves as evidence that perhaps this area, which was later more squarely positioned within the Southeastern limits of the Maya cultural area, also may have had more significant southeasterly connections during period 3.

### Period 4 (250 BC–AD 250)

On a mini-max network plot (Fig. 5), much of the structure evident in period 3 networks appears to be retained, including a bipartite structure with Gulf Coast routes

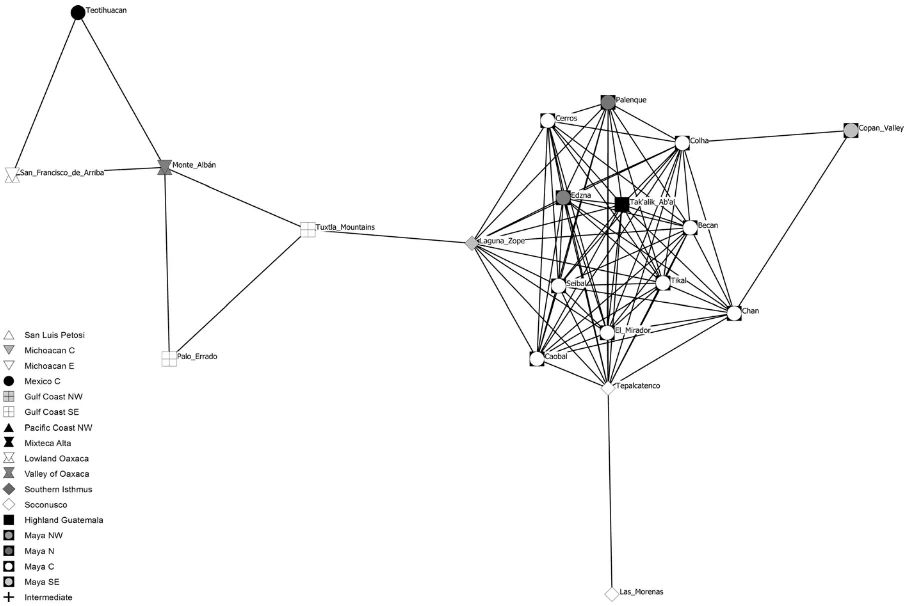

**Fig. 5** Spring-embedded network graph of period 4 (250 BC–AD 250) obsidian assemblages with edges drawn at a threshold value of ≥51, the minimum value at which all nodes connect into the network. Nodes are coded by region as in Fig. 1

still forming a bridge between central Mexico, the Southern Isthmus, and finally the Maya lowlands. However, with nodes positioned geographically (Fig. 6), it is evident that connections along the Pacific Coast now appear to be the primary ones that link eastern and western Mesoamerica, and the Gulf Coast linkage apparent during period 3 is diminished in importance. At the same time, both the number and strength of links crossing the Isthmus of Tehuantepec are reduced relative to earlier (period 3), and even considering the smaller number of sites in our period 4 sample, the density and weight of links within western Mesoamerica (central Mexico, Oaxaca, and the Gulf Coast) are generally lower than in the period 3 network. The major center of Teotihuacan, which was founded and rose to unprecedented size during this time period (Cowgill 1997), does not appear central when considering overall network positioning on the mini-max plot. Based on these graphs, we see little indication that the control of long-distance obsidian trade was a key factor in Teotihuacan's emergence.

Eastern Mesoamerica (the Maya area) is much more tightly integrated internally than was the case during period 3, with "strong" links between most sites included in our sample. The Copan Valley is incorporated into the network at the mini-max threshold value of 51, so in contrast to period 3, the southeastern fringe of the Maya region was now well linked into eastern Mesoamerican obsidian exchange networks. Inter-settlement networks seem to have been an important feature in fostering the emergence of larger Maya settlements during this period. Overall for Mesoamerica, the mini-max value is slightly lower than during period 3. This change reflects the weakening of connections on a pan-Mesoamerican level. As during period 3, sites in Soconusco are relatively peripheral to the overall network structure, but do link to geographically proximal sites in the Guatemalan Highlands and Maya lowlands.

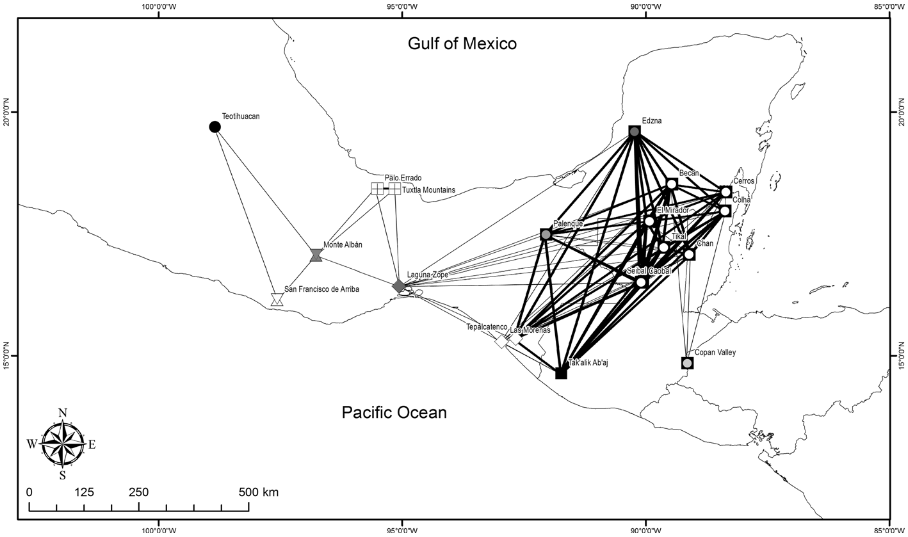

**Fig. 6** Period 4 (250 BC–AD 250) network links with nodes positioned geographically. *Edge thickness* corresponds to link strength—*thin edges* represent links of 94≥BR≥30, while *thick edges* represent links of BR≥94

## Period 5 (AD 300–600)

When viewed as a mini-max graph (Fig. 7), the network for period 5 is in many ways topologically similar to that for period 4, with sites along the Pacific Coast in lowland Oaxaca and the Southern Isthmus forming the principal links between eastern and western Mesoamerica. In comparison to period 4, Teotihuacan is somewhat more central to the graph, and links directly to sites along the Pacific Coast rather than falling within a cluster of sites in central Mexico, Oaxaca, and the Gulf Coast that only link weakly to the Pacific Coast. Monte Albán—the largest center in the Valley of Oaxaca during much of the later Preclassic and Classic periods—serves as another important bridging site, linking Oaxaca and the Gulf coast to the Pacific Coast and sites further east. However, the most important bridging sites in the network during this period are Los Horcones, on the Pacific Coast, and Punta de Chimino, in the Petexbatún region of the Maya lowlands. The former appears to have been a key node linking eastern and western Mesoamerica, while the later seems to have been a key link between Pacific coastal sites and Maya settlements to its north in the Petén.

When positioned geographically (Fig. 8), much of the patterning evident in the mini-max plot is retained, particularly the relatively strong links along the Pacific coast. However, it is also clear that the Gulf Coast and Oaxaca are more tightly interconnected than they were during preceding time periods. Demographic expansion in Oaxaca, Puebla, and Veracruz (e.g., Blanton *et al.* 1993; Daneels 1997; Plunket and Uruñuela 2005; Santley 2007) during this period may have contributed to a general strengthening

