Mind the Network: Rock Art, Cultural Transmission, and Mutual Information

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Mind the Network: Rock Art, Cultural Transmission, and Mutual Information

Inés Caridi and Vivian Scheinsohn

Abstract Decorative patterns have long been considered suitable for determining descent, since they are categorized as homologous and adaptively neutral. Rock art, for its part, has often been left aside due to a lack of chronological control. In this paper, we propose a way to treat rock art in order to track Cultural Transmission Paths by means of motif distribution using Northwestern Patagonia as a case study. We present a theoretical and methodological framework for modeling Cultural Transmission Archaeological Paths by constructing a Mutual Information Network between motifs, identifying clusters and defining their associated Site Networks. The results allow us to suggest a hypothetical nuclear region, well known and transited by hunter-gatherers, with few connections to the more distant parts of the study area. This pattern may be related to Patagonia's population models and fit the suggestion from other fields of inquiry that a sparsely connected and not unnecessarily complex network will be robust enough to sustain information flux.

Keywords Rock Art • Patagonia • Hunter gatherers • Mutual Information

1 Introduction

Since Dunnell's seminal work (Dunnell 1978), several researchers have considered stylistic characters as adaptively neutral. Decorative patterns, in particular, have been considered as nonfunctional or selectively neutral, since they are not

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Fig. 1 Map of the study area of Patagonia

tied to functional constraints. For instance, in pottery, decorative patterns are considered so complex that the probability of duplication by chance would be small. So, if two vessels with the same decorative pattern are found "(…), the more parsimonious explanation of such phenomenon is that the vessels share a common developmental history and are from the same tradition" (O'Brien and Lyman 2003: 19). This property of decorative patterns has allowed the establishment of cultural lineages derived from them. There are, for example, several works that have employed ceramic decorative patterns to establish cultural lineages (i.e., Neiman 1995; Shennan and Wilkinson 2001; Cochrane and Lipo 2010). The same has been done with textiles (Tehrani and Collard 2002) and basketry (Jordan and Shennan 2003). However, rock art, despite its potential to track Cultural Transmission processes and their patterns, has been left aside. In this work we present a theoretical and methodological framework for modeling Cultural Transmission Archaeological Paths by constructing a Mutual Information Network between motifs, identifying clusters, and defining their associated Site Networks. We will develop this proposal applying it to our study area, NW Patagonia, which includes nine regions (see Fig. 1). Table 1 shows a detailed list of sites by region.

Table 1 Archaeological sites in our study area, organized in 9 regions (first column)

Region	Site	Simplified site name	Source	Amount of unrepeated motifs
Traful	Alero Las Mellizas	ALM	Silveira and Fernández (1991)	17
	Alero Los Cipreses	ALC	Silveira and Fernández (1991), Silveira (1996)	5
	Alero Lariviere	AL	Silveira (1988–1989, 1999), Silveira and Fernández (1991)	10
Piedra Parada	Campo Moncada 1	CM1	Aschero et al. (1983), Onetto (1986–1987), Pérez de Micou (1979–1882)	7
	Campo Nassif 1	CN1	Aschero et al. (1983), Onetto (1986–1987), Pérez de Micou (1979–1882)	14
	Piedra Parada 1	PP 1	Aschero et al. (1983), Onetto (1986–1987), Pérez de Micou (1979–1982)	12
	Piedra Parada 4	PP 4	Aschero et al. (1983), Onetto (1986–1987), Pérez de Micou (1979–1982)	12
	Campo Cretón 1	CCR1	Aschero et al. (1983), Onetto (1986–1987), Pérez de Micou (1979–1982)	11
Comarca Andina del Paralelo 42°	Peñasco	PE	Firsthand data set	16
	Cerro Pintado	CP	Firsthand data set	29
	Risco de Azócar 1	RA1	Firsthand data set	12
	Risco de Azócar 2	RA2	Firsthand data set	13
	El Radal	ER	Firsthand data set	15
	Paredón Lanfré	PL	Firsthand data set	12
	Peumayén 2	PEU2	Podestá et al. (2009)	17
Pilcaniyeu	Cueva Sarita 3	CS3	Boschín (2000, 2009)	13
	Cueva Sarita 4	CS4	Boschín (2000, 2009)	1
	Cueva Comallo 1	CCO1	Boschín (2000, 2009)	16
	La Figura 1	LF1	Boschín (2000, 2009)	2
	Cueva Pulpulcurá 2	PUL2	Boschín (2000, 2009)	5
	Abrigo de Pilcaniyeu	PIL	Boschín (2000, 2009)	8
	Cueva Cuadro Leleque 1	CCLE1	Boschín (2000, 2009)	15
	Cueva 1 del río Pichileufu	PICH	Boschín (2000, 2009)	10
	IV 2a Puerto Tranquilo Sección 17	PT	Pedersen (1978)	16

(continued)

Table 1 (continued)

Region	Site	Simplified site name	Source	Amount of unrepeated motifs
Nahuel Huapi	Cerro Leones	CLEO	Vignati (1944)	4
	LNH1 Puerto Tigre	Pti	Pedersen (1978)	20
	LNH2 Nariz del Diablo	ND 1	Pedersen (1978)	13
	IV 4 Puerto Vargas	PV	Pedersen (1978)	10
	Estancia Huemul	EHUE	Vignati (1944)	5
	IV 3 al Norte de Puerto Vargas	NPV	Pedersen (1978)	7
	Chavol I	CHAI	Albornoz (1996)	1
	Chavol II	CHAII	Albornoz (1996)	7
	Bahia Lopez	BL	Albornoz (1996)	6
	Cerro Campanario I	CCAM	Albornoz (1996)	6
	El Trébol	ET	Albornoz (1996), Hajduk et al. (2004, 2009)	11
Parque Nacional Los Alerces	Alero del Sendero de Interpretación	ASI	Arrigoni (1997), Arrigoni and Fernández (2004)	12
	Alero del Shamán	ASH	Arrigoni (1997) Arrigoni and Fernández (2004)	19
Lago Lácar	Catritre 1	CA1	Albornoz and Cúneo (2000)	13
	Quila Quina 1	QQ1	Albornoz and Cúneo (2000)	13
	Curruhuinca 1	CUR1	Albornoz and Cúneo (2000)	10
Guenguel/Río Mayo	Guenguel	GUE	Pérez de Micou et al. (2009)	5
	Manantial 1	MA1	Pérez de Micou et al. (2009)	5
	Manantial 2	MA2	Pérez de Micou et al. (2009)	7
	Viejo Corral	VCO	Pérez de Micou et al. (2009)	7
	Bardas Blancas	BB	Pérez de Micou et al. (2009)	10
Lago Verde/Río Pico	Acevedo 1	A1	Firsthand data set	9
	Solís 1	S1	Firsthand data set	5
	Lago Verde 1	LV1	Firsthand data set	3
	Lago Verde 2	LV2	Firsthand data set	2

We present the name of the site (second column); their simplified names (third column) source of information for each site (fourth column) and amount of motifs for each site (fifth column)

2 Rock Art and Information

Rock art is one of humankind's most ancient channels of visual communication. In fact, among prehistoric hunter-gatherers, few others existed beside face-to-face interaction (e.g., smoke signals, stylistic messages conveyed in artifacts, etc.; see Wobst 1977). Archaeologists have always been aware of the communicative role of rock art and its information storing capacity. This idea has been formalized in the "information storage model" (Barton et al. 1994; Conkey 1978; Gamble 1991; Mithen 1988; among others), which argues that rock art can store different kinds of information: from social interaction (e.g., Conkey 1978; Gamble 1991) to potential resources (e.g., Mithen 1988) or altered states of consciousness ("shamanic approach"; see Dowson 1998; Lewis-Williams and Dowson 1988). Whallon has argued that such an information storage system only functions as long as the knowledge of how to retrieve that information is present in a social group. When that knowledge is lost, it becomes impossible to access it (Whallon 2011). Nevertheless, setting meaning aside (which we will not discuss in this work, as explained below), there is information contained in the spatial distribution of rock art motifs, which could be retrieved. We will specifically focus on this point; appealing to Information Theory (Whallon 2011 is also anticipated this possibility).

3 Information Theory and Mutual Information

As Mackay (2003) has pointed out, communication does not have to involve information transfer from one point to another, as in a phone call. When we write a file on a computer and save it, for example, we can retrieve it from the same location, but at a later time. This was recognized by Wobst who, in his 1977 pioneering paper, affirmed that emission and reception may be separated from each other spatially and temporally. That is what happens when we visit a rock art site: the message is transmitted from the past (recent or remote) to the present. In fact, any temporal process could be thought of as a communication channel that links the past to the future (Crutchfield et al. 2009). But, in the case of rock art, we also deal with a spatial dimension set across a geographical area. Therefore, the spatial distribution of rock art motifs, paraphrasing White's affirmation about artifacts, can be viewed as the material residues of "spatially-situated, network-mediated systems of social learning and information exchange" (White 2013:1).

As mentioned above, Information Theory allows us to treat information content without any concern for meaning. When we observe two sources of messages, we are interested in detecting whether there is any type of correlation between the messages sent from both of the sources. Mutual Information is a measure of the amount of information that one message contains about the other. It measures the average reduction in uncertainty about a message from the first source that results from knowing the message from the second source, or vice versa (see details below in Appendix 1). What we want to stress here is that the Mutual Information concept (Cover and Thomas 1991), as applied in communications, could play an important role when analyzing rock art. Specifically, we propose applying Mutual Information to formalize correlations between presence and absence of rock art motifs in archaeological sites. Mutual Information (see Appendix 1 for details) quantifies a correlation, describing a pattern of motif presence and absence across different sites. But, what process produces that pattern? Given a motif is complex enough, and assuming a correlation threshold that allows us to discard chance as a factor, if a correlation exists, we may assume that the only process that could explain this pattern is Cultural Transmission, no matter the social (individual or group), temporal (motifs inscribed at the same time or in different moments), or spatial scales (in a close or wide range) at which occurs. Rock art, as a communicational channel, is intended to transmit information to others, not necessarily present at the moment when a motif is made. In this sense, it could function as either an inter- or intragenerational channel.

As an example of how to apply Mutual Information to rock art, let us introduce variable X, representing a particular motif, which can take two possible values: 0 means the absence of the motif in a particular site and 1 its presence. The same occurs with a second motif (variable Y). Mutual Information between these two motifs, $I(X,Y)$, quantifies their correlation: greater values of $I(X,Y)$ means that the presence (or absence) of motif X occurs simultaneously with the presence (or absence) of motif Y.

To visualize the patterns of Mutual Information, we will construct a network defined by two sets: a set of nodes (rock art motifs) and a set of links (Mutual Information between them). In a social network, nodes can represent individuals, and links can represent some type of relationship or cooperation among individuals (see Watts and Strogatz 1998). In biology, networks are used to represent patterns of interaction between biological elements; sometimes, links in a network represent explicit relations between nodes, because there is a physical element such as a route or because there is a known interaction. But sometimes connections are not explicit. In such cases, connections may be inferred from the attributes of the nodes, by formalizing a correlation network. In genome research, gene coexpression networks were formalized by detecting strong correlations that may exist between gene expression patterns (Torkamaniet et al. 2010). In this area, Mutual Information is used to detect correlations in order to formalize the Mutual Information Network of coexpression of proteins (Simonetti et al. 2013). In our case, links will represent certain values of Mutual Information between pairs of motifs. If this Mutual Information Network (MIN) can help us to formalize motif correlations, we also need to evaluate how this MIN was established in a certain space, i.e., our study area. In so doing we will determine the Cultural Transmission Paths that constituted the MIN.

