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Nets and canoes: A network approach to the pre-Hispanic settlement system in the Upper Delta of the Paraná River (Argentina)

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ABSTRACT

Graph theory-based network analysis provides useful methodological tools for the exploration of several landscape related issues. In particular, it favours the examination of the topological configuration of space; that is, the arrangement of its constitutive elements into a relational order. This is an important aspect of spatiality in terms of its social significance for it reflects, as well as shapes, the way in which social relations are structured. Based on this approach, a case study from the Paraná River Delta, where occupation strategies included the construction of earth-mounds and mobility strongly depended upon water courses, is herein presented. In this scenario, we examined the ways in which spatial arrangement of settlements and waterways linking them through the landscape reflected and shaped social interaction. More specifically, we evaluated the spatial configuration of the Paraná Delta hydrographic network in relation to settlement distribution and hierarchy. Thereafter, we found that archaeological sites are mainly located in highly accessible locations and that the most prominent sites within the settlement system are located at high centrality areas. Subsequently, we discussed the implications of these results for the understanding of the emergence of incipient social hierarchies and the significance of earthworking for the topographic writing of cultural landscapes in the studied area.

1. Introduction

The deeply entangled relationship between human societies and their inhabited landscapes has been a major topic of interest for many archaeologists in the past several decades. On the one hand, it has been stated that social interactions are woven into networks traced over the physical environment in ways in which socialized landscapes are created (Conkey, 1984; Gamble, 1998, see also Langley, 2013). The key elements in these socially constructed territories are paths and trackways along which information flows in order to join individuals and groups together (Gamble, 1998). On the other hand, it has also been widely recognized that landscape in not merely an external scenario where social relationships take place but a social production where meaning is imbued into the physical features of the terrain, both natural and anthropic (Bender, 1993; Cosgrove, 1997; Ingold, 1992, 1997; Thomas, 2001; Tilley, 1993). Moreover, significant spaces, landmarks and the pathways that connect them through landscape topography are attached to meanings and stories which are evoked over the generations. Such continuum contributes to the construction and transmission of historical memory and the constitution of group and individual identity (Bender, 1993; Ingold, 1997; Thomas, 2001). These socially constituted spaces in turn play an active and significant role in the organization, reproduction and transformation of social life. In other words, spatiality at any scale (landscape, places, settlement systems, architectonic spaces) enables and shapes certain social relationships, practices and meanings while other actions and connections are disabled or ignored (Hillier and Hanson, 1984; Giddens, 1984; Rapoport, 1990, see also Acuto, 2013).

In line with the abovementioned considerations, the configuration of space -that is, the arrangement of its constitutive elements into a relational order- proves one of the most prominent properties of spatiality in terms of social significance. Social spaces display an organization that reflects, as well as shapes, the way in which social relations are structured (Giddens, 1984). An important issue that arises then is how to recognize and depict this topological configuration. In this regard, graph theory-based network analyses provide quantitative tools and concepts for analyzing and representing spatial structurations. An example of such

Abbreviations: PUD, Paraná Upper Delta; HTN, Hydrographic Transport Network model; ASN, Archaeological Sites Network model.

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approach is provided by space syntax, a graph theory-based analysis drawn upon to assess social aspects expressed in the distribution and design of architectonic spaces (Bermejo Tirado, 2009; Dawson, 2002; Hillier, 1996; Hillier and Hanson, 1984). We believe that graph theory concepts applied to network analysis may also prove useful tools for the study of social structuration of space in a broader scale and considering a landscape perspective, a subject which has been hardly explored but for a few notable exceptions (Brughmans et al., 2015).

In recent years, network science applications to archaeology have significantly increased. Such studies place relationships in the core of our analytical techniques and allow us to approach a great variety of topics such as hierarchy emergence, settlement systems and circulation of information, people and goods, among others (Brughmans, 2013; Collar et al., 2015; Knappett, 2013; Mizoguchi, 2009). Usually, these relationships are traced among common features of material culture in order to create relational webs (Collar et al., 2015). An alternative way of benefiting from network methods involves shifting the focus of attention to the spatial properties of the archaeological record and analyzing inter-site connections in a landscape framework. In this paper, we explore these ideas via the pondering of a case study from South American lowlands.

Of late, the traditional point of view regarding South American lowlands as pristine habitats occupied by egalitarian forager bands who had no significant impact over the environment has been challenged by increasing evidence of anthropically modified landscapes. Theoretical contributions on Amazonian anthropology, especially Historical Ecology, have been highly influential in this regard (Balée and Erikson, 2006; Hornborg, 2005; Hornborg and Hill, 2011). Pre-Hispanic societies from different regions of South America developed wetland management strategies involving the transformation of the landscape through the mobilization of great volumes of sediments. Such strategies developed into a rich tradition of earth engineering incorporating mounds, raised fields, channels and other earthworks spread all along the major South American basins (Amazon, Orinoco and Paraná-Plata) and transcending cultural and linguistic boundaries (Gianotti and Bonomo, 2013; Heckenberger and Neves, 2009; Rostain, 2010; Souza et al., 2016).

Herein, we provide a case study from one of the southernmost expressions of this earthworking phenomenon, the Paraná River Delta. In this flood-prone wetland, occupation strategies included the construction and habitation of earth-mounds and other topographically elevated areas in an environment where mobility greatly depended upon water courses. Based on this scenario, we hereby address how spatial arrangement of settlements and waterways linking them through the landscape reflected and shaped social interaction. For assessing this topologic configuration, we resort to a graph theory-based network analysis. Spatial structuration of waterways in the study area defined movement and circulation of information, goods and people hence conditioning interaction possibilities that produce and reproduce social networks. In this way, mobility pattern observations provide information on social connectivity and, also, inequality (Howey, 2011; Richards-Rissetto and Landau, 2014). Spaces are usually tied together in the form of webs within which some locations are more accessible than others or boast higher potential for controlling communications. This structuration both influences and reflects mediation and interpellation abilities of social actors and the range and nature of the strategies they can implement (Dobres and Robb, 2000; Mizoguchi, 2009). We discuss the implications of these ideas for the understanding of the emergence of incipient social hierarchies and the significance of earthworking in the construction of cultural landscapes in the study area.

2. Graph theory and network analysis in archaeology

Formal properties of networks can be mathematically addressed through graph theory. "Graph" is a term utilized to describe a twodimensional structure composed of spatially distinct points or nodes connected by lines or edges. The relevance of this approach lies on the fact that its use favours the representation of topological links between network elements beyond the nature or specific content of these relationships (Cardozo et al., 2009; Hage and Harary, 1983; Wallis, 2007; Wilson, 2014). Therefore, graphs have been used to represent structures as diverse as neural circuits, urban transportation systems, insect colonies or social networks while currently being widely applied to disciplines such as Physics, Neuroscience, Sociology, Geography, Computer Science and Economics, among others. One of the most remarkable properties of graphs is centrality. Graph centrality measures are mathematical methods for quantifying the importance of each node in terms of its position with respect to the surrounding elements in the network. Two of the most commonly used centrality measures are betweenness and closeness. These measures indicate how accessible a location is and the potential for mediation or control that it may exercise with respect to the traffic between other nodes in the network (Freeman, 1977; Friedkin, 1991; Sevtsuk and Mekonnen, 2012).