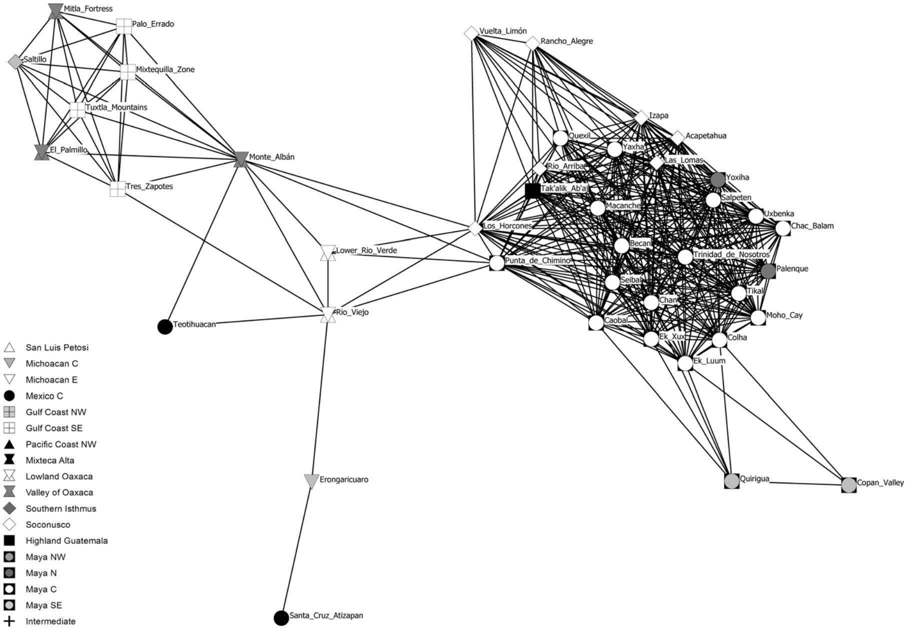

**Fig. 7** Spring-embedded network graph of period 5 (AD 300–600) obsidian assemblages with edges drawn at a threshold value of ≥55, the minimum value at which all nodes connect into the network. Nodes are coded by region as in Fig. 1

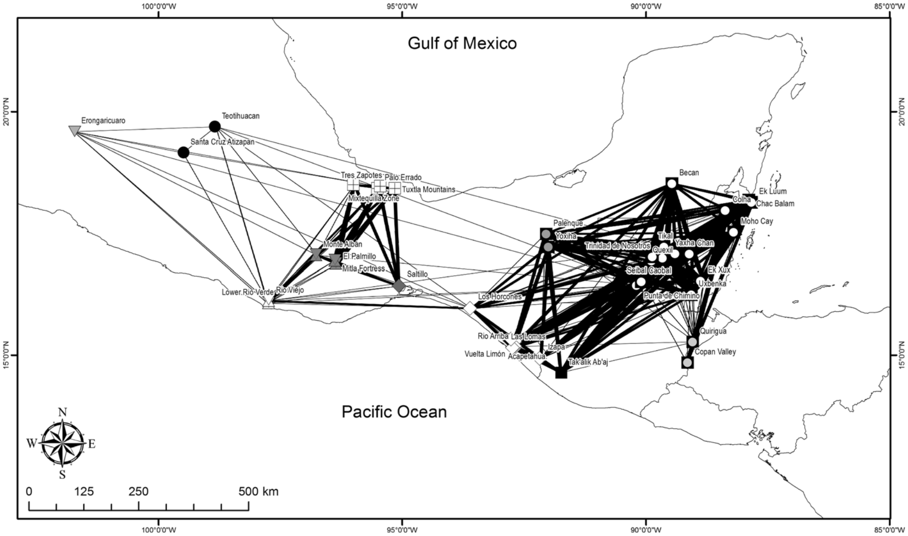

**Fig. 8** Period 5 (AD 300–600) network links with nodes positioned geographically. *Edge thickness* corresponds to link strength—*thin edges* represent links of 94≥BR≥30, while *thick edges* represent links of BR≥94

of intersettlement links within western Mesoamerica in period 5. Nevertheless, the period 5 graphs do not correspond at all with the notion of a Teotihuacan monopoly of widespread obsidian transfer (cf. Santley 1983, 1984; Santley *et al.* 1986).

During this period, the Maya area also is an extremely well-integrated network component or subgraph that includes the formerly more weakly linked Southeastern Maya region. The Copan Valley is now connected to the broader Maya region by strong links of BR>94. In part, this reflects the increasing distribution of Ixtepeque obsidian via the Copan Valley and maritime routes along the Belizean coast that we noted in our earlier network analysis of the Maya area (Golitko *et al.* 2012).

All transport between eastern and western Mesoamerica did not occur along the Pacific Coast. Further north, the major centers of Tikal and Seibal, although primarily linked southwards towards the Guatemalan Highlands, also have weak ties with Teotihuacan and other central Mexican sites, possibly via the Gulf Coast lowlands (these links also are apparent when nodes are geographically positioned). It is likely that several routes connected eastern and western Mesoamerica during this time period. Relative to period 4, the mini-max threshold for period 5 increases moderately to 55, which indicates relatively greater connectivity across Mesoamerica than during period 4. Larger urban centers, with more hierarchical governance institutions that had wider spans of control, along with developing marketplace exchange systems (e.g., Garraty and Stark 2010) all may have factored into this shift.

### Period 6 (AD 600–900)

The central importance of Chichén Itzá and affiliated locations (Isla Cerritos, Oxkintok, Yaxuna) in the northern Yucatan to network structure is evident on the mini-max graph generated from period 6 assemblages (Fig. 9). These sites serve as some of the main linkages between western and eastern Mesoamerica, and are in fact more closely

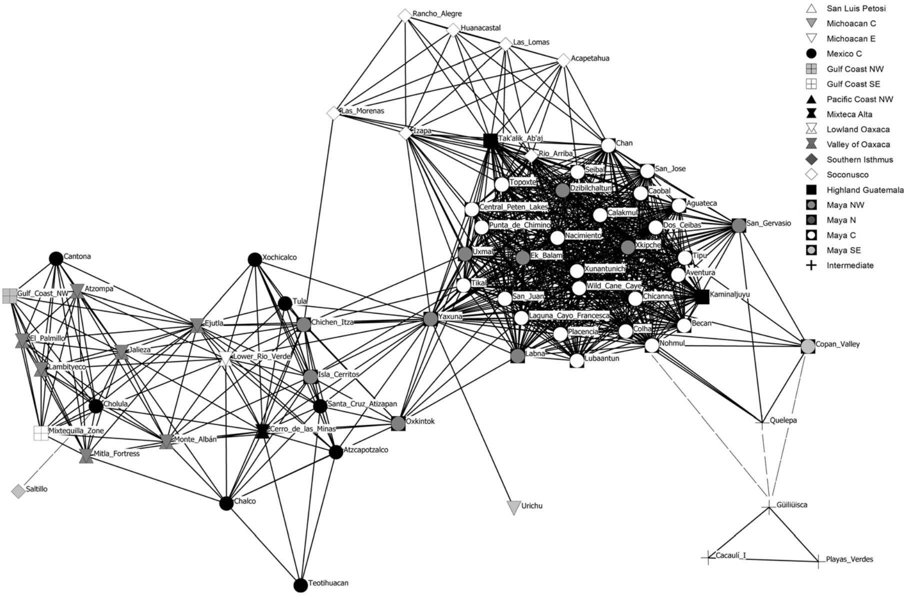

**Fig. 9** Spring-embedded network graph of period 6 (AD 600–900) obsidian assemblages with edges drawn at a threshold value of ≥66, the minimum value at which all nodes other than those in Nicaragua and the Southern Isthmus of Tehuantepec connect into the network. The Nicaraguan sites connect to sites in El Salvador, Honduras, and along the Belizean coast at a BR value of 30 (*dotted edges*), while Saltillo connects to Cholula at the same value. Nodes are coded by region as in Fig. 1

positioned to many central Mexican sites than to other sites in the Maya area, suggesting a weakening of the basic bipartite western/eastern division evident in earlier period graphs. The most direct of these links connects Tula to Chichén Itzá—these were two of the preeminent centers of the Terminal/Epi-classic period, and it has been suggested that much of the obsidian recovered at Chichén Itzá may have been obtained from Tula (Healan 2007). However, Chichén Itzá is also strongly connected to sites further down the Belizean coast and as far south as Soconusco, which indicates a degree of pan-regional importance for this center that was not evident for any settlement represented in the earlier time blocks. Whereas Tula and other sites in central Mexico are tightly linked into the northern Yucatan, links within central Mexico are diverse, and some sites further to the south and east have more direct affiliations to the Gulf Coast and Oaxaca, so clearly inland transport within western Mesoamerica remained highly important.