4 Cultural Transmission, Rock Art, and Archaeological Cultural Transmission Paths

4.1 Cultural Transmission Theory in Systemic and Archaeological Contexts

Cultural Transmission could be defined as the "information capable of affecting individuals' behavior that they acquire from other members of their species through teaching, imitation, and other forms of social transmission" (Richerson and Boyd 2005: 5). The debate around Cultural Transmission Theory in anthropology (Cavalli-Sforza and Feldman 1981; Boyd and Richerson 1985) begun with the inception of what has been termed Dual-inheritance or Gene-culture coevolutionary models (GCC models; see Ross and Richerson 2014) in human evolution. These models posit that although genetic evolution is still present in human evolution, there are several other forces driving cultural evolution that are distinctive and derived from the fact that culture can be transmitted through social networks in ways that are much more complex than gene transmission. Cultural agents can often choose from a wide array of cultural variants, and the choice could be random or nonrandom. In the last case, biasing forces could be involved, such as direct, frequency, prestige, or other biases (Boyd and Richerson 1985). These biases and nonrandom innovation can create strong directional forces in cultural evolution (Ross and Richerson 2014: 103–104). Non-genetic transmission of behavior is much more varied and flexible than genetic transmission (Barton and Clark 1997): Cultural Transmission can go from parents to offspring (vertical transmission) as in genetic transmission but also can be dispersed among non-related individuals (horizontal transmission; see Borgerhoff Mulder et al. 2006). Current approaches to studying Cultural Transmission are set either at a micro- or macro temporal and spatial scales of analysis (Stark et al. 2008). While Cultural Transmission is studied among living populations, archaeological studies "look at actual, unsimulated, large-scale transmission through entire populations involving countless unidentified individuals from successive biological generations" (Mesoudi 2008: 97). As Mesoudi has stated, "the macroevolutionary patterns studied by archaeologists are the product of the microevolutionary transmission mechanisms studied by psychologists but the gap between these two scales of analysis still remains unexplored" (Mesoudi 2008: 99). Although the work developed around Cultural Transmission is quite abundant, few papers have focused on the networks that allow that transmission. Most works are based on the assumption that information transmission is unstructured although "the structure of interaction makes a difference to the outcomes of Cultural Transmission processes and should be considered a potentially important causal factor" (White 2013: 22).

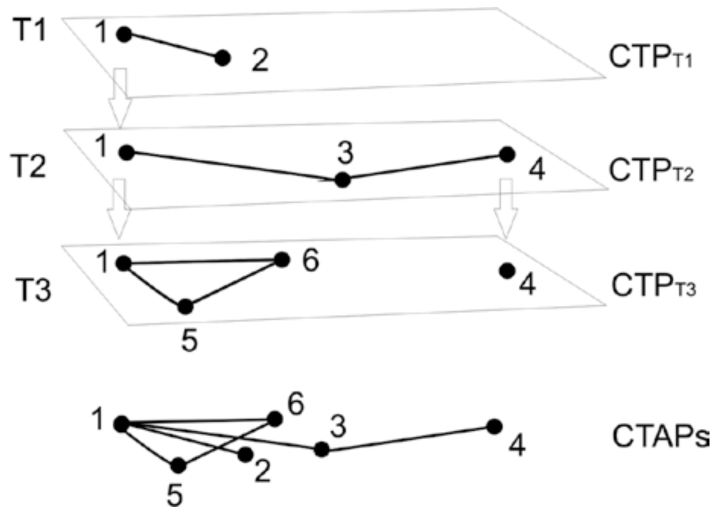


Fig. 2 Cultural Transmission Paths and the construction of a Cultural Transmission Archaeological Path

Rock art is a product of Cultural Transmission. In a systemic context (*sensu* Schiffer 1972), we assume that the process leading to the distribution of motifs in the landscape begins when someone paints a motif on one site. That very same person, or another, could store it in his/her memory and reproduce it at the same site or elsewhere (immediately or at a later moment). There, the motif is seen by others who repeat it and can add other motifs. This process iterates for days, years, and/or centuries. As a result, some motifs will not be reproduced, while others will be distributed in a wide area. In this manner, we obtain a process of Cultural Transmission in which a social network replicates a set of motifs. The product of that process is a differential pattern of motif distribution in the landscape. In archaeology, we cannot track that social network because it is gone, but we have a "fossil" pattern, a relic of that process. Since the pattern does not mirror the network that produced it (reasons below), we need to introduce a new concept in order to separate the process (related to social network activities) and its (patterned) material evidence. On this basis, we can model a Cultural Transmission Path (CTP), a pattern left as a rock art motif distribution in the landscape (space) corresponding to a social network (social relationships) and a certain moment (time).

Figure 2 further explains this concept. At time 1 (T1), there were two nodes (sites), 1 and 2, in a given region (represented by a rectangle). As a result of a social network, there was information flow between those sites (represented by rock art motif sharing, similar vessel decoration, or else). In order to model it, we establish a link between those sites. This model is a Cultural Transmission Path for T1 (CTP_{T1}). At time 2 (T2), node 1 is still active but node 2 is inactive. Instead, two other nodes arise, 3 and 4. For the same reasons as before, we establish a link between 1 and 3 and between 3 and 4. So we now have the Cultural Transmission Path for T2 (CTP_{T2}) which is different from CTP_{T1}, although they share a node (1). At time 3 (T3) we can see that node 1 is still active, but its Cultural Transmission Path (CTP_{T3}) relates it to two new nodes, 5 and 6. Node 3 is inactive, while node 4 is still active, but it does not share a CTP with node 1 anymore.

From these three situations, archaeologically, we only can establish the Cultural Transmission Archaeological Paths (CTAPs) that are represented in Fig. 2 below. CTAPs are not related to a specific time, but they are the sum of many CTP. We prefer the term CTAPs for the latter since what we have is an archaeologically determined channel of Cultural Transmission left by the sum of past moments in the same area. Although several "time slices" are mixed up, it is not possible to isolate them (which is why we use "paths" in plural) unless we have detailed radiocarbon dates or some other chronological control. The difference between pattern (CTAPs) and processes arises from two sources: Cultural Transmission and taphonomic processes. Let us review them.

4.2 Cultural Transmission Processes in Rock Art

As a consequence of the bias forces implied in Cultural Transmission processes Henrich et al. (2008) has pointed out that, "ideas are not transmitted intact from one brain to another. Instead, the mental representations in one brain generate observable behavior, a 'public representation' in Sperber's terminology. Someone else then observes this public representation, and then (somehow) infers the underlying mental representation necessary to generate a similar public representation. The problem is that there is no guarantee that the mental representation in the second brain is the same as it is in the first. (…) Moreover, inferential processes often systematically transform mental representations, so that unlike genetic transmission, Cultural Transmission is highly biased toward particular representations. Following Sperber (1996), we call the representations favored by processes of psychological inference (including storage and retrieval) 'cognitive attractors'" (Henrich et al. 2008: 121). As a part of these processes, inferential transformation accounts for why some representations are favored over others. Instead, selective attention (see Chabris and Simons 2010) accounts for why individuals pay particular attention to some individuals or events and not to others. In addition, error occurs during each copying or replication. The presence of error is based on inherent constraints not only on human perception but also on motor abilities. For instance, the percentage of error in lithic manufacture has been set at around 3–5 % (e.g., Eerkens 2000).

As culturally transmitted behaviors, recurrent rock art motifs are probably constituted as cognitive attractors, and the process that constitutes them as such has to do with copying errors, inferential transformation, and selective attention. Also intentional factors, such as element additions or subtractions on a motif, could produce totally new motifs. As studies dealing with pictorial stimuli have shown, "there is a general reduction in the length or complexity of the material, that much of the detail is lost, and only the overall impression of the material is preserved" (Mesoudi 2008: 93) Still, none of these studies have dealt with rock art motifs, so it still remains to be studied how content bias, for instance, affects its replication (Scheinsohn and Caridi in prep.) Beside the need to model how the transmission process functions in a systemic context, there are other issues that require attention in terms of the archaeological context.

4.3 Taphonomic Processes in Rock Art

The passage of time between the inscription of a motif on a rock and its observation (days, years, or centuries after) introduces noise in two ways: (a) Attrition or losses of motifs: weathering provoked by wind, precipitations, and erosion could affect the rock art support, allowing for the loss of motifs or the destruction of painted areas, (b) accretion or addition of motifs: rock art motifs could be the result of many painting or engraving events at the very same site. What we find, after many years, could be the result of accretion (continuous or discrete episodes) or a single event. This can be identified only by the existence of superposition among motifs in a certain site, but its absence does not mean that there is no accretion but simply that accretion is not recognizable.

Rock art stores information, and, as a signal, it has the advantage of great longevity. But the lack of chronological control introduced by accretion and/or attrition processes at the site scale intrudes the tracking of lineages in a direct way. To do this, we have to add the process that leads to CTAPs. Mutual Information allows us to solve this problem. But before proceeding to methodological issues, we will first contextualize our case study.

5 The Archeological Problem: Late Holocene Rock Art in NW Patagonia

5.1 Patagonia and Its Native Peoples

In the Southern Hemisphere, Patagonia is the only landmass projecting southward from 46° latitude on. Its shape determines an oceanic influence which creates a lack of tundra and permafrost in spite of its high latitude (Morello 1984). Due to the rain shadow effect provoked by the cordillera, or Andean mountain range, Patagonia is divided into two contrasting environments: a forested and rugged area present on both sides of the Andes and a stepped area, which covers most of its surface. Nowadays the Andes also divide Patagonia politically, between Argentina and Chile (see Fig. 1).