Formal network analysis through graph theory has been applied to archaeological research since, at least, the 1960s (Brughmans, 2013). In two influential articles, Pitts (1965, 1979) used measures of closeness and betweenness to analyze Moscow's strategic position within the river trade network of medieval Russia. The archaeological potential of network analysis was clearly recognized in the 1970s by Irwin-Williams (1977), who described the analytical possibilities offered by network models for quantitative analyses of prehistoric trade. Particularly, the author explored the potential of these models when addressing the influence of exchange systems in prehistoric settlements of northwestern New Mexico. For his part, Rothman (1987) highlighted the advantages of graph theory in settlement systems analysis in terms of how it allows researchers to test hypotheses drawn from anthropological theories bringing into play mathematically objective measures. The author illustrated this approach by applying graph theory concepts to the interpretation of regional survey data from south-western Iran. Influenced by these works, Peregrine (1991) used centrality measures to explore the evolution of the Cahokia center within the Mississippi Basin. He visualized this basin as a graph where lines represent the rivers and nodes correspond to river heads and junctions. By applying measures of degree, betweenness and closeness, he argued that the evolution of Cahokia was possible due to its strategic central position at the confluence of several major rivers which facilitated control over riverine exchange.

These early applications of graph theory in archaeology developed discontinuously and had no significant influence on the widespread adoption of network techniques in later archaeological research (Brughmans, 2013, 2014). Network analyses in archaeology faced a significant breakthrough in the last ten years and were influenced by two research traditions (Brughmans, 2014): social network analysis (Wasserman and Faust, 1994) and studies of complex networks in physics (Barabási and Albert, 1999). The issues addressed in archaeological network analyses are as diverse as the methods therein applied: spread of information following the Antonine Itinerary (Graham, 2006), religious innovations in the Roman Empire (Collar, 2007), impact of natural disasters on maritime connectivity in the Aegean Bronze Age (Knappett et al., 2008), identification of social and cultural boundaries in Papua New Guinea (Terrell, 2010), distribution of Roman pottery (Brughmans and Poblome, 2016), social interactions between Near

East sites during Epipalaeolithic and early Neolithic times (Coward, 2013), centralization of lowland Maya political networks (Munson and Macri, 2009), procurement and distribution of pre-Hispanic Mesoamerican obsidian (Golitko and Feinman, 2015) and intervisibility of Iron Age and Roman sites in southern Spain (Brughmans et al., 2015), among others.

Beyond thematic diversity, several specific contributions address issues of particular relevance a propos of the aims of the study hereby conducted: transportation systems and mobility throughout the landscape and emergence of social hierarchies. Similarly to Peregrine (1991), Jenkins (2001) resorted to measures of degree, closeness and betweenness to explore the properties of the Inca transport network. Particularly, the author discussed the topological advantage of administrative centers, production sites and storage sites placed in strategic locations within the Inca road system. Similarly, Isaksen (2007, 2008) analyzed the Roman road system in southern Spain and highlighted the potential of GIS when studying this sort of geographical networks (Brughmans, 2014; Knappett, 2013). For his part, Mizoguchi (2009) applied multiple centrality measures to assess the emergence of centralized hierarchies in the Japanese initial Kofun period. Such contribution concludes by determining that the topological position of political units within a social network can be a significant cause of the emergence of hierarchical relationships among them. Centrality measures are the most commonly used methodological tools for studies such as these, where the basis consist of the identification of nodes that feature either a better access to information/ resources or an intermediate position that allows them to control the connections between other nodes and, hence, the circulation within the network.

Stemming from a different tradition, another interesting contribution to archaeology involving graph theory is space syntax. This approach studies the ways in which built spaces constituting architectural ensembles are related and organized. The point of such pondering is to assess the underlying social logic of such structuration (Bermejo Tirado, 2009). In this framework, the relationship between society and space is a dynamic one, where each variable modifies and restructures the other (Bafna, 2003). Originally developed by architects (Hillier, 1996; Hillier and Hanson, 1984), space syntax has been used in archaeology to examine spatial configuration of past public and domestic architecture (Dawson, 2002; Bermejo Tirado, 2009).

Finally, a graph theory derived tool, circuit theory, has been recently adapted from electrical engineering to biology sciences and, thereafter, to archaeology. This approach is used in biology to model environment connectivity and predict patterns of movement, gene flow and genetic differentiation among plant and animal populations (McRae, 2006; McRae and Beier, 2007). In landscape archaeology, circuit theory has been drawn upon as a novel and complementary approach to least-cost models in order to study mobility patterns and trace past pathways through landscape (Howey, 2011; Thayn et al., 2016).

3. Waterways, graphs and centrality in the Paraná Delta

The Paraná River is, with a total length of more than 3500 km and an extensive delta system located in its lower section, one of the most important fluvial courses of South America. The Paraná Delta consists of a dense and complex fluvial network comprising rivers, streams, ponds and temporary narrow water courses surrounding elevated landforms (Iriondo, 2004). In this environmental context, such network is, both at present and in the past, the main transport route for human mobility. Sixteenth-century ethnohistorical sources describe canoe mobility among the Chaná, the Timbú, the ChanáBeguá, the ChanáTimbú and other groups that inhabited the region (Fernández de Oviedo y Valdez, 1547; Medina, 1908; Ramírez [1528], 2007; Santa Cruz [1540], 1918; Schmidl [1567], 1980). Dugout canoes found in the Paraná Delta and Río de la Plata River are material records evidencing these practices in the pre-Hispanic past (Bonomo, 2012; Serrano, 1950). Furthermore, navigation is the main form of transportation among the "islanders" inhabiting the region even at present.

Archaeological research in the Paraná Upper Delta (hereafter referred to as PUD) enabled the detection of more than 60 sites typically emplaced at high landforms of different origin (mainly mounds, locally known as "cerritos" and levees) and often located near the intersection of two or more fluvial channels. Such emplacement would allow easy access to waterways (Bonomo, 2012; Gianotti and Bonomo, 2013). In addition to exhibiting functional and seasonal differences, the sites presumably reflect a settlement hierarchy in which some localities are characterized by the size or quantity of the mounds therein emplaced, the effort invested in their construction, their temporal stability, the ritual use of burial areas and the presence of exotic goods. Based on this evidence, the fact that indigenous groups who inhabited PUD (ethnohistorically known by the generic term of ChanáTimbú) and their predecessors centuries prior to the Hispanic conquest (related to the Goya-Malabrigo archaeological entity) lived in the frame of a sociopolitical organization corresponding to a ranked society has been proposed. In such societies, high ranked individuals exert regular and repetitive authority but their followers are not bound to obey them (Chapman, 2003). In addition to the archaeological evidence, this proposal is based on several allusions, found in sixteenth-century chronicles, to the existence of charismatic and powerful leaders with the ability to form alliances with each other and coordinate regional exchange networks (Bonomo et al., 2011; Politis and Bonomo, 2012).

Due to the importance of fluvial transport in the study area, we believe that a thorough analysis of the Paraná fluvial network is crucial for the exploration of human settlement, mobility and exchange and, hence, for understanding the way in which social interactions were structured over the landscape. Therefore, we evaluate the spatial configuration of the waterway transport system in relation to distribution and hierarchy of the settlements and circulation of foreign materials. We pursue these goals by way of resorting to an approach that combines social network analysis concepts derived from graph theory with GIS tools. This is accomplished by making use of software originally developed for urban network analysis. With such software, it is possible to model both topological and metric (geographical) networks which therefore favours the combination of measurements derived from network analysis and the analytical advantages of quantitative spatial variables.

In this paper, we model the Paraná Upper Delta fluvial network as a graph in which nodes represent waterway intersections and edges stand for the fluvial streams themselves. Based on this model, which we call Hydrographic Transport Network, an Archaeological Sites Network model is developed to explore the relationships between archaeological sites (nodes) connected by fluvial channels (edges). Two centrality measures, betweenness and closeness, are calculated via these models in order to account for differences in accessibility and potential for controlling communications over the landscape. Considering the fact that spatial structuration of settlements and mobility reflected as well as shaped social interactions, several expectations can be outlined. Firstly, it is hypothesized that archaeological site distribution will relate to variations in the degree of accessibility within the hydrographical network. Secondly, the most prominent sites within the settlement system are expected to be located in areas with high communication potential that may also allow better control over the flow of information, goods and people. Therefore, it is also expected that central points of the landscape concentrate the highest amount of exotic goods since these points are better connected and present an advantageous position within the exchange network.