While the greater part of period 6 dataset can be linked at a BR value of 72, both Saltillo (Southern Isthmus) and sites in the southern Intermediate area (for which we have data beginning in period 6) are much more weakly linked at a value of 30. The relatively weak linkage of the Southern Isthmus into the network is surprising given the important role that this area had in bridging all prior networks. The significant diminishment of connectivity along the Pacific coast likely reflect several factors including the pan-regional importance of Chichén Itzá and its trade routes, but also the process of abandonment at Maya lowland centers and their surrounds that began during period 6. Demographic declines in the Maya lowlands might have left the Pacific Coast as a relative backwater in pan-Mesoamerican networks during this time. The political and demographic decline of Teotihuacan also may have had a role in precipitating the shift in transfer networks from the Pacific (where Teotihuacan has long been thought to have had links) (Sanders and Michels 1977) to the Gulf. If we excise these peripheral areas (in a network sense) from the graph, the core of the period 6 network links together at a much higher BR value than for earlier periods. Pan-regionally, we see a far higher degree of integration than for any period between 900 BC and AD 600, continuing a trend towards greater connectivity that began centuries earlier (Table 2). The greater connectivity in the pan-Mesoamerican graph evidenced in the wake of Teotihuacan's decline provides further indication that the prior obsidian distribution networks were neither primarily integrated nor monopolized by that central Mexican metropolis.

When positioned geographically (Fig. 10), the degree to which linkages in the period 6 network are oriented towards the northern Yucatan is apparent. The dominance of the Gulf-Yucatan link is evidenced by the relative isolation of Pacific coastal settlements in this sample, with no links (even if links weaker than BR=30 are included) bridging the gap between Saltillo and Rio Arriba (Soconusco), the Guatemalan Highlands, or central Maya area. However, taken as a whole, the links bridging Mesoamerica in our period 6 networks are far stronger than those found for any preceding time period. In part, greater connectivity likely reflects the increasing role of maritime transport that we noted in our earlier analysis (Golitko *et al.* 2012), but elsewhere may reflect increasing overland travel through highland Oaxaca, which appears to have served as a strong bridge between the Gulf Coast and lowland Oaxaca.

### Period 7 (AD 900–1200)

Viewed both as a min-max graph (Fig. 11) and with nodes positioned geographically (Fig. 12), the period 7 network resembles a low-density, fragmented version of the period 6 network. Links between western and eastern Mesoamerica still run through the northern Yucatan. Isla Cerritos serves as the only significant link between the two macroregions, likely reflecting the final century of settlement at Chichén Itzá, which was occupied into the first century of this time block (Andrews *et al.* 2003). As in period 6, Isla Cerritos is closely linked to Tula, but is relatively weakly linked to the rest of the Maya area. Instead, most links for sites in the Maya area extend southeastwards, including the southernmost parts of this graph, which were tightly integrated into the Maya area during period 7. This shift may well have resulted from an increasing maritime orientation of transport (Golitko *et al.* 2012), also reflected in higher frequencies of Guatemalan obsidians, principally Ixtepeque, at sites in Honduras. In turn, La Esperanza obsidian from Honduras appears at some sites in the Guatemalan Highlands and at coastal Maya sites as well.

Evidence for a Pacific coastal route remains absent—as in period 6, no links of any strength connect the Southern Isthmus to Soconusco (Izapa). The absence of a Pacific route of transport during the Early Postclassic has been suggested on the basis of excavations at Rio Viejo (Lowland Oaxaca), where King (2008) sees little evidence for connection to coastal trade routes, arguing instead for primary linkage inland into Valley of Oaxaca, a pattern confirmed by our analysis. If one removes Isla Cerritos, there is virtually no connection at all between eastern and western Mesoamerica, indicating that after AD 1000, when Chichén Itzá was largely abandoned, the Mesoamerican obsidian distribution network may have fragmented into two unlinked components at times, or was at best very weakly connected across the Isthmus of Tehuantepec.

The fragmentary nature of the period 7 network is reflected in the mini-max threshold of 49, which is the lowest value present in any of our networks (with the exception of the Intermediate Area for period 6). Visually, the evident reduction in connectivity from the prior period corresponds with the decline of many of the long-standing and largest urban centers in pre-Hispanic Mesoamerica (e.g., Teotihuacan, Monte Albán, Tikal) and the region's subsequent reorganization (e.g., Diehl and Berlo 1989; Willey 1991). Geographically, the basic positioning of the network links did not change markedly with these dynamic episodes of urban decline that in certain instances were accompanied by shifts in the ways that leadership and power were manifested locally (e.g., Chase and Chase 2006; Feinman and Nicholas 2013, pp. 141–156; Grube and Krochock 2007). Although this period was not marked by a total or catastrophic collapse, institutions did fall and change while the degree of connectedness across Mesoamerican regions decreased significantly.

### Period 8 (AD 1200–1520)

Both mini-max (Fig. 13) and geographically positioned (Fig. 14) network maps indicate a major realignment of network links in period 8 relative to periods 6 and 7. A consideration of the mini-max plot reveals a generally geographically oriented positioning of nodes, with different regions situated as separate network clusters. In part, this network structure reflects the relatively high mini-max threshold (94) for period 8, which omits many weaker links from the graph that might bridge these apparent clusters. Nevertheless, it is noteworthy that for the first time the clear spatial definition between east/west network segments that the distribution of obsidian sources (as well as long-standing linguistic and cultural differences) would lead one to expect is only weakly present. While graphs for periods 3–7 exhibit a generally bipartite structure reflecting a division between eastern and western Mesoamerica (as defined above), that for period 8 reflects greater clustering at the regional level, but more links spanning the Isthmus of Tehuantepec. The relatively high mini-max threshold also indicates that connections are evenly distributed during period 8, and all regions of Mesoamerica for which we have data were strongly integrated into the broader pan-regional system of distribution. The high degree of overall connectivity along with the tightly integrated and geographically oriented subgraphs, together, are indicative of a different integrative topology then has been found in any previous period. Over time, the loss of pan-regional connectivity in the prior period (7) was followed by the establishment of a new basis for connectedness in period 8, likely fostered by greater commercialism and (towards the end of this period) Aztec imperial expansion, which sometimes opened new economic links (Berdan 2003).

Viewed geographically, it is evident that the Pacific coastal route was once again the most significant bridge between western and eastern Mesoamerica during period 8, however, there is a generally high density of links connecting across the Isthmus of Tehuantepec, which signals that inland routes may have regained importance as well, particularly in comparison to periods 6–7. Although maritime transport up the eastern coast of Yucatan Peninsula remains important (Golitko *et al.* 2012), there is little evidence on the basis of our analysis to infer connections around the northern Yucatan peninsula. These routes diminished in conjunction with the earlier declines of Chichén Itzá and Isla Cerritos. Even the preeminent northern Maya center of the time, Mayapan (Milbrath and Peraza Lope 2003), links principally further south into the Maya area, and has no direct ties with sites in western Mesoamerica.

Within central Mexico, there is a clear network discontinuity between the major competing polities of the day, the Tarascan (Michoacan sites on maps and network plots) and Aztec (Mexico C sites on maps and network plots) empires (Berdan and Smith 2003; Pollard 2003), with only weak links connecting settlements on their respective southern fringes—these relatively peripheral settlements (in a geographical sense) may have occupied important brokerage locations relative to the Aztec and Tarascan polities consequently. Sites at the eastern boundary of the Tarascan Empire primarily link back to the Tarascan core area rather than bridging Michoacan and Central Mexico, in accordance with the idea that the primary frontier zone between the empires also served as a boundary between network clusters, across which only limited obsidian flow occurred (see Pollard and Smith 2003). The relatively isolated position of the Tarascan sites from other network nodes is consistent with known political geography—the Tarascan Empire was more strongly economically and politically oriented towards the south and northwest (Pollard 2003), areas for which we have no data. However, the presence of numerous obsidian sources in both Tarascan and Aztec territory allows for the possibility that obsidian data may underestimate the movement of other types of goods between these two polities. Also consistent with known political geography, Aztec empire sites are relatively directly connected with some sites located in the State of Oaxaca (Mitla Fortress and Tamazulapan) and Soconusco (Ocelacalco) (Berdan *et al.* 1996; Feinman and Nicholas 2012; Gasco and Voorhies 1989; Smith and Berdan 2003).