Patagonia was peopled around 11,000 BP (Borrero and Franco 1997). The steppe has been occupied continuously since then. The role of forested environments for hunter-gatherers is widely debated (see Bellelli et al. 2003), but in any case, the Andean forest shows occupational discontinuities until approximately 3000 BP, when the archaeological signal strengthens and becomes continuous. Europeans arrived in Patagonia during the sixteenth century. Spanish settlers occupied single spots in the Western slope of the cordillera (Chile). Some of them did not thrive and returned home, abandoning their livestock, which became *cimarrón* (wild). That was the cattle that native Patagonians initially adopted. What North American anthropologists called the "horse complex" had its expression in South America with the introduction of habits related to the horse (Scheinsohn 2003). Ethnographically, the Eastern slope of the cordillera was inhabited by Tehuelches (Casamiquela 1965; Escalada 1949), hunter-gatherers who in the nineteenth century engaged in pastoral-

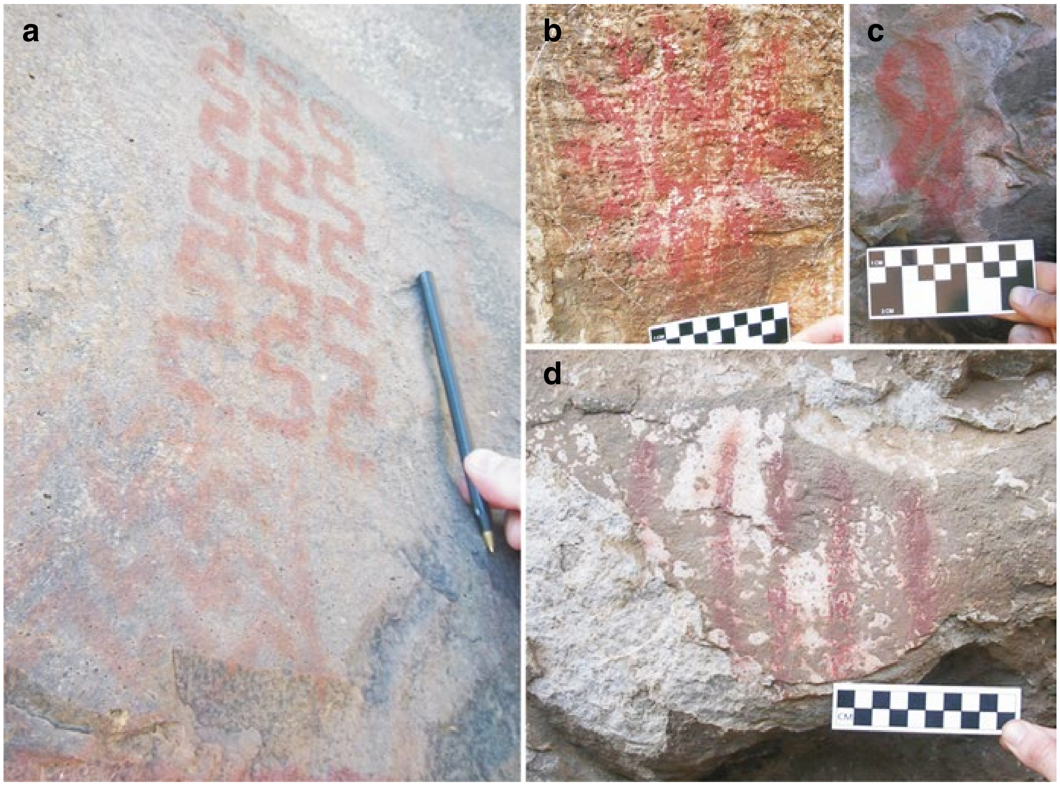


Fig. 3 Rock art motifs from NW Patagonia: A Motif 8 - Character state 5 (see Appendix 2) Double opposed regular fret; B Motif 19 Character state 1 (see Appendix 2) Sun; C Motif 24 - Character state 5 (see Appendix 2) Linked rhombuses; D Motif 1 - Character state 2 (see Appendix 2) Aligned strokes

ist living related with European cattle. On the western side of the cordillera lived the Mapuches, horticulturists who engaged in weaving and metalworking and controlled horse trading. Both were defeated and almost exterminated by the Argentinean and Chilean armies, and their territories incorporated to the Modern State Nations at the end of the nineteenth century. The survivors were turned into rural workers.

5.2 *Late Holocene Rock Art in Patagonia*

After this brief review, we may say that, before the European colonization, the Late Holocene period in Patagonia is supposed to involve a relative increase in population density and a demographic expansion (see Barrientos and Perez 2004 among others). This process should correlate with restricted residential mobility and wide exchange networks, as indicated by obsidian exchange and other items traded with non-hunter neighbors (see Scheinsohn 2003).

Late Holocene rock art sites are characterized by a single style called "Estilo de grecas" (or Fret style; see Menghin 1957), also termed Complex Geometrical Abstract Trend (CGAT; see Gradin 1999). This geometric style is identified by broken lines forming complex stepped-crenellated patterns (called *grecas* or frets Fig. 3a), resembling labyrinths or bounding motifs. They are accompanied by zigzags (13, Appendix 2), circles (5, Appendix 2), rhombuses (24, Appendix 2), crosses (21, Appendix 2), tridents (46, Appendix 2), squares (22, Appendix 2), and other polygons (see Appendix 2 and Fig. 3b–d). The style has a wide distribution in Patagonia (from 36° to 47° south latitude and from the Atlantic coast to the cordillera).

Many interpretations have been postulated to explain the processes that led to this unique rock art style, the CGAT. At their core, they can be reduced to two opposing models (Scheinsohn 2011): (1) Broad-scale model: where the CGAT style reflects a wide interaction network at a macroregional level, with no internal differentiation, and (2) territorial model: Under this view, the CGAT reflects territorial circumscription and ethnic differentiation in the context of increases in population density, territorial sizes, or home range reduction. The hypothesis that the observed rock art differences could be interpreted in terms of territorial marking was not supported by an endemicity analysis performed in previous work (Scheinsohn et al. 2009; Scheinsohn 2011).

Our picture of Northwestern Patagonia in late Holocene times is one of hunter-gatherers trying to maintain links between different places. Most researchers agree that during that period, a steppe-based population had been incorporating forested environments, a process in which rock art would have been part of the colonizing social repertoire, and shared graphics would be present across thousands of kilometers (a similar case as the one posited for the initial settlement of the arid zone of Australia, McDonald and Veth 2011). The establishment and maintenance of regional social ties has been recognized as an important part of hunter-gatherer adaptations to uncertain environments, in terms of creating a "safety net" of contacts and relations that can be critical to survival (Whallon 2006).

5.3 *The Question of Meaning in Patagonian Rock Art*

Although many researchers adhere to the perspective that rock art was made during ritual activities (Whitley 2005, 2011), we think that it is problematic to assume this by default in the Patagonian case. Even though ritual interpretations have been proposed for some sites (Carden 2009), others have been effectively associated to domestic activities (Aschero 1996) indicating mixed situations. But we can also assume that rock art practices were interrupted at some point after the European arrival in Patagonia, because they were never witnessed by the authors of historical sources. In addition, written documents report that the Tehuelche said that the rock art had been made by their ancestors in the very remote past (or even by mythical beings; see references about Elengassen in Moreno 1997 and Claraz 2008). Some sources suggest that the Tehuelche used to avoid rock art sites, because staying there provoked madness (Millán de Palavecino 1963: 429) or bad luck (Castro 2010: 93). This indicates a lack of continuity between the historical Tehuelches and the rock art, hindering our possibility to interpret the meaning of the motifs. Although we acknowledge the meaningfulness of rock art motifs, we have decided to set the question of meaning aside and treat our NW Patagonian rock art motif database without any reference to meaning, since it is not relevant for our purposes.

6 Methods and Materials

6.1 Mutual Information Network (MIN)

In this work we will define the MIN for a rock art motif database from Northwestern Patagonia. Using this MIN, we will track the CTAPs in the study area. In order to do so, we have selected a set of highly correlating pairs of motifs which we define as a cluster in the MIN. For each cluster we will analyze the sites where those motifs are present and we will establish a link between two sites when they share two or more state of characters. When those links are mapped into a geographical region, we obtain a Site Network (SN) associated to that cluster (set of motifs). Based on geographical data, the SNs could result in (1) different spatial territories (if they do not overlap spatially) or (2) overlapping spaces.

7 Database

We have analyzed 49 rock art archaeological sites from northwestern Patagonia, located in the steppe, the forest, and their ecotone in a study area located between the 40° 10′ and 45° 50′ parallels (600 lineal km from North to South; see Fig. 1). This is a small area within the whole recorded distribution of the CGAT style. We have organized the studied sites in nine regions which are detailed in Table 1. We have considered only the painted motifs. Engravings were left aside in order to avoid noise due to issues related to manufacture techniques. This decision does not seem to affect the sample representativeness. The most recent revision of rock art techniques in Patagonia (Fiore 2006) considers that from the whole of the sample (including all sites since human peopling), only 22 % are engraved and very few (7 %) record combinations of paintings and engravings. Even if we restrict ourselves to the CGAT style, it is mostly composed by painted motifs (Fiore 2006: 46).

All the rock art sites included in our database are rock shelters.[1] The lack of organic content in the paintings impedes direct dating. So we have assumed that the presence of the CGAT style has a chronological content related to the Late Holocene period, as suggested previously by various researchers (Belardi 2004; Podestá et al. 2008 among others). Moreover, for Fiore (2006), the preservation of the CGAT style attests to its lack of antiquity.

[1] Parts of this database have been previously used in Scheinsohn et al. (2009, 2015).

Every motif present in each site was tabulated (see Appendix 2 and Scheinsohn et al. 2009). Departing for a "lumper" classification (see Scheinsohn et al. 2015 for details) of 59 motifs, each motif type was considered a "character" that may or may not be present in a given site and could have different states of character. For example, the "circle" motif type included all those figures described by a circle, with 13 distinguishable states, including "filled circle," "empty circle," "circle with a point," or their spatial disposition (in groups, aligned, etc.; see Appendix 2, character 5). Coding was carried out by defining different states on the basis of the morphological aspects of the figures found at each site. In order to minimize the degree of subjectivity in the process of assigning a figure to a motif type and the codification of each state of character, each figure underwent intersubjective testing. Three operators, separately, identified a figure, either from a narrated description or illustration, with a motif type. Afterward, it was verified if the figure was assigned to the same motif type by each operator. In case of disagreement (i.e., that the same figure was assigned to different motif types by different operators), the figure was identified by the majority's opinion (see details in Scheinsohn et al. 2015).

It should be noticed that although we have analyzed all the published sites for this study area, the whole universe of sites is unknown since it is a reasonable guess that many rock art sites are still undiscovered, especially in the forested part of the area, due to archaeological visibility problems (see Scheinsohn 2011; Scheinsohn and Matteucci 2013).

Also, as is characteristic of decorative patterns, in this dataset we have a quantity of motifs which in their majority are absent from most sites (Scheinsohn et al. 2009, 2015; see also Shennan and Bentley 2008 for ceramic decoration) and whose frequencies are distributed "with a large number of variants occurring only in small numbers but a small number being copied frequently and thus occurring a large number of times" (Shennan and Bentley 2008: 170). Since decorative patterns are unconstrained, variability is high. This results in a database with many "zero" data which posits an analytical challenge and leads us to a specific data treatment.