4. Environmental framework

The Upper Delta of the Paraná River covers the area between Diamante City (32°41′10.96″S and 60°38′16.34″W) to the north and the Paraná Pavón River to the south while it is bounded to the east and west by the cliffs that define the transition to the high plains of Entre Ríos and Santa Fe Provinces (Fig. 1). The study area is characterized as a gently sloping floodplain with a complex hydrological regime subject to periodical floodings. Extensive lowlands represented by permanent and temporary ponds, floodplains and ancient tidal plains which surround elevated landforms such as fluvial banks, leeves, meander scrolls and sand dunes can be recognized (Castiñeira et al., 2014; Cavallotto et al., 2005).

The PUD is part of the littoral complex that developed in the lower section of the Paraná River over four phases (Iriondo, 2004). The fluvio-eolian initial phase is represented today by the Pleistocene Flood Plain, the oldest part of this complex. Subsequently, the middle Holocene marine ingression led to the development of a sand barrier, a lagoon, minor tributary deltas and estuaries and well developed regressive deposits. During the successive estuarine phase, an extensive tidal plain developed in the center of the littoral complex. Finally, the current fluvial-deltaic period is marked by channel and deltaic deposits advancing into the Río de La Plata. Within the study area, located to the north of this littoral complex, several geomorphological units corresponding to this evolutionary sequence can be recognized (Iriondo, 2004) (Fig. 1). The Pleistocene Flood Plain is the result of a long evolution under flood dynamics. It consists of a vast hindered-drainage plain characterized by a large number of shallow lakes, ponds and swamps cut by minor adventitious channels. These channels are bordered by well developed levees which isolate them, except during floods events, from active channels. South of this unit and during the retreat of the sea, a set of beach ridges consisting of a sequence of beaches juxtaposed or separated by mudflats was formed. Adjacent to these beaches, a tidal plain composed of estuarine sediments deposited after the higher phase of the Holocene ingression was developed. Such tidal plain is characterized by subparallel tidal channels presenting straight segments and well-defined angles. This particular unit is currently subjected to fluvial dynamics with floods that partly run through the tidal channel network and modify it in some areas. Throughout the late Holocene and at present, the fluvial dynamics of the Paraná River and its tributaries have resulted in bar and meander belts as well as a plain of narrow meanders. The first unit developed in high energy environments during the current fluvial-deltaic phase and is the most active geomorphological unit of the study area. It is formed by bedload deposition along the main channels of the Paraná River. This deposition generates bars that eventually become permanent islands due to vertical aggradation. The plain of narrow meanders, characterized by a large number of sinuous low-energy channels following flow-paths that operate independently over considerable distances, represents the oldest portion of the floodplain and was generated by the lateral migration of quite active distributaries of the left bank of the main channel. At present, this process of lateral migration continues to develop reworking sediments of older units, principally the Pleistocene Flood Plain and the Tidal Plain. However, as evidenced by persisting features of older units, this alteration of forms is not intense (Iriondo, 2004; Iriondo and Kröhling, 2008; Milana and Kröhling, 2015; Paira and Drago, 2007).

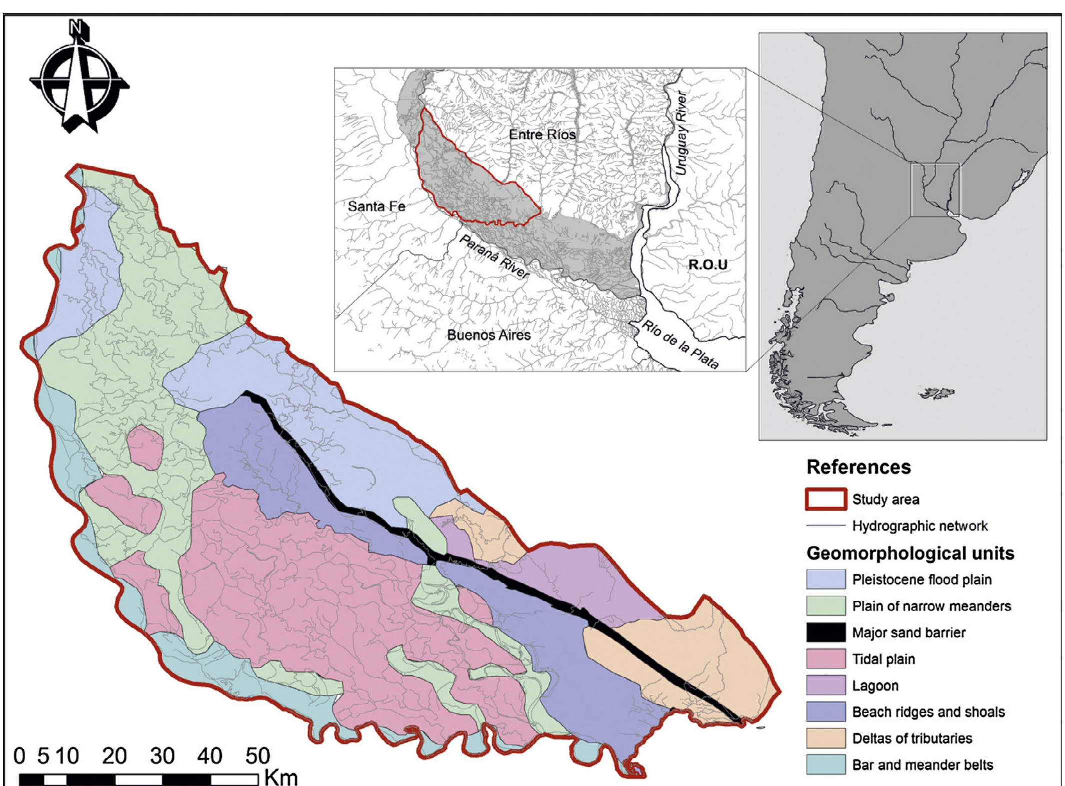

Fig. 1. Location of the Upper Paraná Delta within the southern cone of America and geomorphological units of the study area (modified from Iriondo, 2004).

5. Archaeological framework

As a result of the research project conducted by Drs. Politis and Bonomo in the Diamante, Victoria, Gualeguay (Entre Ríos Province) and San Jerónimo (Santa Fe Province) Departments, 84 archaeological sites were detected of which most are located in the insular area of this geographical region. Radiocarbon dates obtained so far yield a time span of ca. 1920-500 14^{C} years BP which reveals that human occupation probably took place after the establishment of the current geographical configuration (Apolinaire et al., 2016; Bonomo, 2012; Bonomo et al., 2010, 2014; Castiñeira et al., 2012, 2014; Gianotti and Bonomo, 2013; Politis et al., 2011). There is clear evidence of earthmounds, which represent about 50% of the detected sites, since, at least, ca. 1900 BP (Apolinaire et al., 2015; Castiñeira et al., 2014). Such mound-building activity has been associated with Goya-Malabrigo, an archaeological entity probably corresponding to the ancestors of historical ethnic groups generically known as Chaná-Timbú. Goya-Malabrigo has been characterized by a particular pottery style marked by emblematic forms such as "campanas" and zoomorphic appendices (Ceruti, 2003; Politis and Bonomo, 2012; Serrano, 1950). Additionally, a mixed economy mainly based on fishing and semi-aquatic mammal hunting (Bastourre, 2015) complemented by gathering and maize, bean and squash horticulture (Sánchez et al., 2013) has been suggested. This aquatic oriented economy is associated to the development of fluvial technology consisting of fishing nets, harpoons and dugout canoes.