The site of Meztitlan, located north of the primary Aztec heartland, is virtually disconnected from the network, linking to other sites in our sample only when the threshold BR value is set at two. The assemblage there consists entirely of Zacualtipan obsidian, a source located only 13 km from the site itself. This source appears only sporadically at a few relatively randomly positioned sites in our sample for period 8, and does not seem to have been commonly traded into our primary study region during this time. In contrast, Zacualtipan obsidian is present at a number of sites as distant as Belize during periods 6 and 7. Although the predominance of the Zacualtipan obsidian at Meztitlan could reflect the proximity of the source, it is noteworthy that the small assemblage (five sourced pieces) in our database from the site of Tamohi, located further north in San Luis Petosí, also contains only Zacualtipan obsidian. These findings indicate an apparent disjuncture in the Late Postclassic obsidian distribution network north of the Basin of Mexico. For the purposes of formal network measures (see below), we treat Meztitlan as part of a separate distribution network and omit it from the quantitative measures for this period.

## Networks Shifts and the Structure of the Pre-Hispanic Economy

Our visual inspection of network graphs indicates that pre-Hispanic Mesoamerican distributional networks changed significantly in their topology relative to real world geography during the period 900 BC to AD 1520. However, visual graphical representations may mask other significant patterning because they compress full network patterning down to a two-dimensional representation. Consequently, we formally address changes in networks structure using the aforementioned formal network metrics (Table 2) to more robustly evaluate how closely the Mesoamerican system conforms to the expectations of a static and localized view of ancient economy. Although it is already evident from our visual analysis of graphs that the Mesoamerican distributional economy was pan-regionally interconnected as early as 900 BC, formal network metrics indicate that the Mesoamerican system (a) generally became more integrated over time, (b) shifted from a pattern of network integration we label "intensive" to one we label "extensive" after a period of network fragmentation

**Table 2** Sample and network summary statistics for time periods 3–8. Only assemblages containing ten or more analyzed obsidian samples are included in these measures

| | Period | | | | | |
|---|---|---|---|---|---|---|
| | 3 | 4 | 5 | 6 | 7 | 8 |
| Sample summary statistics | | | | | | |
| Nodes | 28 | 20 | 42[a] | 69[b] | 28 | 61[c] |
| Mean sample size[d] | 653 | 221 | 311 | 273 | 265 | 374 |
| Median sample size | 93 | 60 | 55 | 73 | 45 | 65 |
| Total sources | 18 | 15 | 17 | 18 | 19 | 24 |
| Average sources/site | 3.96 | 3.45 | 3.43 | 4.41 | 3.75 | 3.74 |
| Source σ | 2.08 | 1.63 | 1.55 | 2.21 | 1.62 | 1.98 |
| Network density | | | | | | |
| Minimax threshold BR | 57 (11) | 5 1 | 55 | 72 (30) | 4 9 | 94 (2) |
| Full matrix | 0.72 | 0.73 | 0.68 | 0.79 | 0.69 | 0.62 |
| Minimax threshold density | 0.30 | 0.44 | 0.43 | 0.32 | 0.29 | 0.14 |
| BR ≥30 density | 0.47 | 0.53 | 0.50 | 0.50 | 0.36 | 0.37 |
| BR ≥94 density | 0.15 | 0.29 | 0.34 | 0.27 | 0.17 | 0.14 |
| Network size measures | | | | | | |
| Diameter | 7.31 | 6.3 7 | 5.17 | 5.08 (6.73) | 3.6 4 | 3.0 2 |
| Average path length | 1.64 | 2.24 | 1.81 | 1.34 (1.5) | 1.43 | 1.32 |
| %RSD | 84 % | 72 % | 60 % | 58 % (64 %) | 51 % | 46 % |
| Network centralization | | | | | | |
| Weighted degree centralization | 0.10 | 0.2 1 | 0.1 7 | 0.1 7 | 0.0 8 | 0.1 3 |
| Weighted eigenvector centralization | 0.14 | 0.19 | 0.11 | 0.09 | 0.19 | 0.09 |
| Weighted betweenness Centralization | 0.26 | 0.38 | 0.31 | 0.26 | 0.44 (0.29)[e] | 0.49 |

[a] Omits surface collections from the Valley of Oaxaca

[b] Includes pooled assemblages for Gulf Coast NW sites

[c] Includes pooled assemblages for Michoacan E sites

[d] The distribution of sample size is highly right-skewed due to the presence of visually sourced assemblages

[e] Excluding Isla Cerritos

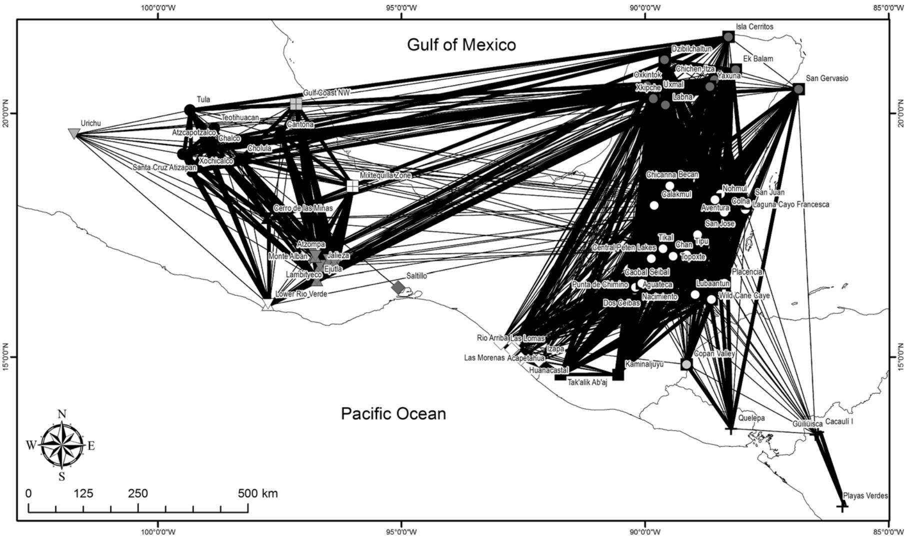

**Fig. 10** Period 6 (AD 600–900) network links with nodes positioned geographically. *Edge thickness* corresponds to link strength—*thin edges* represent links of 94≥BR≥30, while *thick edges* represent links of BR≥94

between AD 900–1200, (c) became progressively less hierarchically organized, and (d) underwent broad cyclical patterning.

We interpret these diachronic patterns on the basis of several trends evident in the formal network measures we calculate. First, we examine measures of network density

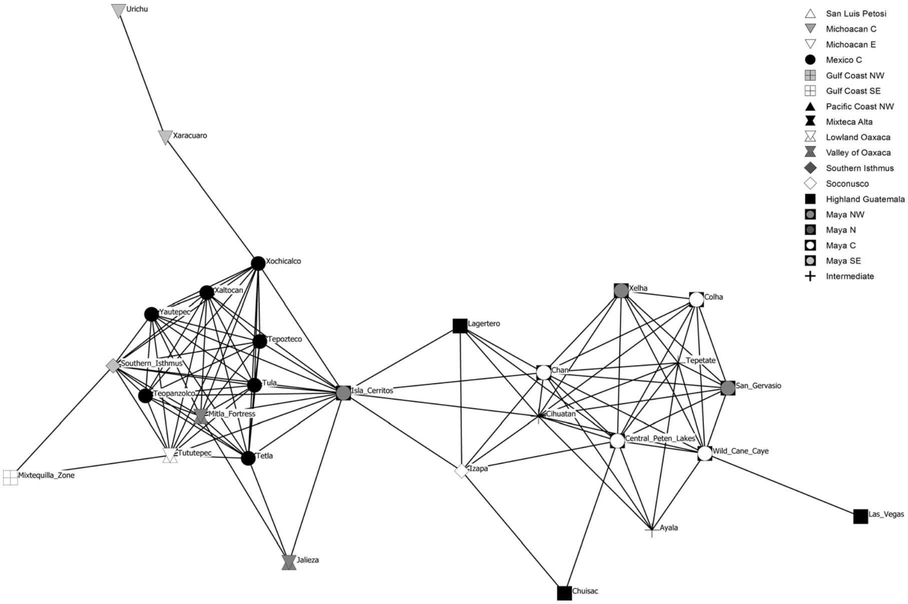

**Fig. 11** Spring-embedded network graph of period 7 (AD 900–1200) obsidian assemblages with edges drawn at a threshold value of ≥49, the minimum value at which all nodes connect into the network. Nodes are coded by region as in Fig. 1