7.1 Mutual Information Network (MIN) Construction

In order to avoid the noise introduced by the "zero" data, we considered a dataset of 43 motifs (those of the original 59 motifs of the dataset used in Scheinsohn et al. 2015 which are present in three or more sites) of 49 assessed sites. We defined a variable associated with each of the motifs which received value 1 when the motif was present (no matter the state of character of the motif) and value 0 when it was absent from a particular site. For example, X_1 variable contains the information of motif 1; thus $X_1 = (1,1,1,0,0,0,\ldots 1,0,0)$ (this motif is present in sites 1, 2, 3 and absent in sites 4, 5, 6, etc.), X_2 variable contains information of motif 2 and so on. We performed the calculus of Mutual Information for each pair of motifs, and we selected the correlated pairs of motifs that had greater values of mutual information. A Threshold value for Mutual Information called u and we fix it (set it, established it) in 0.093, which left 2.5 % of cases showing a value greater than u (see details in Appendix 3). In Table 2

Table 2 Pairs of motifs selected to establish links on the MIN

Motif *X* number	Motif *Y* number	Mutual Information	Presence of *X*	Presence of *Y*	Sense of correlation
50	15	0.093	3	5	+
33	26	0.093	5	3	+
56	48	0.093	3	5	+
36	8	0.094	3	31	−
21	4	0.096	24	11	+
38	11	0.096	13	10	+
5	2	0.097	32	7	+
6	5	0.097	7	32	+
25	14	0.099	3	17	+
22	11	0.104	9	10	+
33	3	0.105	5	13	+
27	25	0.105	16	3	+
27	10	0.112	16	6	+
53	24	0.114	14	10	−
23	2	0.124	18	7	+
36	3	0.126	3	13	+
50	38	0.126	3	13	+
8	50	0.134	12	3	+
56	54	0.134	3	12	+
12	1	0.138	9	31	+
25	20	0.143	3	11	+
23	21	0.145	18	24	+
35	22	0.156	5	9	+
24	13	0.284	10	22	+

In columns 1 and 2, the two motifs involved in the pair, which were generically called *X* and *Y* Motif number is referred to Appendix 2; column 3 is the Mutual Information for that pair $I(X, Y)$; and in column 4, the sense of the correlation is expressed with (+) when positively correlated and with (−) when negatively correlated

we show the 24 pairs of selected motifs, the presence of each of the motifs of the pairs, and the value of the Mutual Information obtained.

We used these 24 pairs in order to construct the MIN and define clusters in it. The threshold defines the links we use for defining the MIN. If we decreased or increased the threshold, we would define more or less links. This would modify the cluster structure on the network.

In our case, the Mutual Information could be a positive (if *X* is present, *Y* is present) or negative correlation (if *X* is present, *Y* is absent), given the variable has two possible states: presence or absence of the motif.

As we explained previously, we defined an associated Site Network (SN) for each cluster. We established a link between two nodes (sites) if they shared two or more character states of the motifs in the cluster, where the characters could be part of the same or of different motifs. Next, we analyze the structure of each resulting SN in terms of the degree of distribution and clustering coefficient, which measures the transitivity of the network by quantifying how frequently two neighbors of a node are each other's neighbor. We finally analyze the geographical location of each network to evaluate if there is overlapping between SNs, using the RgoogleMaps package of R project (R Development Core Team 2008; Loecher 2012). To simplify, we grouped sites which are closer than 5 km as one point in the map.

8 Results

Figure 4 shows the MIN obtained for the threshold u. As it can be seen (also in Table 2), only two links are negatively correlated; the rest of the links represent positively correlated pairs of motifs. We can observe six clusters on the MIN (the

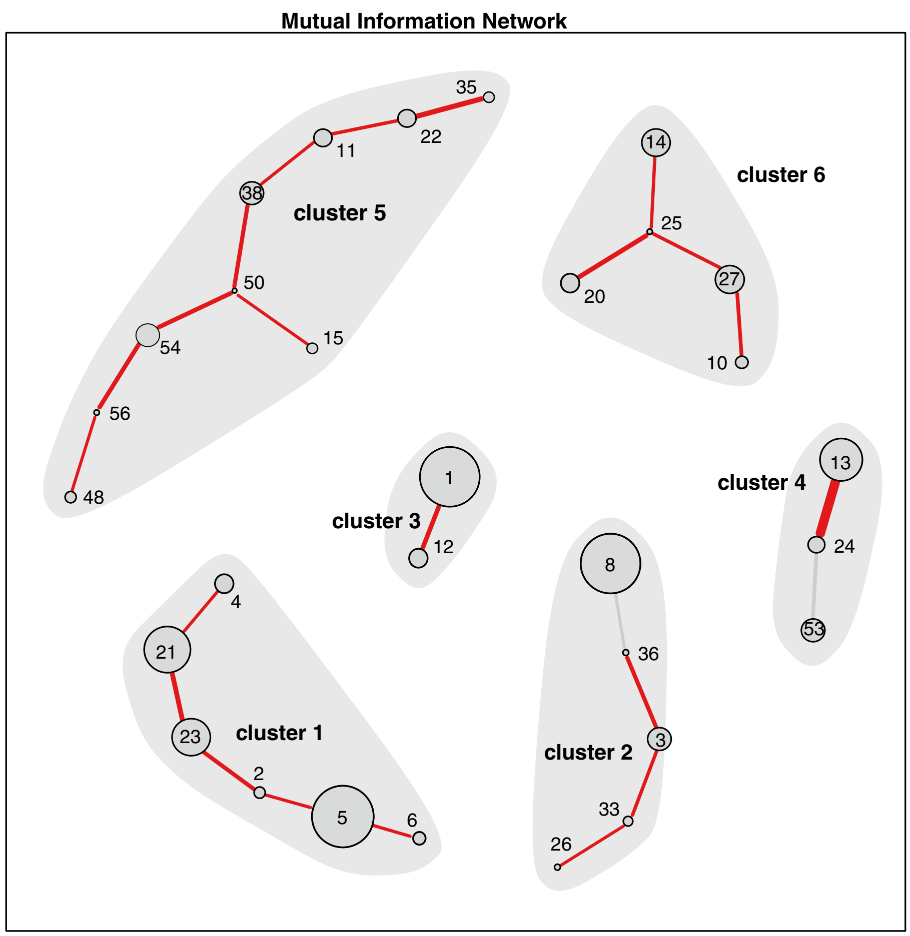


Fig. 4 Mutual Information Network of motifs plotted using the igraph package for the R project (R Development Core Team 2008; Csardi and Nepusz 2006). Nodes represent motifs, and links represent the most correlated set of motifs in terms of presence/absence (without the detail of the states of the character of the motif). The size of the nodes is proportional to the presence of the motif in the sites of the studied area. The width of the links is proportional to the value of the Mutual Information between motifs. Bold links (*red* in the digital version) represent positively correlated motifs, while soft-colored links (*grey* in the printed version) represent the two cases of negatively correlated motifs

clusters are shaded in Fig. 4). Each cluster represents a set of independent motifs. Note that clusters are separated because we are not considering values of Mutual Information below *u*.

Below we analyze each cluster of the MIN and its associated SN:

- Cluster 1 links motifs 4, 21, 23, 2, 5, and 6 (see Appendix 2) in a lineal way. In Fig. 5 we see the Site Network associated to cluster 1, and in Fig. 6 we can see the same network in its geographical location. There are 30 sites which compose the SN. The connectivity results in a mean degree of 8.27, which means that each node (site) has, on average, approximately 8 neighbors. Nevertheless, the most frequent degree value is 5. Additionally, over half of the nodes have a degree of less than or equal to 5, and there are 7 nodes highly connected with more than 13 neighbors each. The most connected site is Cerro Pintado (CP) linked with all the other sites except two. Other sites with high degree values are Quila Quina 1 (QQ1, 19 neighbors), Risco de Azócar 2 (RA2, 18 neighbors), Puerto Tranquilo

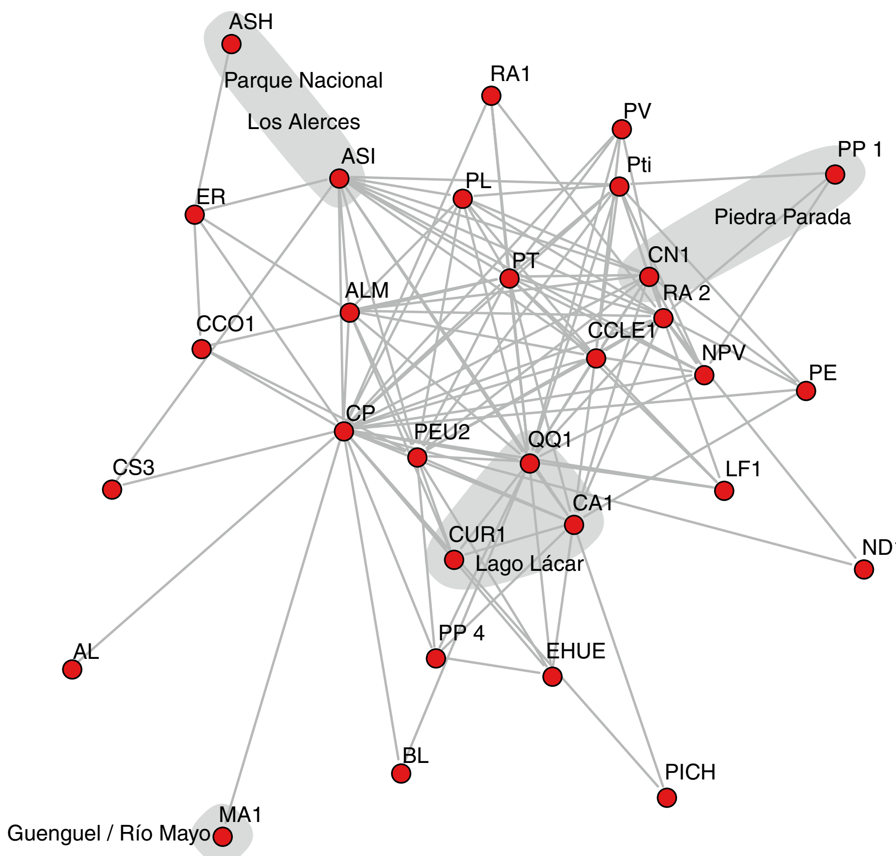


Fig. 5 Cluster 1 SN plotted using (R Development Core Team 2008) igraph. Nodes represent archaeological sites; links are established when two sites share at least two character states of motifs from cluster 1. There are 12 sites isolated that were removed from the figure because they did not fit this last requirement, and only those nodes which had at least one link on the network were represented. Sites located less than 5 km from each other and Manantial 1 (MA1) are shaded, and the name of the corresponding region has been added