Archaeological research at PUD enabled the identification of a settlement system where sites presenting different functions, hierarchy and occupation intensity can be recognized (Politis and Bonomo, 2012). Major residential settlements were located at the highest landscape positions (unaffected by floods except in times of extraordinary inundations) and consist of anthropogenic mounds, as well as natural landforms such as dunes and levees. These settlements, interpreted as actual villages, were semi-permanently occupied during prolonged periods of stability followed by abandonment and subsequent reoccupation. Second order settlements consist of less intensive occupations in naturally elevated landforms slightly lifted by human activity. These sites were not periodically reoccupied and their function could be related to the exploitation of certain resources. Also, there were other settlements, perhaps oriented to specific activities, consistent with more sporadic, shorter and less dense occupations than those characteristic of the previous case (Bonomo et al., 2011; Politis and Bonomo, 2012). Archaeological topographic surveys at PUD enabled the design of digital elevation models of 20 mound-like structures and the calculation of their size and volume (Bonomo et al., 2011; Castiñeira et al., 2014). These structures are either isolated in the landscape or aggregated in groups of two or three in which one is usually larger than the others. These mound-like structures typically exhibit elliptical shapes and, although some have been altered by erosion, their heights range from 0.5 to 2.2 m. Their sizes and volumes present considerable variations marked by volume values ranging from 140 to 3912 m^3 and major axis lengths between 35.4 and 84.2 m.

Settlements within the study area have not been isolated but integrated into regional interaction systems and connected to supra-regional exchange networks. This is reflected in the presence of foreign rocks with natural outcrops located medium to long distances away from the archaeological sites: sandstones from the Ituzaingó Formation to the north (middle Paraná River); silicified limestones, sandstones and basalts that outcrop along the Uruguay River to the east; quartz from the Sierras de Córdoba to the west and orthoquartzites from the Balcarce Formation to the south (Bonomo and Blasi, 2010). In fact, considering the absence of natural outcrops in the study area, lithic raw materials are rare at archaeological sites and mainly have a foreign origin. The information available for Goya-Malabrigo from both PUD and other sectors within its dispersal area indicates that, in addition to rocks, other items (such as copper artifacts, malachite beads, textiles and domestic camelids) have circulated among these supra-regional networks, thus evidencing links with the southern Andean region and Central Sierras of Argentina (Bonomo et al., 2011).

Politis and Bonomo (2012) suggested that social groups associated to the GoyaMalabrigo archaeological entity lived in the frame of a socio-political organization corresponding to what is usually known as ranked society (sensu Chapman, 2003). In these societies, highly ranked individuals enjoy differential access to exotic products and prestige goods yet all individuals equally access the same basic resources regardless of their social position. Moreover, chiefs have the role of preventing fragmentation within the group, coordinating collective work and controlling long-distance exchanges. Such hypothesis is based on archaeological evidence of burials containing prestige goods, the existence of a hierarchical settlement system that could reflect social distinctions and the presence of relatively large and grouped mounds for the construction of which the organization of communal work must have been required. Furthermore, sixteenthcentury ethnohistorical documents mention the existence of chiefs or "mayorales" -identified by their power, representativeness and paraphernalia- who had the ability to federate several groups to engage in warfare against the Spanish conquerors (Bonomo et al., 2011; Fernández de Oviedo y Valdez [1547], 1851; Lopes de Sousa [1530-32] 1839; Medina, 1908; Schmidl [1567], 1980).

6. Material and methods

The hydrographic network of the Paraná Upper Delta was modelled using GIS tools. To this aim, we resorted to information from the Instituto Geográfico Nacional (IGN) (SIG250) as a source of hydrographic vector data. This fluvial network was extended and detailed by means of the digitization of minor streams. For such purpose, satellite images obtained from Google Earth (Google Inc.) and Bing Maps (Microsoft Corp.) servers were worked at a scale of 1:75,000. These images display dates ranging from 2012 to 2013 and were obtained from months during which the Paraná River level at Rosario City Port ranged between 2.25 and 3.25 m. The obtained vector data were processed with Network Analyst package (ArcGIS, ESRI Inc.) to attain a Hydrographic Transport Network model (hereafter HTN) in which lines represent waterways and nodes herald places where the waterways intersect (junctions) or stream endpoints can be found. In the HTN, lines are undirected given the fact that they adopt no fixed direction of flow and connect nodes in both directions. In this model, flow impedance is defined by waterway length measured in meters. The lagoons were modelled as central nodes connecting all the lines that converge into them.

Centrality measures for nodes in the HTN were calculated using the Urban Network Analyst package (Sevtsuk and Mekonnen, 2012). Two measures were considered: closeness centrality and betweenness centrality. Closeness centrality measures the proximity of a node to all other nodes in the network. Formally, it can be defined as:

$$C^r_{c[i]} = \frac{1}{\sum_{j \in G-\{i\}, d[i,j] \leqslant r} d[i,j]}$$

Closeness centrality $C^r_{c[i]}$ of a node i in a graph G is the inverse of the sum of the distances between i and all other nodes that are reachable in G within radius r following the shortest paths (Sevtsuk and Mekonnen, 2012). For this study, the distance was measured in meters and the radius considered included the entire network. Closeness centrality quantifies the ease with which a node can reach and be reached by every other node in the network. Specifically, it can be regarded as a useful measure for assessing the importance of a given node in terms of its accessibility.

Betweenness centrality (Freeman, 1977), $C^r_{I[i]}$, indicates the frequency with which a node lies on the shortest path between any pair of other nodes in the network. It is defined as:

$$C^r_{I[i]} = \sum_{j,k \in G-\{i\}, d[j,k] \leqslant r} \frac{n_{jk}[i]}{n_{jk}}$$

where n_{jk} is the number of shortest paths from node j to k in G and $n_{jk}[i]$ is the number of shortest paths from j to k passing through i, with j and k lying within the radius r from i (Sevtsuk and Mekonnen, 2012). Unlike closeness, which illustrates the ease with which a node can reach and be reached by other nodes, betweenness indicates the potential of a node to be "on the way" between any other pair of nodes in the network, when the shortest paths are considered. Elevated betweenness values for a given node suggest a high degree of control of such node over the network since many other nodes depend on it to connect with each other. In other words, a node with high betweenness centrality mediates interactions within the network to a greater extent than others. In a transport network, these key nodes may have the potential to influence the flow of goods, information and people (Isaksen, 2008; Mizoguchi, 2009).

A raster image with a cell size of 20 m was generated from the interpolation (kriging method) of the centrality values calculated for the HTN nodes. Thus, centrality values could be assigned to each cell of the matrix, obtaining closeness and betweenness maps with values for each point of the study area. Finally, centrality values were extrapolated to archaeological sites based on their geographic position within these maps. We assume that these values indicate the accessibility of a settlement and its ability to control the hydrographic transport network. Since HTN is a geographic model independent from archaeological variables, site centrality values obtained from closeness and betweenness maps are not affected by any archaeological sampling biases.

Based on the HTN, a second model was developed to account for connections among archaeological sites. In this case, each site was represented as a node linked to the HTN edges through the shortest line; that is, to the closest point along the nearest water course. On this basis, the Archaeological Sites Network model (hereafter ASN) was obtained. In the ASN model nodes represent sites and lines, plotted on the hydrographic network, correspond to the shortest waterways connecting the nodes together. Finally, centrality measures for nodes in the ASN were computed. Unlike the HTN model, where closeness and betweenness measures indicate accessibility and control over the fluvial landscape, in the ASN model, these measures reflect site centrality in relation to other archaeological sites in the study area. More precisely, closeness indicates the ease with which a site can access or be accessed by another one while betweenness reveals its potential for controlling communications among sites.

Thereafter, we relate the results obtained from these analyses to several features of the regional archaeological record that are of relevance for the aims of this work: distribution of archaeological sites, settlement hierarchy and presence of foreign materials. We considered a total of 58 archaeological sites detected during surveys in PUD and described in several publications (Bonomo et al., 2010, 2014; Gianotti and Bonomo, 2013). Although the southeast sector was not as deeply prospected, these surveys were intensive in most of the study area (Bonomo et al., 2010). Due to the regional scale utilized, localities with archaeological sites separated by distances of less than 1 km were considered a single entity thus reducing the sample considered to 51 analysis units.