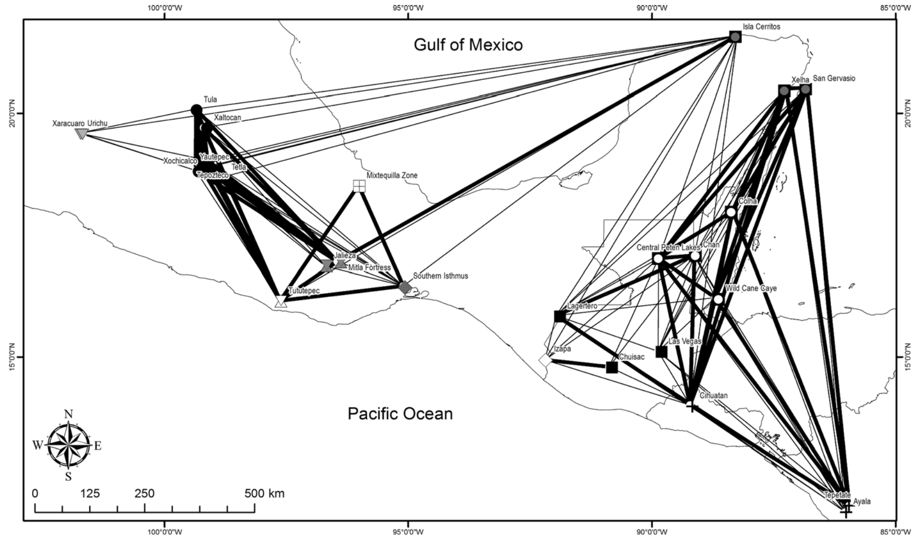

**Fig. 12** Period 7 (AD 900–1200) network links with nodes positioned geographically. *Edge thickness* corresponds to link strength—*thin edges* represent links of 94≥BR≥30, while *thick edges* represent links of BR≥94

and size to examine the degree and kinds of integration in pre-Hispanic distribution networks.

In respect to network size measures, two conceptual axes—volume of flow through a network, and distribution of links through which flow passes—may result in some

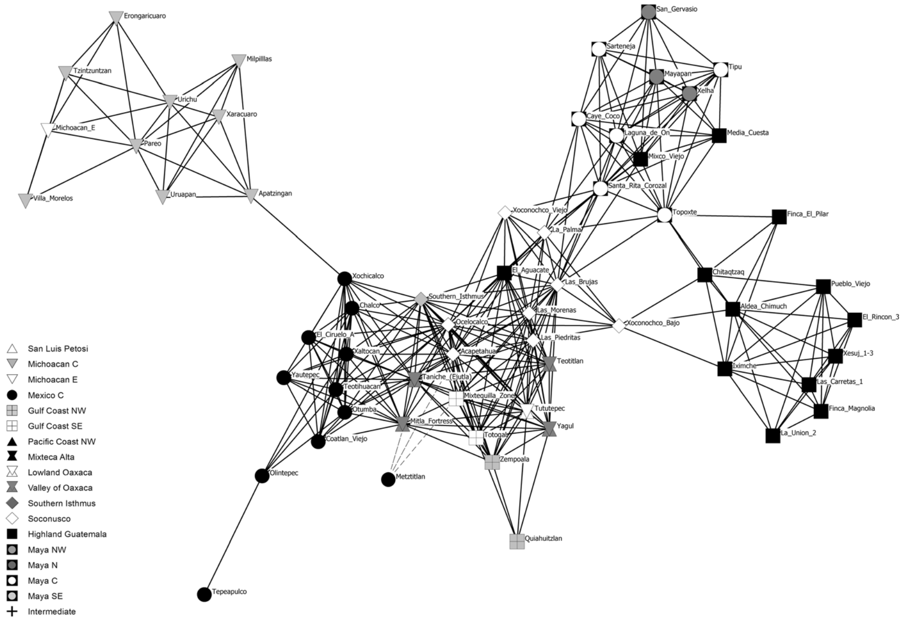

**Fig. 13** Spring-embedded network graph of period 8 (AD 1200–1520) obsidian assemblages with edges drawn at a threshold value of ≥94, the minimum value at which all nodes other than Metztitlan connect into the network. Metztitlan links into the network at a BR value of 2 (*dotted edges*). Nodes are coded by region as in Fig. 1

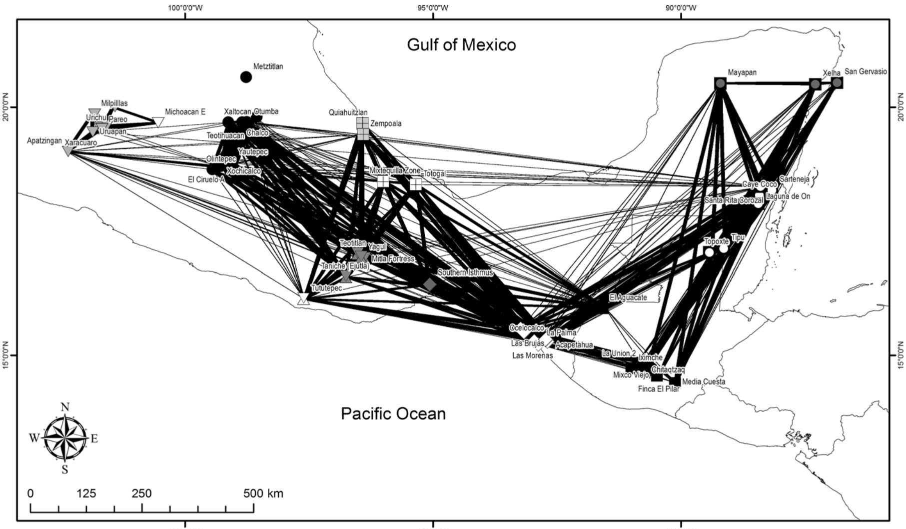

**Fig. 14** Period 8 (AD 1200–1520) network links with nodes positioned geographically. *Edge thickness* corresponds to link strength—*thin edges* represent links of 94≥BR≥30, while *thick edges* represent links of BR≥94

interpretative confusion. When we refer to a system as "smaller" in network terminology, we refer to a particular topological property of the network—how costly it is to move from one link to another. We do not intend this term to reflect on the size of the economy in general—for instance, the volume of production, intensity of activity, number of locations or people integrated into the economy, or any other measure that archaeologists and economists working on ancient or modern economies might understand when referring to the "size" of an economy. In fact, a "larger" economy—in the sense of one in which more goods are produced and transported—may contribute to a "smaller" distribution system in the network sense, but the two may be only loosely related. In this analysis, we can only speculate as to the size of the economy by examining inferred patterns of distribution and endeavor to support these arguments by drawing on more traditional archaeological studies of production and consumption volume. This is comparable to economic network studies that examine globalization, for instance, through the treatment of production and export volume as one variable that is contrasted to the distribution of ties, which is a separate analytical dimension (e.g., Kim and Shin 2002; Mahutga 2002).

As Peeples and Roberts (2013) demonstrate, many formal metrics may be highly impacted by choosing threshold cutoff values for link inclusion, and they consequently advocate using full-weighted relational matrices when calculating network metrics for archaeological data. In our view, weaker network connections are less likely to represent real and significant ancient links between nodes. Consequently, we calculate (for certain indices) metrics at a variety of threshold cutoffs to assess how the differences between chronological periods may be impacted through the inclusion of "weak" links versus only stronger links. In particular, we calculate network density at four different threshold values—with all existing links included (BR>0), at the respective mini-max threshold for each period, at our "weak" link threshold value of 30, and at our "strong" link threshold value of 94. This approach is revealing of how different link weights are distributed across time periods, and what impact this has on how integrated one network is relative to another. For instance, a network with an overall high density of links may actually have few stronger links, so that as a whole it is less well connected than a network with many strong links but a lower overall density. For other measures such as network size, we only calculate metrics using the full matrix of network links, as the fragmentation of some networks when weaker links are removed results in diameter and average path lengths being calculated only for the remaining "giant connected component," the largest linked component of the graph. In that case, size measures for the entire set of nodes are infinite and cannot be meaningfully compared across time periods.