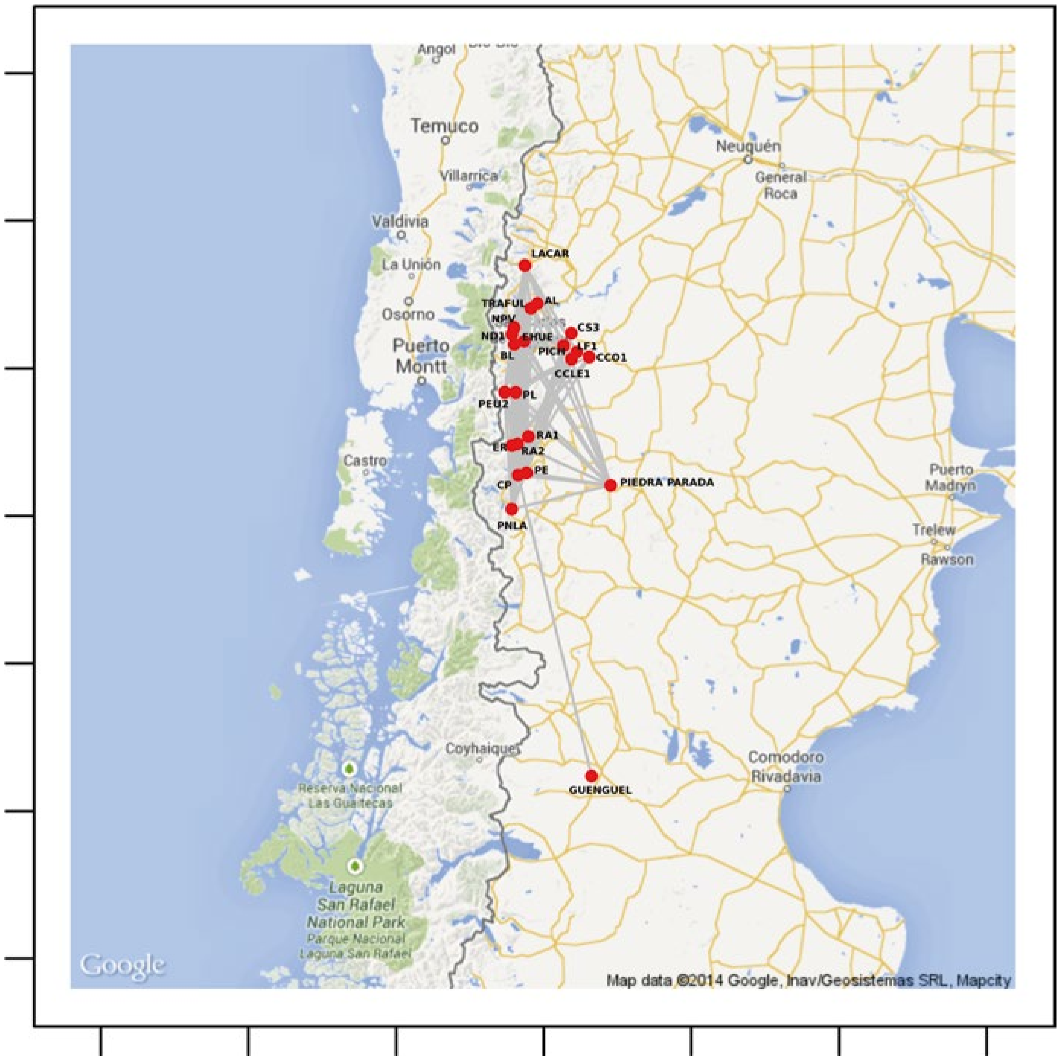


Fig. 6 Cluster 1 SN with nodes geographically located, using the RgoogleMaps package of R project (R Development Core Team 2008; Loecher 2012). Nodes represent archaeological sites. In those cases in which two sites were less than 5 km apart, we joined and labeled them with the region's name, for example, *PP1* Piedra Parada 1, *PP4* Piedra Parada 4, and *CN1* Campo Nassif 1 are shown as Piedra Parada region

(PT, 16 neighbors), Peumayén 1 (PEU2, 15), Alero del Sendero de Interpretación (ASI), and Cueva Cuadro Leleque 1 (CCLE1, both with 14 neighbors). The clustering coefficient of this network is 0.56. A clustering of a random network with the same number of nodes and links but randomly allocated would be 0.28 approximately, which means that in this SN, the probability of two neighbors of a node being connected to each other is approximately two times the randomly allocated links. From a geographical standpoint, this network integrates all the regions of the study area but one (Lago Verde/Río Pico; see Fig. 1 and Table 1).

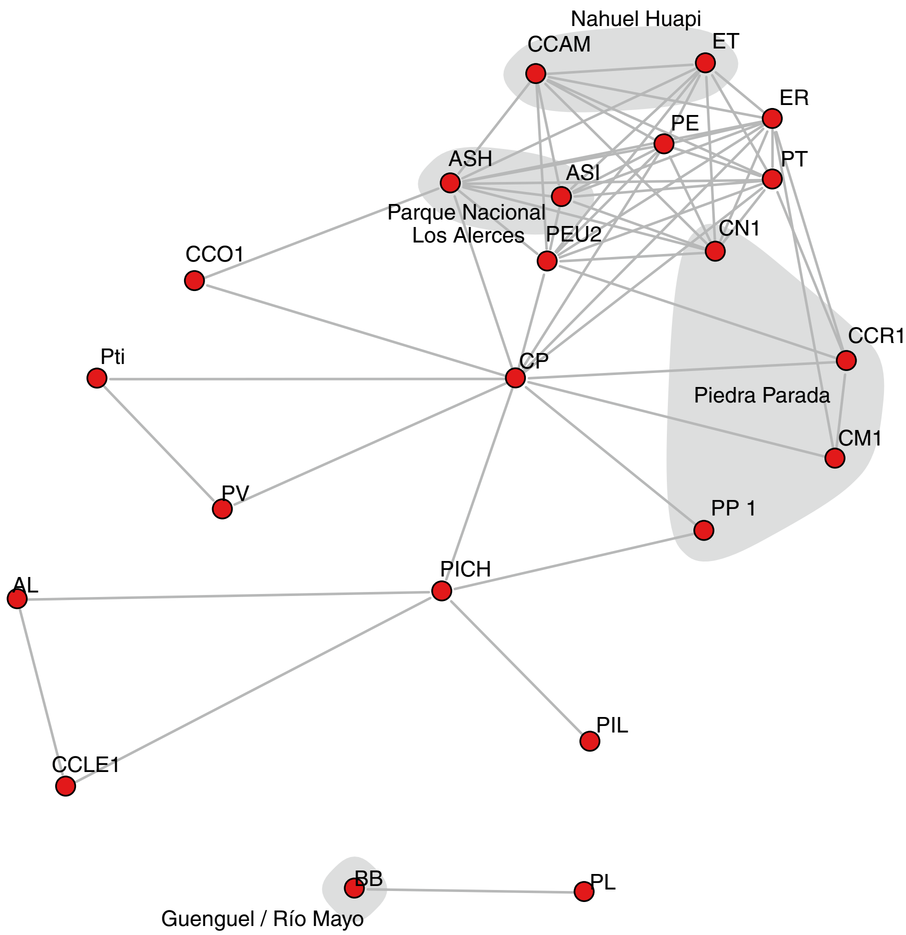


Fig. 7 Cluster 2 SN. Nodes represent archaeological sites; links are established when two sites share at least two character states of motifs from cluster 2. There were 17 isolated sites that were removed from the figure because they did not fulfill this last requirement

- Cluster 2 is composed by the following motifs: 8 (fret or *greca;* see Fig. 3a), 36, 3, 33, and 26 in a chain. The outstanding fact is that, other than the fret (*grecas*), this network is composed by animal footprints. Also, the relationship between frets and human feet is negatively correlated: each time a fret is present, human feet are not (but notice that human feet are present only in three sites in this sample). In Fig. 7 we can see the cluster 2 SN, which include 22 sites. In this case we can see two clusters (one of two sites and the other with the rest). The sites with a maximum degree are Cerro Pintado (CP, 12 neighbors), El Radal (ER 11 neighbors), Peumayén 2, Puerto Tranquilo y Alero del Shamán (PEU2, PT, and ASH, respectively, 10 neighbors each) although the mean degree is 5.5. Cerro Pintado plays a fundamental role in ensuring the connectivity of the network. If we remove it, the network would split in three disconnected clusters. The clustering coefficient of this network is 0.74; the expected clustering coefficient of a

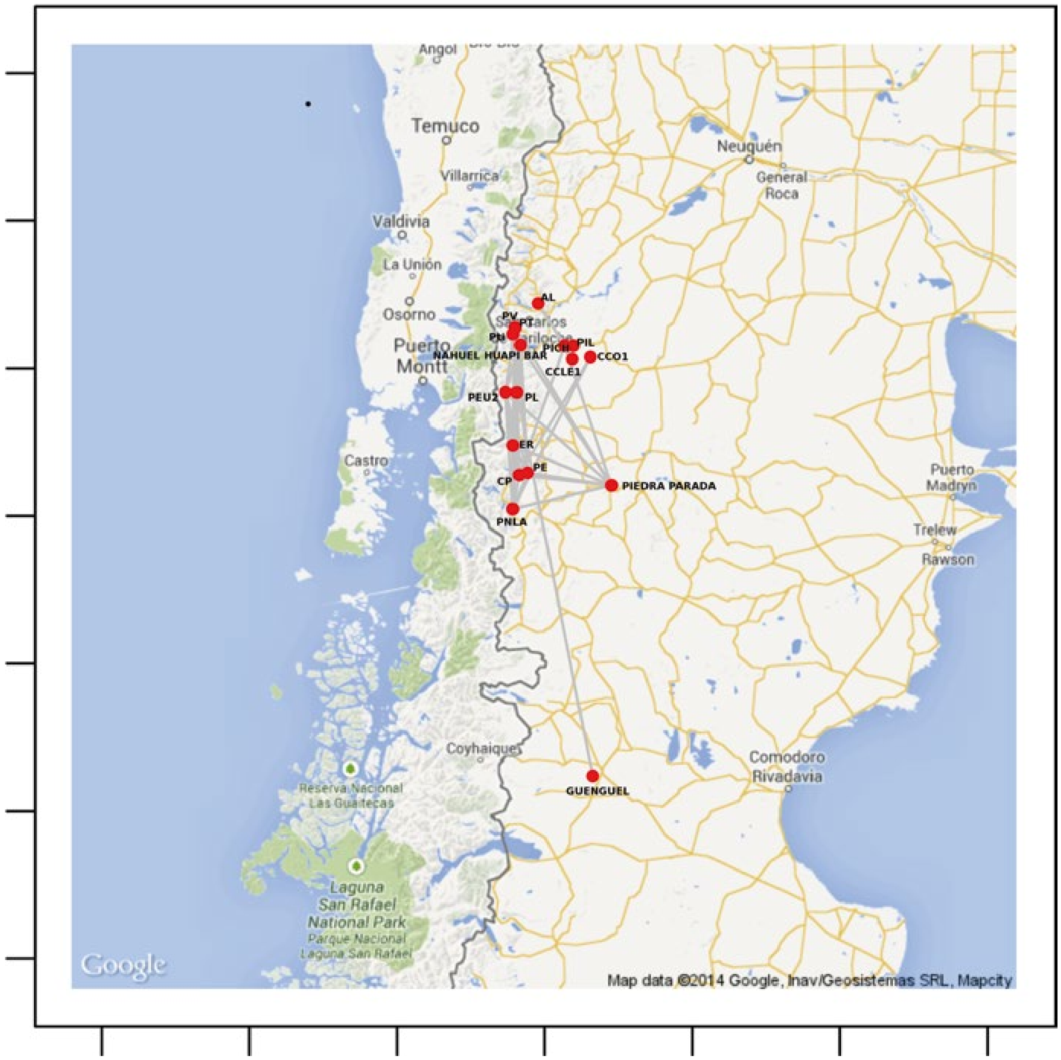


Fig. 8 Cluster 2 SN with nodes geographically located (R Development Core Team 2008; Loecher 2012)

random network with the same number of nodes and links but randomly allocated would be 0.25 approximately. In this case the transitivity of the SN is more important than in the previous one. The interconnectedness of the superior sector of the figure is also surprising, which includes Alero del Shaman (ASH), Cerro Campanario (CCAM), El Trébol (ET), El Radal (ER), Puerto Tranquilo (PT), Campo Nassif (CN1), Peumayén 2 (PEU2), Alero del Sendero de Interpretación (ASI), and Peñasco (PE). This set of sites correspond to the northern region of the study area and are aligned from north to south – with the exception of Campo Nassif 1 (CN1) located at the east; see network on the map in Fig. 8. These sites