As regards site distribution, we evaluated through spatial autocorrelation (Global Moran's I) whether its spatial pattern is random, clustered or dispersed, using centrality values of sites (obtained from the HTN model) as associated attributes. In other words, we examine if archaeological sites are more clustered or dispersed than would be expected if underlying spatial processes were random. In addition, we assessed whether archaeological localities tend to be emplaced in geographical areas marked by high closeness and/or betweenness scores. A Z-test was performed to examine whether closeness values for archaeological sites (obtained on the basis of the HTN) correspond to a random sample drawn from the set of points that make up the study area (namely, the set of cell values comprising the closeness raster map), or instead they are significantly higher than the mean value for the raster. In the case of betweenness, whose distribution is not normal, a Mann-Whitney test was performed to the same end. To avoid potential biases associated to the archaeological survey, these statistical tests were calculated excluding the least prospected sectors from centrality maps.

To examine settlement hierarchy, we considered mound size as an indicator of the importance of each site within the settlement system. For such purposes, we took the area and volume values published for 20 mounds (corresponding to 15 analysis units) of the study area (Bonomo et al., 2011) into account. The mound area, calculated as an ellipse using the length of the major and minor axes of the structure, is herein assumed to represent the inhabitable and anthropogenically modified surface. The mound volume was deemed to be an indicator of the effort invested in earth movement for the construction of the mound (Bonomo, 2012). In localities presenting more than one mound, the areas were summed and the volume was calculated as the average volume multiplied by the number of mounds. Then, area and volume values for these sites were correlated to their centrality scores, computed for both the HTN and the ASN models. Pearson and Spearman's correlation coefficients were used for closeness and betweenness, respectively.

Finally, we examined the relationship between the centrality scores for each site and the presence of foreign rocks. Since not all archaeological localities were studied thoroughly, there are not enough data available to compare frequency and diversity of lithic raw materials between sites. Therefore, the sample of sites was divided based only on the presence or absence of foreign rocks. Then, the centrality mean values of these subsets, calculated for both HTN and ASN models, were compared in search of any significant differences between them. For closeness scores comparisons, a *T*-test was performed while betweenness was analyzed by means of the Mann-Whitney test.

7. Results

The distribution of archaeological sites within the study area is related to the topological structure of the hydrographic network. Fig. 2 illustrates the HTN model and the gradient values of closeness (a) and betweenness (b) calculated through interpolation. As regards closeness, spatial autocorrelation results (Moran's $I = 0.61$, $z = 6.06$, $P < 0.01$) indicate that archaeological sites are not randomly distributed but display a clustered pattern. That is, sites tend to be spatially aggregated according to their closeness values more than would be expected by random chance. As shown in Fig. 2a, archaeological sites are mainly located in areas featuring high closeness scores. In fact, Z-test ($z \geqslant 3.24$, $P < 0.01$) indicate that closeness mean value obtained for site dataset is significantly

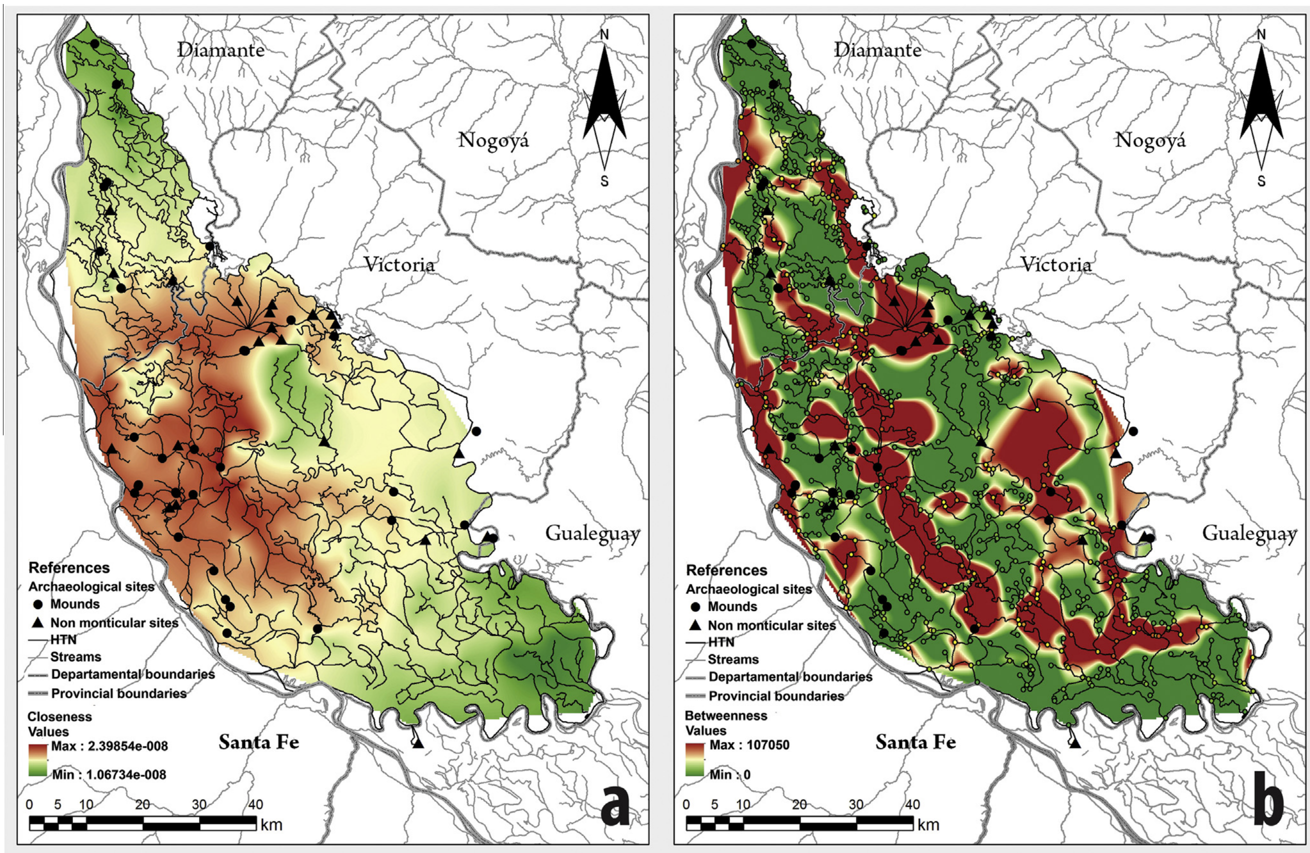

Fig. 2. Distribution of archaeological units in the study area (n = 51) and interpolated centrality values for the Hydrographic Transport Network model.

higher than population mean calculated for the set of HTN raster cells. Thus, the distribution of settlements seems to be related to their potential access to other locations in the landscape. In the case of betweenness centrality, statistical results indicate that this variable is not related to the spatial distribution of archaeological sites. In addition, sites are not necessarily located in areas of high betweenness.

In Table 1, we present closeness and betweenness values for the archaeological sites, calculated for both models (HTN and ASN), along with the areas and volumes of the mounds and the presence/absence of foreign rocks (Bonomo et al., 2011). Closeness values of the sites in the HTN are strongly correlated with both the area ($r = 0.726$, $p < 0.01$) and the volume of the mounds ($r = 0.649$, $p < 0.01$) (Fig. 3a and b). That is, sites with larger mounds tend to be located at the most accessible places of the study area. When considering the archaeological sites network (ASN), we observed a weaker but significant positive correlation between closeness and volume ($r = 0.470$, $p < 0.05$) as well as betweenness and area ($r = 0.479$, $p < 0.05$) (Fig. 3 c and d). In other words, mound size may also be related to its potential to reach and be reached by other sites in the network and to mediate the interactions among them. In no case was there a significant correlation between mound size and betweenness values calculated for the HTN.