### Network Integration

Density measures—expressing the percentage of links present versus those hypothetically possible given the number of nodes present—indicate relatively high densities during earlier time periods represented in the sample. However, density trends do differ depending on the threshold value chosen for link inclusion. Retaining weaker links (all links included) produces a relatively constant high density of links during earlier time periods (3–4), followed by a reduction in density during period 5, a peak in density during period 6, and a drop to a relative low density value during periods 7 and 8. Raising the threshold value rapidly reduces measured density for period 3, raises the densities during periods 4–6, and is followed by a relatively dramatic drop-off during the Postclassic period (periods 7–8). The assessment of these patterns indicates that the links present in the period 3 network are quite weak, and that network density gradually increased through the early Classic period (period 5). Results for period 6 are variable. With all links included, the period 6 network is the densest in our sample. At the highest link threshold, there is a moderate reduction in density relative to the Early Classic. However, regardless of the threshold selected, density drops-off considerably during the Early and Late Postclassic periods.

On face value, these findings might lead to the view that Postclassic distributional networks were less well integrated than during the Classic period. Yet network size measures provide a different picture, which leads us to surmise that not only did the Late Postclassic distributional system reach a level of integration that was not previously seen, but also that the basic topology of the Mesoamerican system may have changed during that time period. For purposes of calculating network size, we have removed very weakly connected nodes, for instance Metztitlan in period 8. For period 6, we calculate all size measures both including and excluding the Intermediate Area and Southern Isthmus. If one excludes these regions for period 6, there is a consistent tendency towards smaller and smaller networks (in network terminology) across the time range we consider. Diameter decreases steadily from a high of 7.31 during period 3 to a low of less than half that value by period 8. Average path length is somewhat more variable, but reaches a maximal value of 2.21 during period 4, followed by a steady decrease reaching a temporary minimum during period 6, followed by an increase during period 7. Average path length then reaches the lowest value of any time period during period 8. The relative standard deviation of path lengths also steadily decreases over time. In sum, paths between sites in our networks grew progressively shorter, path lengths between nodes became more homogenously distributed, and networks grew progressively smaller over time. This implies that by period 8, the network cost of moving from any node in the network to any other had significantly dropped relative to prior time blocks.

The changes we note during period 8 are consistent with increasing commercialization of the Late Postclassic economy, in which the sale of goods, commodities, and services has been argued to have increased as economic relationships were intensified through markets (Berdan 2003; Berdan *et al.* 2003) and new sociopolitical arrangements that facilitated marketplace exchanges (Blanton 2013; Blanton and Fargher 2012). However, while the period 8 economy may have been the more "international," obsidian extraction and usage relative to preceding time periods was actually more locally intensive—the number of total sources represented increases from a steady average of 15–19 sources present in any preceding time period to 24 during the Late Postclassic. This increase in localized source usage primarily reflects innovations in quarrying technologies (Braswell 2003, p. 155), and the distribution of minor sources from both central Mexico and the Guatemalan Highlands, such as Tepalzingo, Fuentezuelas, El Paraiso, Media Cuesta, and San Bartolome Milpas Altas, which were either totally absent or only sporadically represented in our data for earlier time periods. If one excludes sources in the Intermediate Area represented in our period 6 and 7 datasets—the only time periods in which this region is represented, this upturn in the number of sources represented during period 8 is even more pronounced. Although the total number of sources represented increased, the average number of sources represented per site actually decreased during period 8 after reaching a maximal value of 4.41 during period 6.

We suggest that two kinds of integrative "poses" are evident in network structure, the first of which is labeled *network intensive*—during periods 5–6, there is a progressive trend towards densely linked networks characterized by relatively few total sources represented, but a relatively high number of sources present per site. We interpret this as representing a high volume of flow along a series of spatially defined trade routes, with material from any individual source potentially traveling greater distances. This network-intensive pattern also may reflect the importance of maritime transport that we identified during our earlier analysis of the Maya area (Golitko *et al.* 2012), which may have facilitated long-distance direct links between different regions. In contrast, the network topology which emerged during the Late Postclassic was characterized by shorter path lengths, a smaller diameter, a greater number of total sources in circulation, and yet fewer sources on average represented per site. We define this pattern as *network extensive*.

It is tempting to infer the development of the "small-world" phenomenon (Barabási 2003; Schnettler 2009; Sindbæk 2007; Watts 1999) for the Late Postclassic, in which highly localized clusters of nodes are linked by a few weaker or longer-distance links that collectivity create a low density, highly regionally clustered, yet small (in a network sense) network with low diameter and short average path lengths between nodes. The nature of our link construction technique does not allow us to map directly the number of connections linking any two sites, and so does not allow for a true representation of degree distributions as measured in other studies by direct trade volume. So, we refrain from drawing this direct link between the network shifts we document for pre-Hispanic Mesoamerica and the exact topological categories drawn from the theoretical network literature. There is no doubt, however, that the Late Postclassic distributional system was smaller (in a network sense) than during earlier time periods included in our analysis, and by implication less costly to traverse from node to node.

## Network Hierarchy

In addition to a progressive reduction in size (in the network sense) and increase in network integration, formal metrics indicate that the pre-Hispanic Mesoamerican distribution system also grew less hierarchical over time. Although degree distributions are problematic to interpret because of sampling and the way in which our analysis omits volume of flow as a component of link weighting, there is still interpretative value in degree and other measures. Take a hypothetical example in which a single site disseminates most of the obsidian utilized at other sites (a version of the Santley argument for Teotihuacan). The obsidian arriving at all other sites will mostly come from the source site, and therefore primarily reflect the percentages present upon export from that site, mixing with only a small amount of local obsidians or obsidian obtained through other less important routes. Consequently, all sites in the network should both link strongly to one another, but most strongly to that central producing node. In principle, that node should achieve high degree, eigenvector, and betweenness centrality scores relative to other network nodes. Centralization scores should also increase in a more hierarchical network even if sampling and other factors impact the calculation of scores for individual nodes.

Results for the three measures we calculate indicate that centralization was generally higher during earlier time periods considered (3–6) than during the Postclassic period (7–8). There is however a degree of variability in each measure—degree centralization is generally low during period 3, increases during periods 4–6, hits a relative low during period 7, and rises moderately during period 8. Eigenvector centralization similarly increases from periods 3 to 4, but then drops moderately during periods 5–6. After increasing in period 7, eigenvector centralization again drops during period 8 to the same level present in period 6. Betweenness centralization, like degree and eigenvector measures, increases between period 3 and 4, then drops moderately during periods 5–6, before increasing sharply during periods 7 and 8. High betweenness centralization during period 7 reflects the exclusive role of Isla Cerritos as a bridge between eastern and western Mesoamerica during this time—removing this node results in a two-component network, each with relatively low centralization indices (see Table 2). The sharp increase in betweenness centralization during period 8 reflects the more modular structure of that network, with network brokers linking dense, geographically localized network clusters. These results are consistent with views previously advanced regarding the degree to which ancient states influenced economic structure in Mesoamerica. Some scholars (e.g., Blanton *et al.* 1996) argue that Preclassic and Classic period states in Mesoamerica tended to focus to a greater degree on staple (i.e., agrarian) finance of state institutions, and enacted costly strategies to monitor or impede pan-regional exchange. Late Postclassic political arrangements appear to have encouraged or fostered such long-distance movements of goods (Blanton and Fargher 2012; Hirth and Pillsbury 2013), which in conjunction could account for the moderately more hierarchical distribution of network positioning measures for earlier time periods when compared to the Postclassic period.

However, no network that we construct is ever monopolized (or even dominated) by a single central place. Despite the rise of Teotihuacan to primate status among urban areas during period 4 (Cowgill 1997), network topology and metrics actually suggest that the rise of this site occurred at a time when links within western Mesoamerica and between western and eastern Mesoamerica were relatively weak and sparse. While the period 4 network is the most hierarchical of the six we analyze from the perspective of centralization measures, and Teotihuacan does appear to have become more centrally located relative to total network structure by period 5, consistent with its known expansion politically outside of the Basin of Mexico, it never achieved a particularly central role in distribution networks during either time period. In fact, its degree ranking actually drops from 20 out of 31 nodes during period 4 to 40 out of 43 nodes during period 5. Although these values should not be interpreted as representing a literal measure of the importance of this settlement in Late Preclassic and Classic period distribution networks, there is little in our data to support a superordinate role for obsidian trade in explanations for the rise of Teotihuacan, nor to suggest that much of the obsidian utilized elsewhere in Mesoamerican was obtained from this site. Instead, Teotihuacan appears to have been only one node among many advantageously positioned along a route that linked central Mexico via the Pacific coastal trade route passing through coastal centers and connecting into Maya area routes such as the “Great Western Trade Route” that may have been associated with Tikal and affiliated centers during much of the early Classic (Woodfill and Andrieu 2012). Just because Teotihuacan residents may have had a key role in the production of obsidian goods (e.g., Carballo 2013) does not imply that the site’s citizens also had a monopolized role in the goods distribution at the macroregional scale.