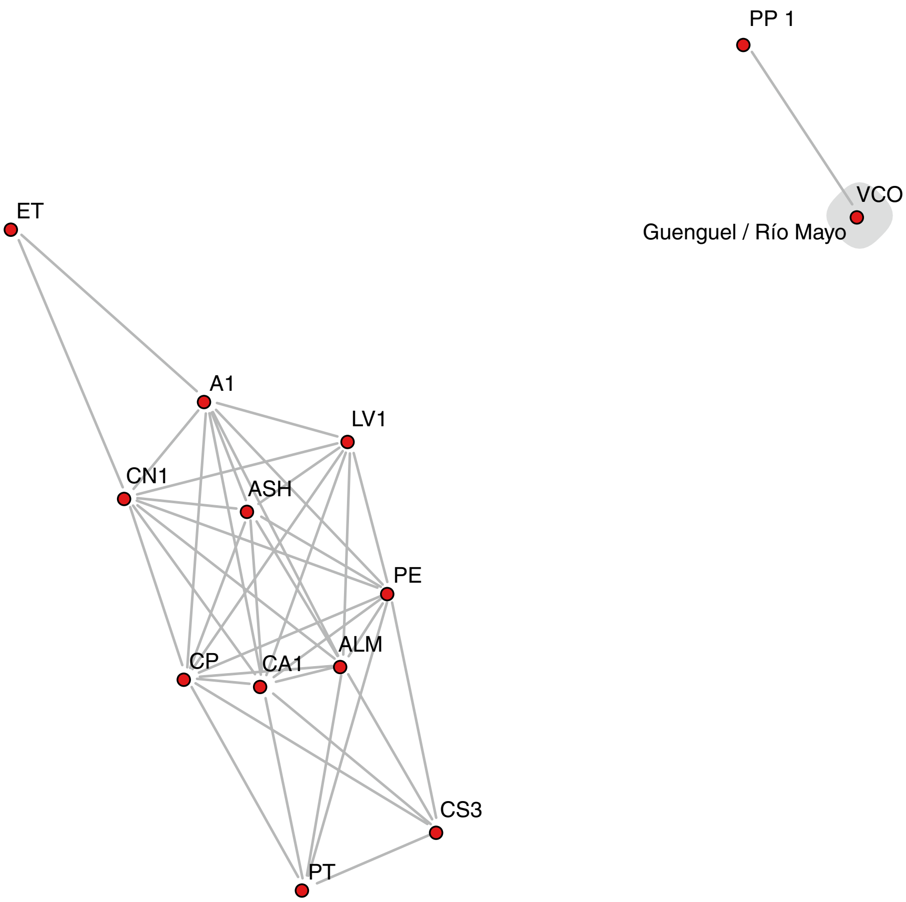


Fig. 9 Cluster 3 SN. Nodes represent archaeological sites; links are established when two sites share at least two character states of motifs from cluster 3. There were 18 isolated sites that were removed from the figure because they did not fulfill this last requirement

share the same pairs of character states for the fret motif. Cluster 2 SN presents all the regions that constitute the study area except for Lago Verde/ Río Pico in the south and Lago Lácar in the north. The Guenguel/Río Mayo region forms a separate cluster (with Bardas Blancas, BB) linked to the core of the geographical region by Paredón Lanfré (PL).

- Cluster 3 links only two motifs: 1 and 12 (see Appendix 2). Cluster 3 SN (see Fig. 9) links few sites highly interconnected in one case and two other sites connected by only one link (superior part of Fig. 9). Guenguel/Río Mayo (Viejo Corral, VCO) again remains attached by only one link, in this case to Piedra Parada 1 (PP1). The wide range of regions in this network is noteworthy (Fig. 10): all the regions that constitute the study area are represented. Although in the SN there are two disconnected structures, two nodes (Piedra Parada 1, PP1, and

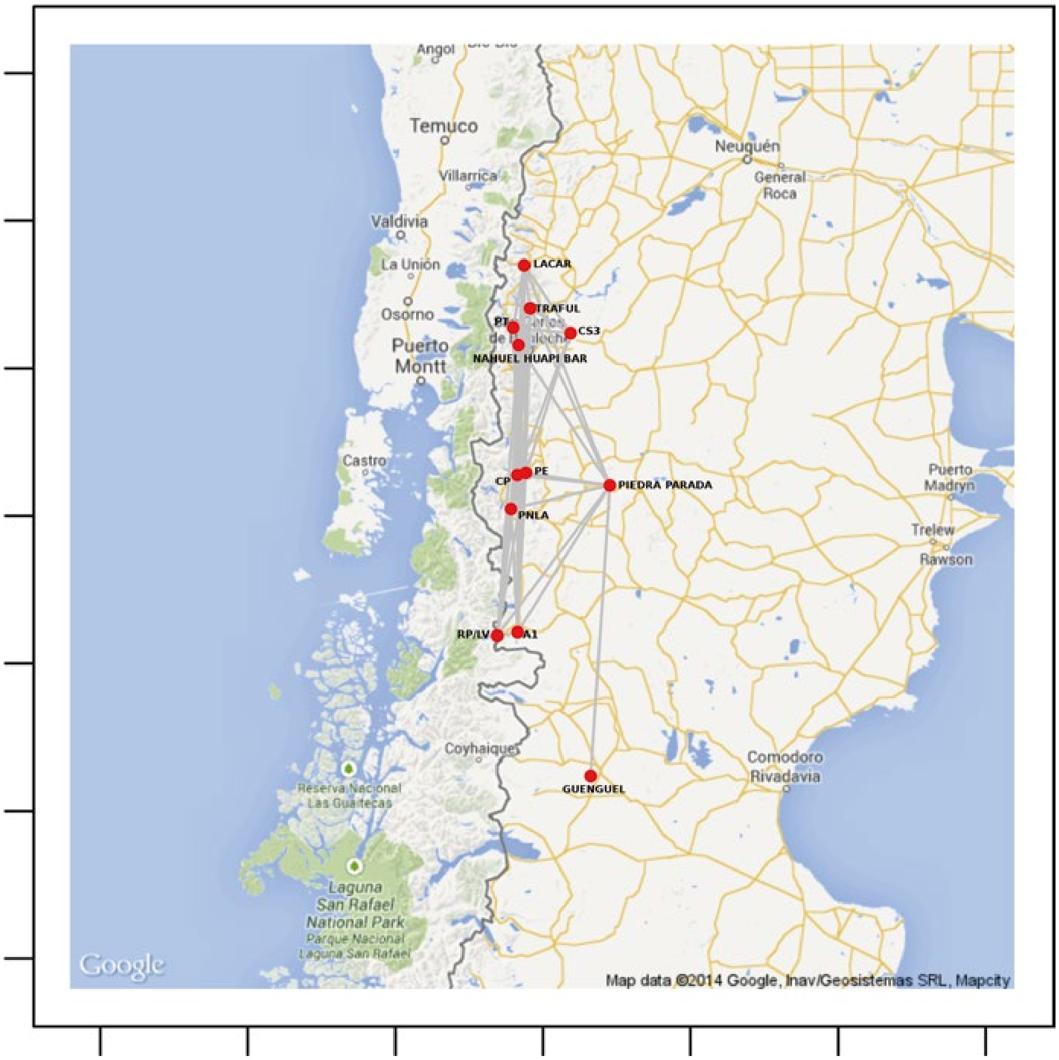


Fig. 10 Cluster 3 SN with nodes geographically located (R Development Core Team 2008; Loecher 2012)

Campo Nassif 1, CN1) are less than 5 km from each other linking the Piedra Parada region with the rest. The clustering coefficient of this network (with a value of 0.83) is twice the value of a network with random assignment links. Cluster 3 SN is the only one which connects the whole area (9 regions).

- Cluster 4 links three motifs: 13, 24, and 53 (see Appendix 2). Motifs 53 and 24 are negatively correlated. Risco de Azócar 1 (RA1) is the most connected site (with 9

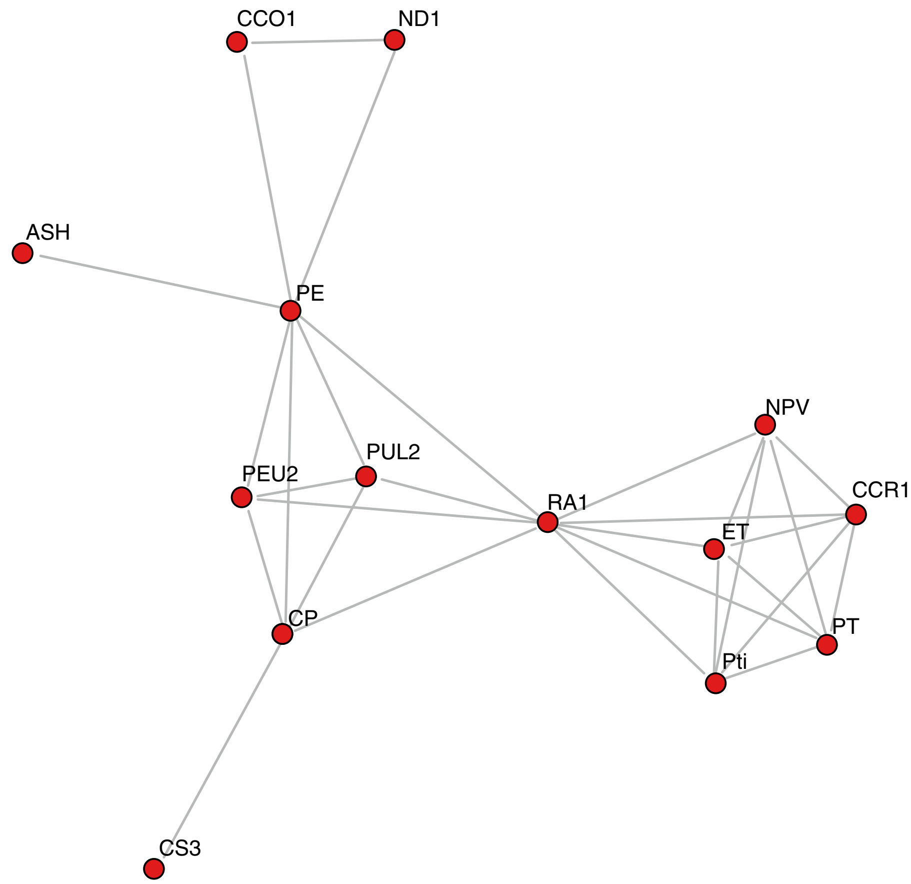


Fig. 11 Cluster 4 SN. Nodes represent archaeological sites; links are established when two sites share at least two character states of motifs from cluster 4. There were 15 isolated sites isolated that were removed from the figure because they did not fulfill this last requirement

neighbors) and plays an important role in connecting two different structures in cluster 4 SN (see Fig. 11). The clustering coefficient of this network is 0.71 (a value of approximately 0.30 would be obtained if the same number of links was randomly allocated on the network). In Fig. 12 we can see the sites located on the map. From the nine regions which make up the study area, only five are represented on this network, leaving aside the extreme north (Lago Lácar and Traful) and the extreme south (Lago Verde/Río Pico and Guenguel/Río Mayo).