When considering the ASN (Fig. 4), we noted that closeness and betweenness scores for the set of archaeological sites featuring foreign materials are significantly higher than the values obtained for cases in which these materials were not detected ($t = 2.033$, $p < 0{,}05$; $u = 395$, $p < 0.1$). However, in the case of HTN, centrality scores present no significant differences between both sets of sites.

8. Discussion

In this work, the Paraná Upper Delta hydrographic network was modelled as a graph using GIS tools. Such network is assumed to have served as a transportation system that facilitated regional circulation and exchange of goods, information and people between roughly synchronous settlements. This assumption involves two problems:

(1) It uses current data to work out a model for the ancient hydrographic network without considering possible topological configuration changes that may occur in a dynamic fluvial system. Paleoenvironmental reconstructions indicate that the Paraná Upper Delta begins to outline its current configuration *circa* 4000 ^{14}C years BP; that is, after the last Holocene marine transgression. According to available radiocarbon dates and as evidenced by the archaeological remains recovered from fluvial flood sediments (Castiñeira et al., 2014), human occupation occurred after such geographical configuration was established. Although river network structures change through time, we believe that, in the time span considered, these alterations were not as substantial as to modify the overall network configuration. In fact, much of the study area corresponds to geomorphological units currently subjected to low energy fluvial action by which the alteration of inherited landforms is not intense (i.e. Pleistocene flood plain, beach ridges, tidal plain and plain of narrow meanders). In some cases, the fact that the current hydrographic network flows through the ancient channels that developed during the post-transgressive estuarine phase can even be observed. However, the bar and

Table 1
Data considered for each analysis unit.

Analysis units	HTN		ASN		Area, m^2	Volume, m^3	Foreign raw materials
	Closeness × 10,0000	Betweeness	Closeness x 100,000	Betweeness			
Cerro de Diego	0.016366	6491.378	0.024237	44	743.968	270.800	Absence
Cerro Lote 11	0.018678	14100.441	0.023073	10	1017.593	325.000	Absence
Cerro El Lucerito	0.018787	5522.407	0.035137	0	1371.588	583.800	Absence
Cerro Justo Norte	0.017887	16328.697	0.029818	12	1570.074	897.300	Absence
Cerro Los Cardos	0.016520	25416.548	0.024435	152	1270.272	901.000	Presence
Cerro Grande	0.019757	31334.808	0.028012	214	1756.669	927.900	Absence
El Cerrito de Puerto Esquina	0.018000	13244.353	0.024104	212	2672.490	973.100	Presence
Cerro de las Cañas	0.016358	5998.290	0.024113	36	1636.463	1232.500	Absence
Cerro Grande de la Isla de los Marinos	0.021189	8631.055	0.032149	30	2158.376	2088.200	Absence
Cerro El Durazno 1	0.021563	1063.572	0.029872	33	2296.135	2660.300	Presence
Cerro Puesto Acosta	0.022793	13594.128	0.030988	99	3651.308	2978.100	Absence
Cerro El Castaño	0.021748	17201.869	0.033006	284	4219.913	3020.200	Presence
Cerro Barrancas	0.017337	6255.802	0.032402	0	1947.065	3064.800	Absence
Los Tres Cerros	0.022256	7859.110	0.025072	106	6312.434	3798.300	Presence
Cerro Tejeira	0.019661	9841.714	0.033833	184	3290.567	3912.600	Presence
A El Espinillo 1	0.018449	4163.601	0.029834	8	–	–	Presence
A El Espinillo 2	0.018488	5140.454	0.029981	42	–	–	Absence
A El Espinillo 3	0.018990	4790.719	0.030616	121	–	–	Absence
Arroyo Las Tejas	0.017644	8217.363	0.021970	102	–	–	Absence
Boca de la Sangría	0.021904	3272.725	0.031278	0	–	–	Absence
Cerro Arena	0.018752	2348.725	0.025684	90	–	–	Absence
Cerro Bella Vista	0.019051	3849.607	0.030218	0	–	–	Absence
Cerro Camino	0.018904	2779.594	0.025477	32	–	–	Absence
Cerro Chico	0.019699	34817.078	0.035022	226	–	–	Presence
Cerro Cortada Pelegrini	0.017882	1651.073	0.022777	0	–	–	Absence
Cerro de Arena	0.020355	13405.304	0.033347	258	–	–	Absence
Cerro de Vázquez	0.018462	13257.694	0.023690	80	–	–	Absence
Cerro de Zamora	0.015383	13944.768	0.020823	0	–	–	Absence
Cerro el Durazno 2	0.020370	4906.858	0.031601	82	–	–	Absence
Cerro El Manolo	0.020291	7766.756	0.027359	152	–	–	Absence
Cerro Farall	0.013273	1221.801	0.019176	0	–	–	Absence
Cerro Rodríguez	0.018977	4890.693	0.030460	0	–	–	Presence
Cerro Tapera Vazquez	0.013192	1462.587	0.019358	0	–	–	Presence
Cerro Las Moras	0.021602	5821.994	0.032334	160	–	–	Absence
El Refugio	0.023936	48507.367	0.034513	403	–	–	Absence
La Banqueta	0.021311	28022.498	0.034837	116	–	–	Absence
La Ciega	0.014000	0.000	0.016334	0	–	–	Absence
La Gotera	0.020470	24927.311	0.034362	174	–	–	Absence
La Horqueta	0.016809	4883.964	0.024896	54	–	–	Presence
La Tortuga 1	0.021353	4495.965	0.031234	56	–	–	Absence
La Tortuga 2	0.021488	5456.028	0.030674	0	–	–	Absence
La Tucura	0.017299	15797.717	0.022464	200	–	–	Absence
Laguna de los Gansos	0.017025	5851.275	0.028143	8	–	–	Presence
Laguna Grande	0.020479	19632.172	0.033910	232	–	–	Presence
Los Baños	0.021758	24888.174	0.032944	0	–	–	Absence
Los Dos Cerros	0.017995	8799.604	0.029367	88	–	–	Presence
Los Laureles	0.019965	15800.887	0.033564	178	–	–	Presence
Los Remanses	0.017293	13569.963	0.023810	184	–	–	Absence
Puesto Gómez	0.022088	18003.418	0.032928	260	–	–	Absence
Puesto La Camiseta	0.016485	6144.892	0.022640	0	–	–	Absence
Rincón Saldana	0.015632	14466.500	0.021127	98	–	–	Absence

meander belts unit, comprising a narrow strip along the main channels of the Paraná, is permanently modified by intense fluvial action (Iriondo, 2004). To consider the modern anthropic alterations of the fluvial system, such as bridges (particularly the Rosario-Victoria Bridge), local embankments and hydroelectric dams located at the upper Paraná River, is also necessary. In sum, even though the fact UPD hydrographic configuration has not been substantially modified since human occupation seems probable, it should be noted that the model proposed herein loses elucidatory potential as it is applied to increasingly early dates.

(2) It considers that archaeological sites represent more or less synchronous occupations within the same settlement system. Although the time scale used in this study covers a period of at least 1400 years (1900 to 500 ^{14}C years BP), it is noteworthy that many sites were repeatedly occupied for extended time intervals. This is the case of Los Tres Cerros 1 marked by 21 radiocarbon dates ranging between 1227 and 560 ^{14}C years BP which evidence an occupational history of over 650 years (Scabuzzo et al., 2015). Additionally, most of the sites considered herein were assigned to the same archaeological entity (Politis and Bonomo, 2012), thus supporting the assumption that their settlements were linked together.