The complete collapse of this Pacific coastal route during period 6—perhaps in part associated with the decline and abandonment of both Teotihuacan in the west and the Maya lowlands to the east—coincides with the rise of Chichén Itzá and its affiliated centers and ports of trade during the Terminal Classic and first century of the Postclassic (Sabloff 2007). No other known political and urban center included in our data reached the degree of influence on network topology achieved by this major northern Yucatan center, which appears to represent the clearest example in our study of a center that had a critical position in pan-regional network structure (Kepecs *et al.* 1994). Chichén Itzá and its affiliated northern Yucatan locations dominate network topology during period 6 and probably also during the first part of period 7. At that time, most major links between western and eastern Mesoamerica passed through the northern Yucatan peninsula—so that these north Yucatán settlements acted as network brokers linking the more densely connected regions of eastern and western Mesoamerica. Chichén Itzá’s westwards links into central Mexico tie very directly to the major Late Classic-Early Postclassic city of Tula, providing further empirical support for the direct economic connection that has been proposed between the two major cities (Healan 2007; Kepecs 2007; Smith 2007). Measured by path length, Tula and Chichén Itzá are among the most proximal sites in the network, and are closer to one another than either of the other sites in their immediate geographical proximity. However, the obsidian assemblage at Chichén Itzá is far more diverse than that at Tula (only two are sources present at Tula, and ten at Chichén Itzá), and it is clear from the number of links that connect Chichén to other sites in the Maya area and elsewhere in Mexico that Chichén Itzá was far better connected pan-regionally than Tula.

While it is difficult to know to what degree the rulers and other economic actors resident at Chichén Itzá attempted to impact total network structure or to what degree they simply benefited from emergent properties of the underlying distribution network they were situated in—the decline of inland Maya centers, termination of transport links along the Pacific coast, demographic relocation, emphasis on maritime transport, and even natural causes such as climate change and shifting rainfall patterns may have contributed towards a focus on circum-Yucatan transport (e.g., Aimers 2007; Kennett *et al.* 2012; Turner and Sabloff 2012)—it is clear that the rising center of Chichén Itzá was then able to play these factors to its advantage to become one of the major urban centers of the tumultuous Terminal Classic-Early Postclassic period. Clearly, the important role of Chichén Itzá in periods 6 and 7 network structure was not a product of its proximity to obsidian—as was the case at Tula, for instance, where central Mexican obsidians were worked—but its geographic positioning as a maritime conduit (e.g., Kepecs 2007).

The rise of Chichén Itzá to a central role within the period 6 distribution network occurred against the backdrop of declining network centralization values, however. Even if this major center occupied a highly central role within the Late Classic-Terminal classic network topology, viewed globally, links were actually more evenly distributed among other sites during this time than during preceding Late Preclassic and Early-Middle Classic periods. Even these earlier networks are relatively nonhierarchical, however, and serve to indicate that the Mesoamerican economic system cannot be productively analyzed by examining only a single perceived primary center and considering how other cities and communities articulate with it. Rather than supporting a hierarchical, "top-down" model of the pre-Hispanic economy, our analysis are consistent with a perspective that the relative influences of known major centers and polities was actually temporally variable, and that the economic basis of one city or state may not have been identical to that of another. Prior historical analysis have perhaps focused too much on the role of the largest and most prominent cities or polities as spurring development outside of perceived "core" areas of Mesoamerica, rather than examining the role of regional distribution structure in creating opportunities for economic advantage.

## Network Brokers and "Gateway Communities"

Many settlements in pre-Hispanic Mesoamerica may have benefited not from their role as producers of commodities such as obsidian, as Santley (1984) and others have emphasized, but from advantageous positioning on network paths. In formal network terminology, such locations are referred to as "brokers," strictly defined as network nodes that bridge dense clusters or communities within a network that are linked only via the broker node, which are thus in a position to mediate interactions (Burt 2005; Peeples and Haas 2013), or in this case, how obsidian moved across the landscape. While archaeologists have long recognized the importance of such places—which Hirth (1978) labeled "gateway communities"—prior analyses largely focused on the diversity of materials present to identify major ports of trade. In part, brokerage locations in our network might be a function of how obsidian sources are distributed—sites located between the major areas of obsidian occurrence (the Isthmus of Tehuantepec, for instance) are likely to connect the major regions of obsidian occurrence in western and eastern Mesoamerica. However, not all such sites are likely to occupy equally important network positions—in many cases, sites located along either the Gulf or Pacific coasts are relatively peripheral, for instance Pacific coast sites such Saltillo during periods 6 and 7, when the Pacific coastal route appears to have collapsed. In archaeological terms, brokerage links may be generated either by having a particularly diverse material assemblage, the kind of gateway community archaeologists have long been able to identify, or by simply linking network components together purely based on the particular topology of the network in which a node is embedded. Although we do not formally calculate brokerage scores here, such metrics are an established part of the SNA cannon (see Peeples and Haas 2013 for an archaeological example).

Examples of both kinds of "brokers" are evident in the networks we construct—the Pacific coastal center of Los Horcones (Cowgill 1997; García-Des Lauriers 2007; Love 2007) in the Early Classic is a prime example. Although traditionally, some scholars (e.g., Sanders and Michels 1977) have focused on the role that Teotihucan played in stimulating the rise of cities along the Pacific Coast and in the Guatemalan Highlands, our analysis focuses on broader network structure. Los Horcones forms a primary bridge (i.e., serves as a broker) between eastern and western Mesoamerica during period 5, and like many modern cities (Alderson and Beckfield 2004), may have benefited from this advantageous positioning relative to Early Classic settlement and distributional system. Network analysis provides a more formal set of techniques for identifying these network brokers (e.g., Peeples and Roberts 2013), and not only for places like Chichén Itzá and Los Horcones, both of which well exceed average levels of source representation for their respective periods. Apatzingan, which serves as a bridge/broker between the Tarascan and Aztec empires, is unremarkable in terms of its assemblage diversity (three sources, slightly lower than the average value for period 8) and understood pre-Hispanic importance (it was a minor center on the edge of the Tarascan sphere), yet emerges as a key structural link when placed into broader period 8 network structure. This second type of "gateway community" or network broker can only be identified within the totality of relationships present in the period 8 network.

## Further Implications of Network Structure

Recognition that even the most major polities of their day had limited and constrained influence within distribution networks also forces us to shift our thinking away from equally hierarchical views of cultural primacy in pre-Hispanic Mesoamerica. For instance, debate continues around the degree to which centers in the Gulf Coast region exercised cultural hegemony over much of Mesoamerica during the Early and Middle Preclassic periods, with some arguing that these centers served as the genesis for a "Mother Culture" from which ideas and goods spread out to other areas of Mesoamerica (e.g., Blomster *et al.* 2005; cf. Stoltman *et al.* 2005). Network analysis has long focused on the role that the directionality and strength of links has on explaining the spread of ideas and information (e.g., Valente 2005)—the presence of stronger links between areas may facilitate the adoption and retention of shared practices (e.g., Collar 2007, 2013), as stronger and denser links between different regions and the lower inferred cost of traversing these paths may have facilitated the flow of goods, ideas, and people. Network structure instead may help identify areas of shared suites of behavior and interaction akin to what some have labeled "communities of practice" (e.g., Knappett 2011, pp. 102–104), and may account for the particular distributions of widespread systems of practice, belief, and symbolism in pre-Hispanic Mesoamerica without needing to identify a primary center from which these ideas all originated (Flannery and Marcus 1994).