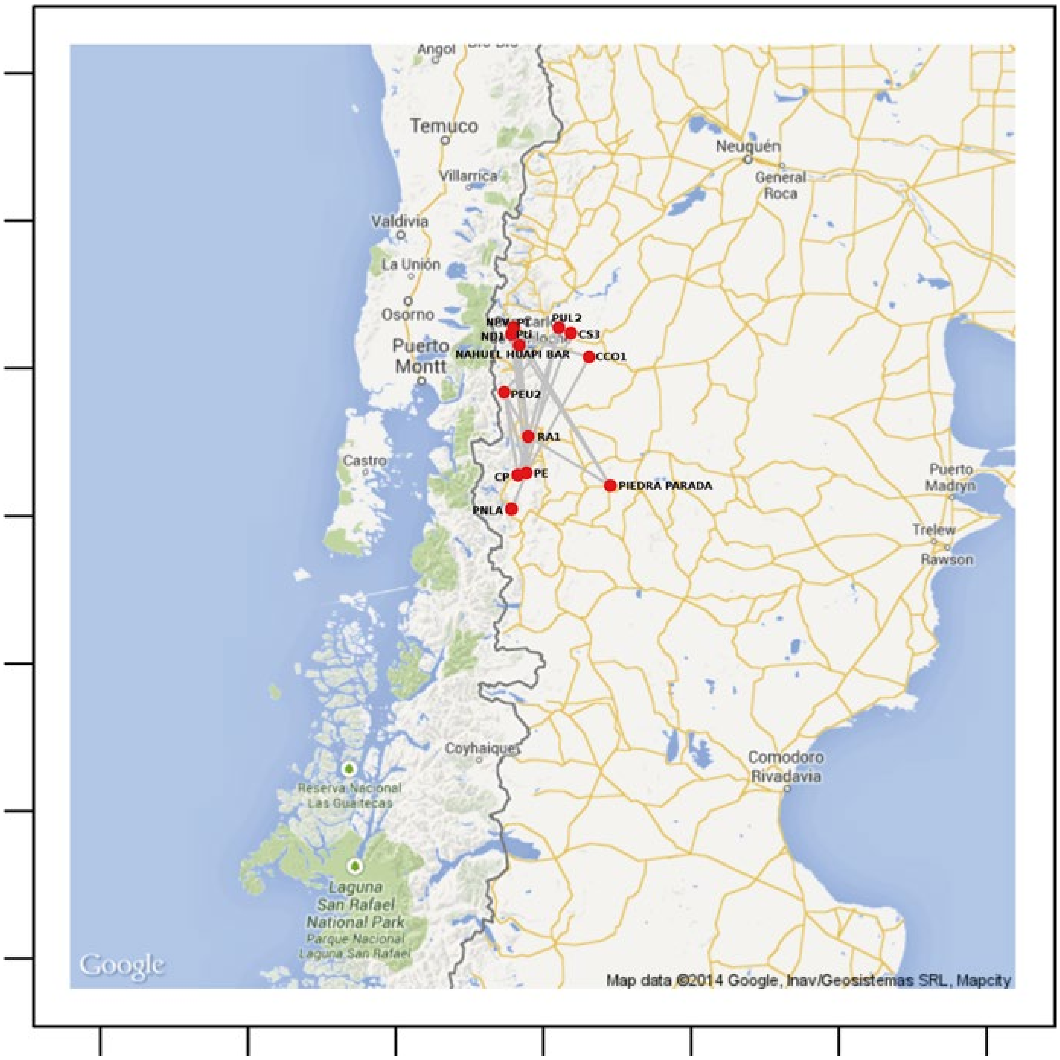


Fig. 12 Cluster 4 SN with nodes geographically located (R Development Core Team 2008; Loecher 2012)

- Cluster 5 links the following motifs: 35, 22, 11, 38, 15, 50, 54, 56, and 48 (see Appendix 2). It is characterized by figurative (35, 38, 15, 56, and 48) and geometric motifs (22, 11, 50, 54). This cluster has the highest quantity of motifs but with few members each, and it is, with cluster 6, the only one that

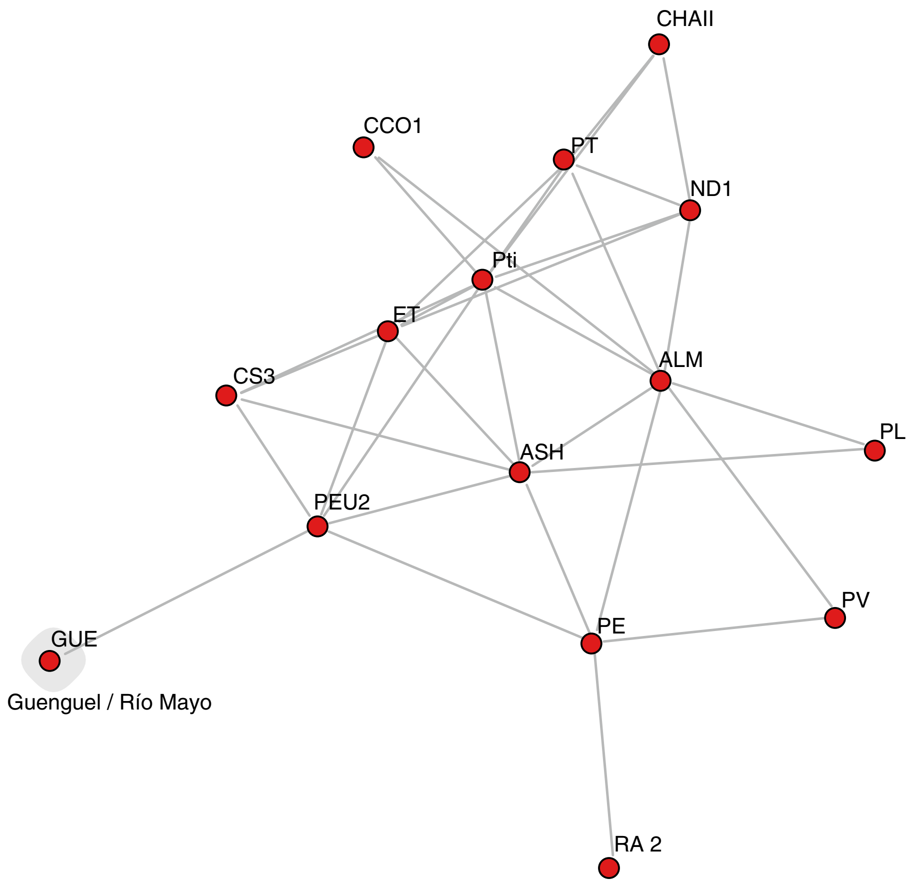


Fig. 13 Cluster 5 SN. Nodes represent archaeological sites; links are established when two sites share at least two character states of motifs from cluster 5. There were 14 isolated sites isolated that were removed from the figure because they do not fulfill this last requirement

does not follow a chain pattern. Motif 50 actually functions as a hub in the cluster. In Fig. 13 we can see cluster 5 SN. Puerto Tigre (Pti) is the most connected node, but its absence would not separate further clusters. Figure 14 presents the sites in the map. There are six regions included. The excluded

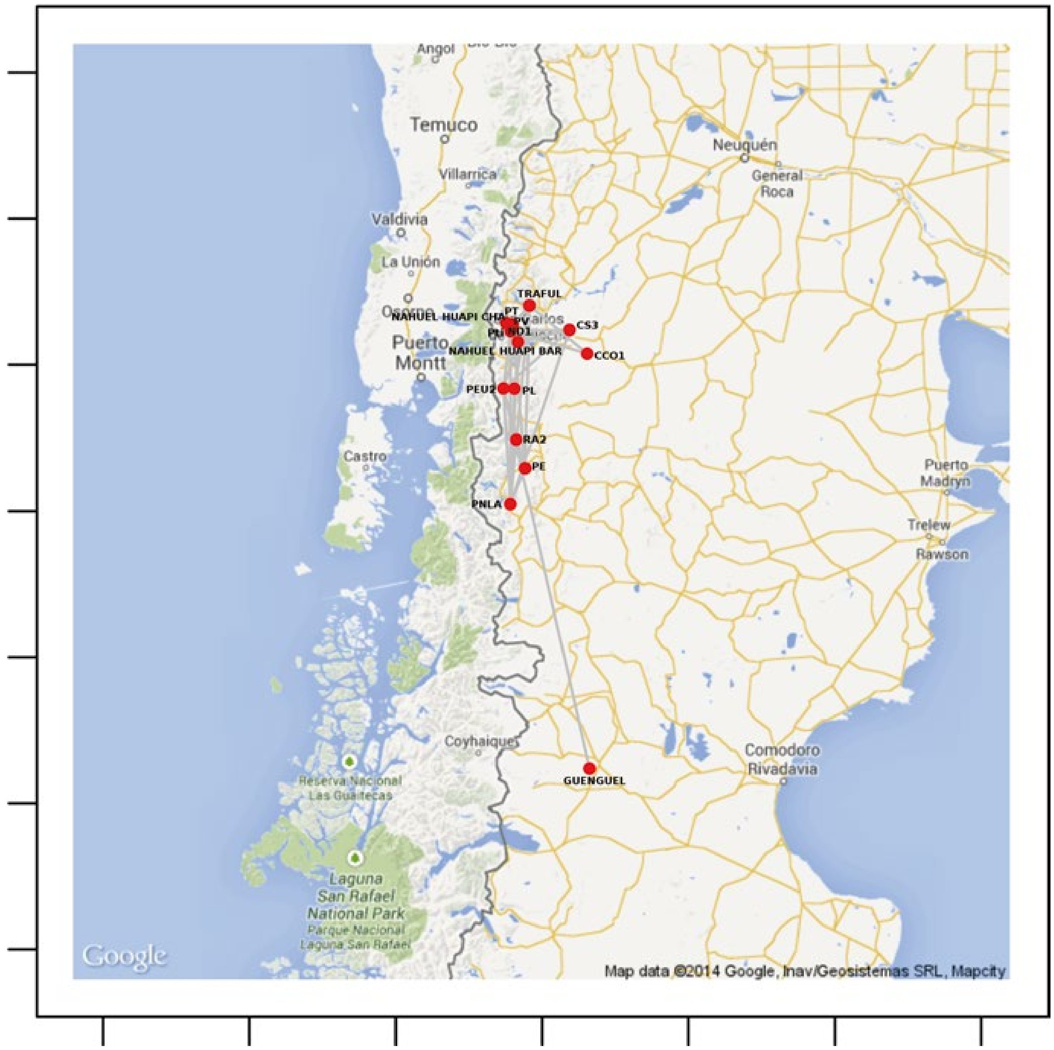


Fig. 14 Cluster 5 SN with nodes geographically located (R Development Core Team 2008; Loecher 2012)

regions are Lago Lácar, Piedra Parada, and Lago Verde/Río Pico. As in the case of cluster 2, Guenguel/Río Mayo is linked to the same region (in this case, by a link with Peumayén 2, PEU2, and not Paredón Lanfré, PL but these sites are very close to each other).