Under these assumptions, the position of the archaeological sites within the hydrographic network model was analyzed. Such assessment resulted in finding that the distribution of sites is clearly related to the network topology: sites are preferably located at places that allow easy access to other points of the landscape, considering distance as the main impedance factor. Therefore, we argue that transportation network structure was an important factor in decisions related to settlement location. Thus, central locations were probably favoured for allowing both a better access to

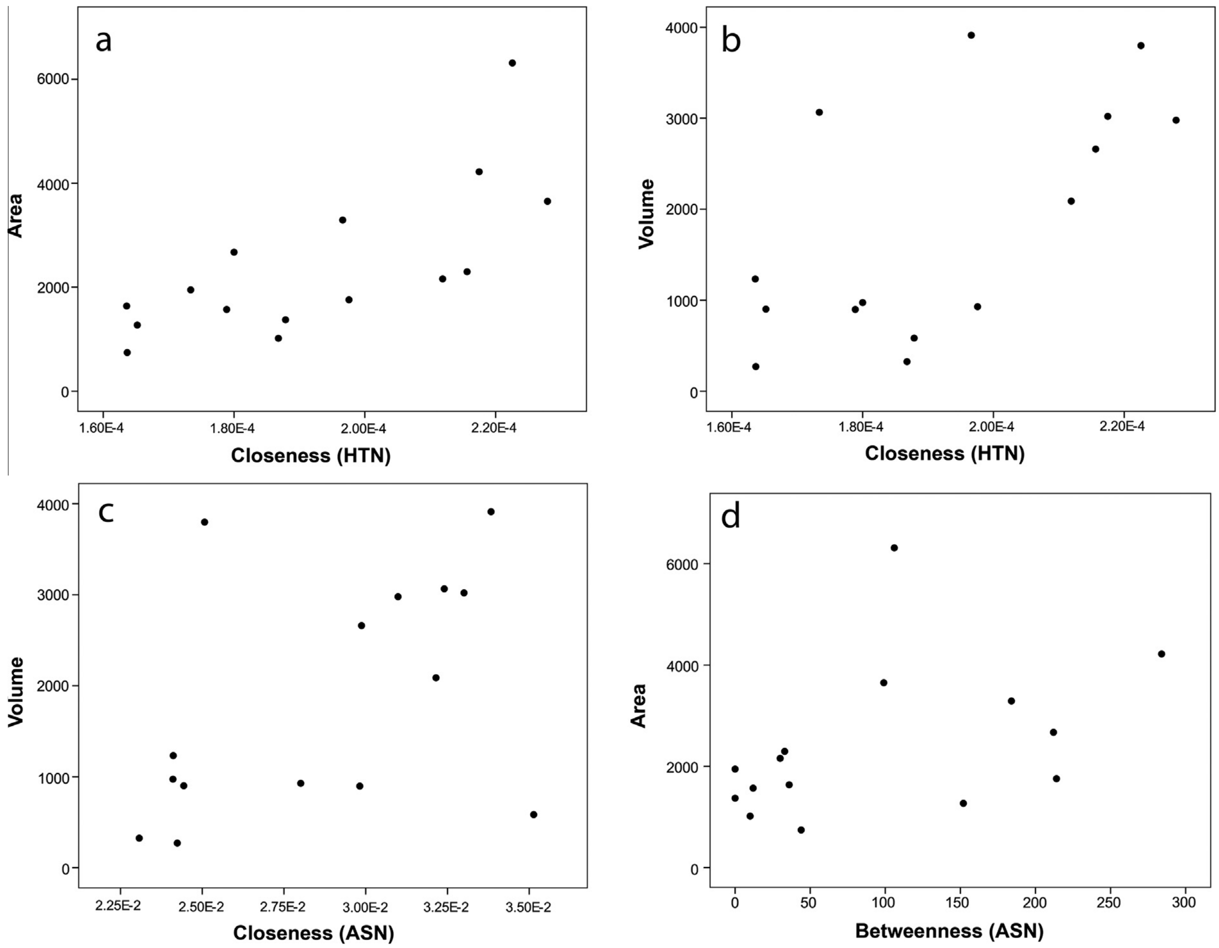

Fig. 3. Scatter plots showing the relationship between mound size and centrality values.

the surrounding resources and better communications with other settlements connected through the transport network.

These results can be discussed in light of the features that have been described for the Goya-Malabrigo archaeological entity and which are shared with Arawak societies extended throughout much of the South American lowlands (Politis and Bonomo, 2012). Without entering into the discussion of GoyaMalabrigo origins and its possible Arawak affiliation, we believe that, from a comparative approach, the ethnographic, historical and archaeological information corpus on Arawak societies (Eriksen, 2011; Hill and Santos-Granero, 2002 Hornborg, 2005; Neves, 2001) is a useful interpretative framework for further exploring our results. In the first place, the location of settlements in accessible and well-connected areas within the fluvial transport network is consistent with the depiction of a society characterized by its connectedness, openness and expansiveness along waterways. This is usually expressed by the development of broad alliances among local and regional groups (both at intra- and inter-ethnic level) and the widespread occurrence of regional and even interregional social formations (Santos-Granero, 2002). The establishment of alliances with neighbouring groups along the rivers is possibly what generated extensive interaction networks between communities linked by kinship, trade and other mechanisms (Eriksen, 2011; Hornborg and Hill, 2011). Another characteristic of the so-called Arawak "ethos", and linked to the abovementioned attributes, is the suppression of *endo*-warfare phenomena. These features are absent among other native communities of the South American lowlands in which social bonds tend to fragment thus resulting in political systems failing to coalesce into larger social formations and where institutionalized cycles of vendettas, organized raiding and other forms of collective violence are part of the constitution of social identities (Santos-Granero, 2002). Some features of this Arawak "ethos" can be distinguished in the GoyaMalabrigo archaeological entity and the historically related ChanáTimbú groups: the existence of exchange networks at local, regional and supraregional levels evidenced by the circulation of foreign materials; the absence of internal conflicts among different ChanáTimbú groups, even though violence episodes did transpired against Guaraníes, Charrúas and Querandíes (as shown by sixteenth-century documents); and the ability to generate regional confederations to raid Spanish settlements (Bonomo and Blasi, 2010; Bonomo et al., 2011; Politis and Bonomo, 2012). In this article, we propose that the existence of these interaction networks was facilitated by the location of settlements in central parts of the hydrographic network.

Within this hydrographic system, certain mound sites stand out due to their size. This earthworks implied a greater mobilization of resources (in terms of earth movement and human labour) to erect enduring structures in the landscape probably occupied by a greater number of people in a relatively stable fashion for several generations. In some cases, such mounds have also been chosen as burial areas, signifying these places in a special way. Through network analysis, it was possible to observe that, furthermore, the topological position of these sites is distinguished by its centrality within the hydrographic network. That is, not only do the settlements tend to be emplaced in accessible areas but, also, the