The central role played by the Gulf Coast centers in obsidian distribution (and perhaps circulation of other commodities as well) during period 3 may account for the wide sharing of ideas, styles, and iconography, sometimes referred to as the “Olmec” horizon or style (Pool 2009), that has been found beyond the limits of any direct political hegemony or unit of cultural affiliation. Ideas that coalesced at the Gulf Coast centers might represent influences transmitted through interactions that crossed various sectors of Mesoamerica, rather than a set of practices or innovations that arose from one specific area. Recognized “Teotihuanco” stylistic influences at sites such as Tikal, Los Horcones, and Kaminaljuyu during the Early Classic (Cowgill 1997; Love 2007) also may have been facilitated by the relatively direct network connections evident in our period 5 data. Likewise, the spread of cult practices, artistic, and architectural styles linking Central Mexico, the Northern Yucatan, and extending down to the Belizean coast during the Terminal/Epi-Classic (Chase and Chase 1982; Ringle *et al.* 1998) may reflect the relative strength of network links that do not necessarily adhere to distance. Similarly, given the small network size and short average path lengths linking much of Mesoamerica together during the Late Postclassic—implying low costs of movement between even distantly located places—it is perhaps to be expected that the Late Postclassic witnesses the spread of truly pan-Mesoamerican sets of styles, iconography, and traditions sometimes referred to as the “Mixteca-Puebla” tradition or “Postclassic international style” (Boone and Smith 2003; Smith 2003b; also see Mills *et al.* 2013a for the similar example of the Salado Polychrome style in the American Southwest).

## Ancient Economies from a Mesoamerican Network Perspective

In a recent reanalysis of the ancient Aegean economy, Morris questions the nature of ancient economies—were they basically static over time, and characterized by local agrarian output consumed at the household level, or were they dynamic and changing systems in which trade and distribution played a fundamental role? “If the later, then ancient economic historians will be challenging one of the fundamental orthodoxies of modern economic historians, that between the rise of the state in later pre-History and the Industrial Revolution after AD 1750, agrarian economies were essentially static” (Morris 2005, pp. 125). Many analyses of the pre-Hispanic Mesoamerican economy have largely drawn on this same substantivist tradition of economic thought that has generated basic assumptions about ancient economies worldwide, emphasizing household agrarian production for local consumption, political control of distribution, and stable structure over long periods of time during the deeper past. Our analysis clearly positions the pre-Hispanic Mesoamerican economy as an important counter example to these static and localized models.

More specifically, our investigation undercuts several basic assumptions often made in regards to ancient economic systems by archaeologists, economists, and economic historians. Although the Mesoamerican system was at its core an agrarian system based on small-scale production at the household level—as were all ancient economies—degrees of larger-scale connectivity was characteristic of the Mesoamerican system as far back as 900 BC (and possibly earlier). Integration progressively increased such that the Mesoamerican distributional system became smaller (in network terms) over time. This finding is not inconsistent with prior world systems analyses of the Mesoamerican economy. Blanton and Fargher (2012) for instance propose that obsidian—which they categorize as a "bulk luxury" good—played an essential role in stimulating economic intensification and regional integration. As a non-essential, but valued, commodity (since chert and other cutting materials are much more broadly accessible) widely available to all segments of Mesoamerican society (e.g., Feinman *et al.* 2013; Moholy-Nagy *et al.* 2013), goods such as obsidian may have driven increasing incorporation of even small households into the regional system, promoting intensified quarrying, longer-distance transport, and higher levels of interconnection between different regions of Mesoamerica. Although our analysis indicates that Mesoamerica can be viewed as a single economic network well before the Classic period, increasing network integration from this era onwards is consistent with their view that "(w)orld-system growth is first evident after about CE 300 with the advent of bulk luxuries…At this time we first detect a process of periphery incorporation." (Blanton and Fargher 2012, p. 14).

Contrary to static views of ancient economies, the structure of connections linking different regions of Mesoamerica to one another shifted dramatically over time, moving obsidian through trade routes that only weakly conform with the geographical positioning of resources, and instead likely reflected a combination of political, geographical, technological, and demographic factors that impacted which sources were quarried, and how and how far they moved across the macroregion. Quarrying and mining of obsidian prior to the Postclassic seems to have focused on a smaller set of sources that were then transported long distances through more tightly circumscribed network links—this mode of integration peaked during the Late Classic and Terminal Classic, when relatively few sources were in use, but any given site received on average material from a more diverse set of sources. The more "international" system of the Late Postclassic (Boone and Smith 2003) is reflected in a basically different network topology—more sources were in use, but fewer were present at any given site, while links were evenly distributed between settlements, resulting in a low-density, "small" network structure implying a tightly integrated system.

Evidence for top-down control by major political centers during each time period we consider is variable, but no one center was able to dominate distribution patterns exclusively. Against a general trend of decreasingly hierarchical network structure (and starting at a relatively low level of hierarchy), individual sites or centers appear to have had principally local import in network structure, rather than dominating distribution on a pan-Mesoamerican level. The macroscale structural properties of distribution networks may help identify variable positional advantages that in part may account for why particular cities or states flourished during particular time periods and declined during others, but the examination of network positioning also allows us to recognize cities such as Teotihuacan that appear not to have relied heavily on long-distance trade networks to underwrite growth. More generally, our results indicate that the ancient Mesoamerican system does not have the spatial linkages that would be expected in a highly centralized command economy.

Both visual inspection of our results and formal network metrics also illustrate that the Mesoamerican distribution system exhibited cyclical patterning with macroregional cycles similar to those identified in other global contexts (e.g., Chase-Dunn and Willard 1993; Frank 1993; Turchin and Hall 2003). Periods of relatively high integration (our periods 3, 5–6, and 8) were followed by phases in which evidence for inter-regional connectivity declined (periods 4 and 7). Notably, these network trends can be viewed as an indication that the Mesoamerican system was functionally linked so that even localized political, environmental, social, or demographic perturbations may have had system wide impacts. For example, we suggest that long-term trends in the Mesoamerican economy and social system contributed to the eventual development of the “extensive” network structure defined during period 8. The Late Postclassic economy emerged from a major transition during period 7, one correlated with wide-ranging but regionally variable patterns of urban, demographic, and political upheaval that extended from the late Classic into the Early Postclassic (Aimers 2007; Sabloff 2007). It is conceivable that a more restricted set of trade and exchange links constrained to a degree by political borders and alliances did in fact increase to some kind of a tipping point during the Terminal Classic. As state and political institutions became overextended, their declines and restructurings likely had implications on the viability of long-distance transport routes. What remained was perhaps the localized and decentralized infrastructure of economic interdependencies and markets that had developed well before that time. These linkages then served as the basis for the new distribution system evident after~AD 1200, however, the local links eventually restructured in new topologies, which underpinned the more extensive network of period 8. However, we stress that the period 8 network and Late Postclassic economy built on economic trends already evident during earlier periods—the development of local markets (Feinman and Garraty 2010; Feinman and Nicholas 2010; Masson and Freidel 2012; Shaw 2012), increasing network integration, and implied economic intensification beginning at least as early as the Classic period (Blanton and Fargher 2012), in tandem with a set of Late Postclassic political practices that facilitated participation in venues of exchange rather than impeding it (Blanton and Fargher 2012; Gutiérrez 2013; Hirth and Pillsbury 2013).

Network analysis is rapidly gaining popularity as a methodological tool in archaeology (e.g., Brughmans 2013; Knappett 2011, 2013; Terrell 2013), but also represents a conceptual shift towards examination of the relational properties of ancient social and economic systems. In the present case, network analysis has enabled us to formally analyze the structure of the pre-Hispanic Mesoamerican economy, to reveal a nonhierarchical, highly dynamic system that does not conform to broadly held notions that preindustrial economic were static and mostly only interconnected at local scales. Although our results confirm trends already noted by other researchers who have cast doubt on such static economic models, our approach allows for a more quantitative and formal examination of changes in integration, directionality of links, and the role of individual network actors. We must emphasize, however, that our analysis largely examines distribution rather than production, and does not examine the social context of consumption—whether particular segments of society were largely at the center of these distributional systems, and whether the social standing of those involved in trade networks shifted over time. We also considered just one commodity, albeit an important one, obsidian. And, because of the historical realities of investigatory process, we only could include those collections of obsidian that were sourced and then published (or available to us). Despite these limitations, the findings and analytical perspectives discussed here help usher in important and necessary new vantages, frames, and queries relevant to the examination of the pre-Hispanic Mesoamerican economy (and preindustrial economies more generally). As these approaches are refined and expanded, we see both local (household) and macroscale (hemispheric) possibilities of considerable prospect for probing the diversity of (and change in) past human economic practice.

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