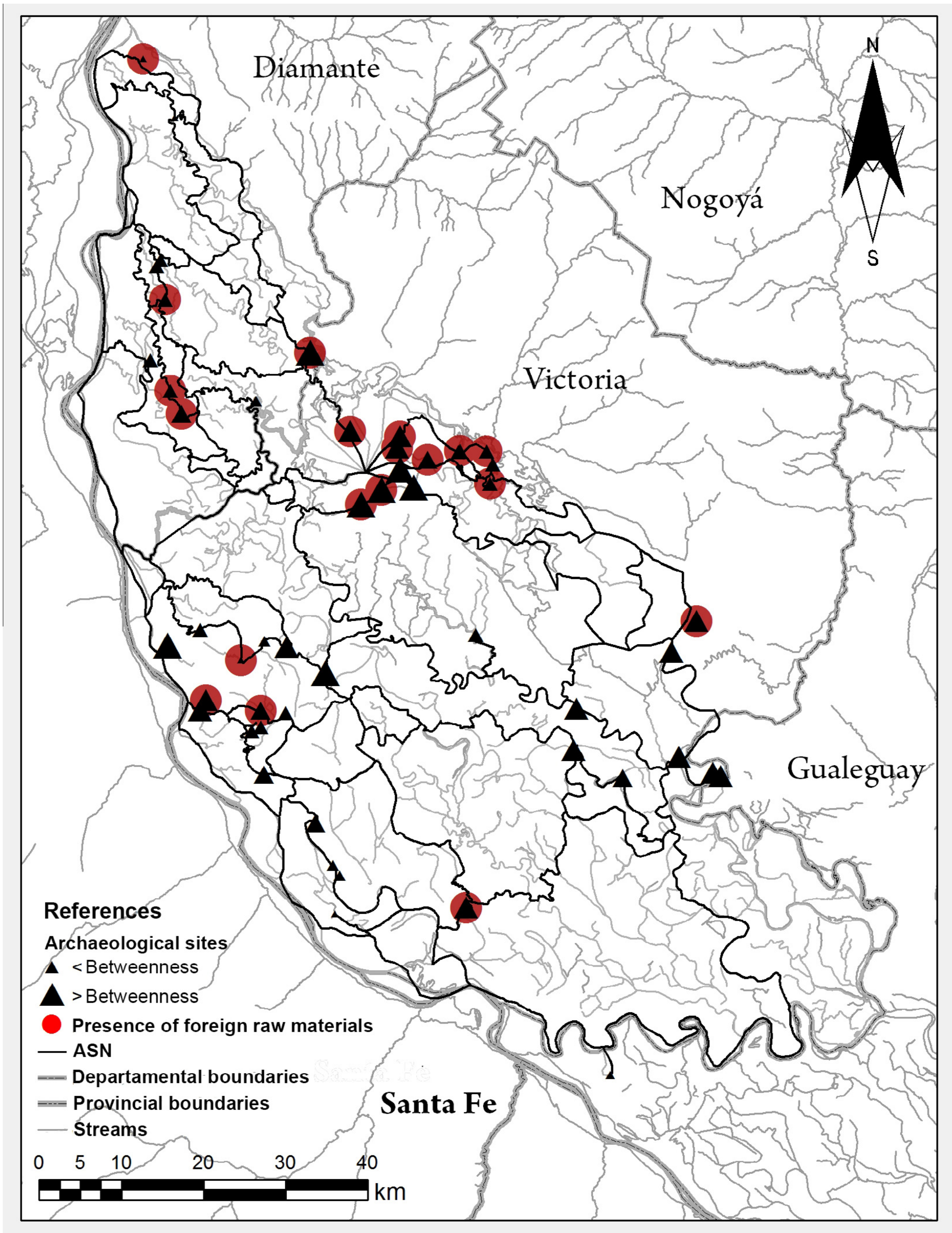

Fig. 4. Archaeological Sites Network model and archaeological sites distinguished by betweenness values and presence of foreign raw materials.

places of greater accessibility appear to be chosen for the establishment of the greatest and most enduring and meaningful mounds.

We believe that the concept of "topographic writing" (Santos-Granero, 1998) becomes of interest when discussing these results. The author stresses the importance, among Arawak groups, of this form of imbuing cultural landscapes with historical knowledge. The topographic writing is based on the existence of landscape features (so-called topograms and topographs) that act as mnemonic devices to evoke and transmit historical events and processes, especially those in which spatial dimension is crucial. In addition, as stated by Eriksen (2011: 6), this system "is often associated with the various high-intensity landscape management systems used by the Arawak, intertwining landscape, history, myth, subsistence, and travel routes". In the case of the Paraná Upper Delta, we believe that earthworking could have served as a form of "topographic writing". Herein, a correlation between the centrality scores of the mounds and the effort invested in their construction was observed. Structures located at key intersections in the transport network could have played the role of topographic references in the cultural landscape. In this sense, they were probably associated to the spatial and historical knowledge transmitted over generations. Even today, both archaeological and modern mounds function as important reference points for circulating within the hydrographic transport network. Thus, earthworks that stand out in terms of size, centrality, settlement stability and association to ancestors could have acted as landmarks and topograms imbued with historical memory. Moreover, this topograms could have been related to each other to create topographs, that is, wider systems of meanings and intertwining stories that are evoked and recreated by means of observation and movement over the landscape (Santos-Granero, 1998). In such way, the space becomes a storied landscape through the active social interaction of people with their environment over time, and this interaction becomes an integral part of social knowledge and identity (Langley, 2013).

When considering the sites network (instead of the hydrographic system as a whole), we observe a positive correlation between mound size and both centrality measures. That is, the largest mounds are located at places that not only provide a better access to other sites but also favour the control over communications between other settlements. As mentioned above, mound construction required the mobilization of resources and organization of communal labour. Such organization, in turn, involves the existence of people with the capacity to interpellate other members of the society. The extent to which social actors can occupy mediation positions depends, partly, on their location within a communication network. Then, social hierarchy and power depend on the way in which social actors are positioned and connected to each other (Mizoguchi, 2009). It has been widely recognized that acquiring, exercising and challenging power are relational processes in which goods, knowledge, symbols and other resources essential for enacting power in all forms, flow differentially. Settlement positions within interaction networks influence the kinds of roles its residents can play in political structures at regional scales (Schortman, 2014). We believe that, in our study case, these topological positions could be a key factor for the existence of "leaders" who, as attested by archaeological and etnohistorical evidence, were characterized by the possession of prestige goods and the ability to create alliances and mobilize resources for exchange, construction, war, etc. Most probably, these individuals were located in strategic positions that allowed them to, on the one hand, better access the hydrographic network and its resources (HTN) and, on the other, enhanced their control over the flow of goods, information and people within the sites network (ASN). All things considered, central network positions would have facilitated the mobilization of resources (including people and earth for erecting mounds) and the control of foreign materials circulation. In effect, the fact that the most central locations within the sites network are those presenting the highest concentration of such materials has been noted.

9. Conclusions and future directions

The methodology resorted to for this article combines GIS tools and concepts derived from graph theory to analyze geographical and regional archaeological data. Through this approach, we assess the topological structure of the Paraná Upper Delta fluvial system and provide an insight as to how the regional archaeological data behave in relation to network models derived from geographical information. Unlike other archaeological approaches to transport systems, where the considered networks are anthropic (e.g. the Inca road, Antonine Itinerary), the geographical configuration of the study area allows us to consider the natural hydrographic system as a transport network and analyze the position of archaeological sites within it. Thus, in the HTN, the transportation network operates as an independent variable with respect to the settlement system.

From these studies, the following observations were made: (1) the sites are not randomly distributed but mainly located in areas of high closeness (i.e. accessibility); (2) there is a positive correlation between mound size and centrality values (both in the hydrographic network and in the sites network); and (3) foreign materials are usually found in sites of high centrality (in relation to the sites network). Based on these results, we propose that (1) the topology of the hydrographic network conditioned the location of settlements, (2) the most prominent places are central in terms of the cultural landscape and (3) the position within interaction networks conditioned the existence of hierarchical relationships and the chances to accumulate foreign goods.

While this work represents a first insight into the nature of the settlement system in the Paraná Upper Delta as regards a network approach, we believe that the research herein conducted can be further extended in several ways; firstly, through the application of other centrality measures as well as the analysis of further network properties and, secondly, by covering a larger spatial scale and analyzing, by way of more detailed chronologies, variations in network configuration along successive time slices. It would also be interesting to compare the hydrographic network model presented in this paper with a network model drawn from satellite images corresponding to Paraná River exceptional floods. For those circumstances, connectivity is expected to have substantially broadened, thus providing a new scenario to be explored. Finally, we believe that the models proposed herein allow us to make predictions regarding site locations that may be tested in future archaeological surveys.

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