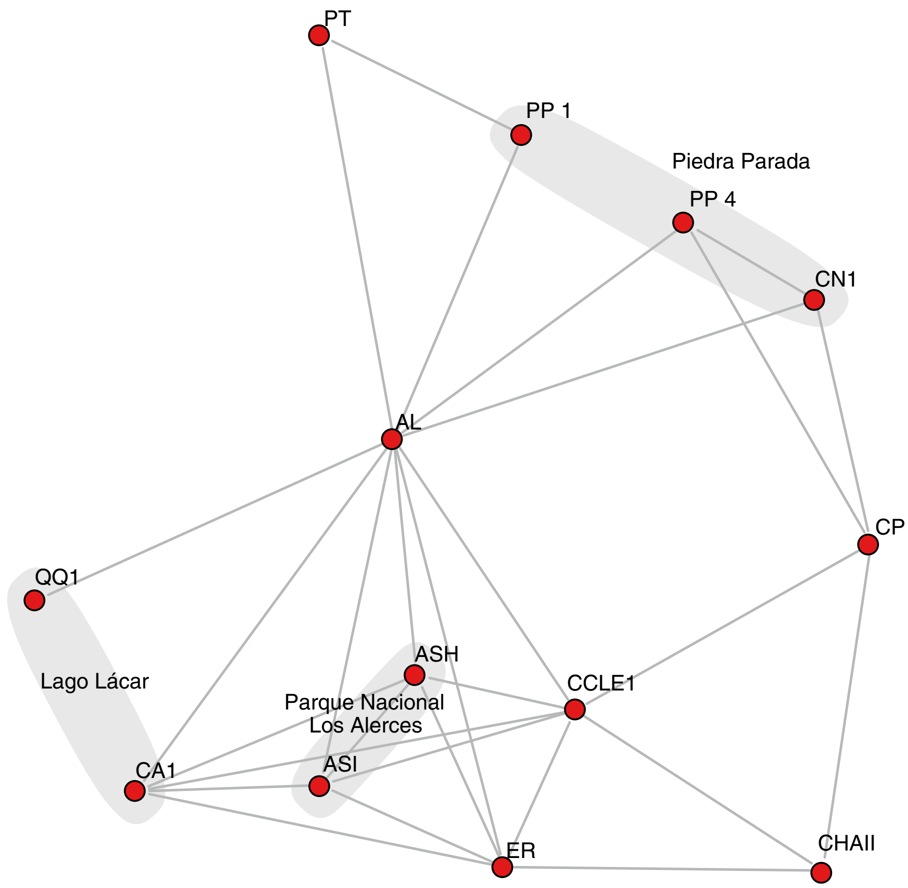


Fig. 15 Cluster 6 SN. Nodes represent archaeological sites; links are established when two sites share at least two character states of motifs from cluster 6. There were 16 isolated sites that were removed from the figure because they do not fulfill this last requirement

- Finally cluster 6 is comprised by five motifs: 10, 27, 25, 20, and 14, disposed in a Y pattern with 25 functioning as a hub. In cluster 6 SN (Fig. 15), the Alero Lariviere (AL) site, located at the north, is the most connected node, and it forms the link between two groups that would otherwise be separated. The inferior part

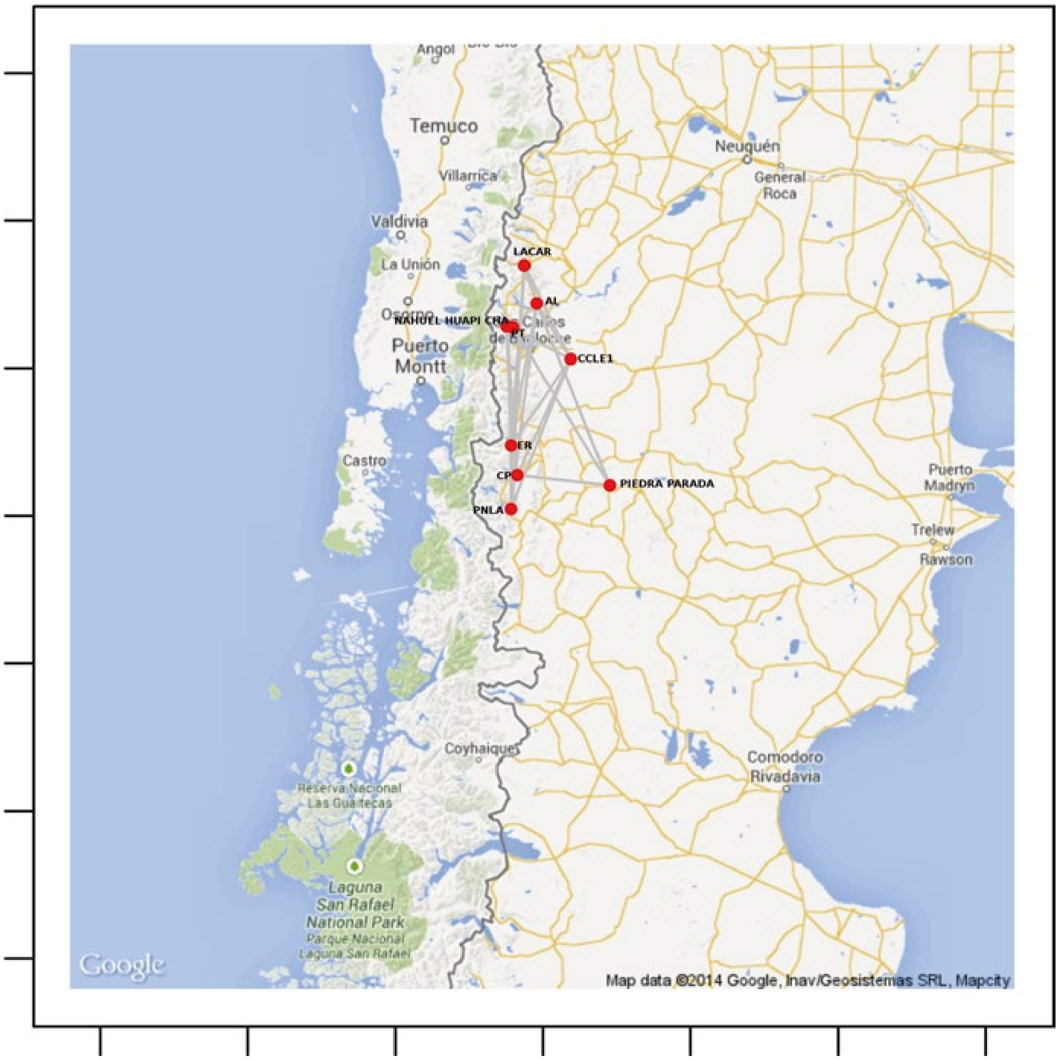


Fig. 16 Cluster 6 SN with nodes geographically located (R Development Core Team 2008; Loecher 2012)

of the SN is highly interconnected. Figure 16 shows its wide geographical dispersion. In this cluster, the two southern regions (Lago Verde/Río Pico y Guenguel/Río Mayo) are not represented.

9 Discussion

The presented results hinge on the threshold for Mutual Information between motifs that was established in order to construct the MIN (therefore, the clusters of defined motifs) and are based on the requirements set for defining the SN (at least two character states had to be shared to establish a link between sites, a very strong condition).

Our results allowed us to detect a strong overlapping in all the SNs and in turn, the SNs connected widely dispersed sites (in the order of 600 km in some extreme cases). As a consequence, we could not separate territories.

We consider that each SN could be interpreted as a different CTAP (see Fig. 2, bottom). Since CTAPs are an archaeological signal of one or many CTPs (see Fig. 2), we believe that our MIN clusters allow us to differentiate CTAPs with temporal and spatial dimensions even if we cannot determine the duration of each chronological "slice" or their sequence (i.e., which one was first and which last). The links that are part of the path could be contemporaneous, or not. In that sense, we cannot trace actual phylogenetic relationships between them, only undirected networks.

The fact that most of the SNs are spatially overlapping for each MIN cluster, and that there are sites that appear connected in many CTAPs, allows for the redundancy of the flow of information. This pattern is stronger in the middle and northern parts of the study area. Redundancy and high connectivity among sites are compatible with accretion and, hence, with elapsed time. Given that some of the sites delimited in the study area are not in close geographical range, we can assume, in archaeological terms, that the middle and northern parts of the study area should be in an effective occupation/colonization phase (see Borrero 1994–1995), while the south part (Guenguel/Río Mayo) and the extreme north (Lago Lácar) should be in an exploration phase (less redundancy and connections with the rest; see Borrero 1994–1995).

The regions that are present in all the SN clusters are Pilcaniyeu, Nahuel Huapi Comarca Andina del Paralelo 42°, and Parque Nacional Los Alerces. In the first three cases, we can argue that in those regions, there are more sites recorded and probably this is due to a sample bias. But in Parque Nacional Los Alerces, there are only two sites. Then, preliminary, we argue that those four regions are the ones in which more time of human occupation elapsed. The regions of Traful and Piedra

Parada could be included because they are absent in only one cluster (Traful does not appear in cluster 4 SN and Piedra Parada in cluster 5 SN). It is remarkable that cluster 6 SN includes only northern sites (from Parque Nacional Los Alerces to the north). Then we can separate a nuclear area (Pilcaniyeu, Nahuel Huapi Comarca Andina del Paralelo 42°, Parque Nacional Los Alerces, Traful, and Piedra Parada) and three other regions (Lago Lácar, Guenguel/Río Mayo, and Lago Verde/Río Pico) that are either in course of incorporation (exploration/colonization phases *sensu* Borrero 1994–1995) or integrated to other CTAPs with a different nuclear area (i.e., North of Santa Cruz Province). This last possibility should be explored in the future.

Also, the importance of the nodes is variable. In the case of the first three clusters, Cerro Pintado (CP), which is located in the middle of the study area (Comarca Andina del Paralelo 42° region), appears as a hub (cluster 1, 2, and 3 SNs, with the same degree of other three sites). Its importance could be related to the fact that it is the biggest sample (see Table 1). But, in addition, in cluster 1 SN, its absence would disconnect the Guenguel/Río Mayo region, while in cluster 2 SN, its absence would imply the disconnection of Pilcaniyeu and Traful from the more interconnected structure. In cluster 4 SN, Risco de Azócar 1 (RA1) has the higher degree, although located in the same region of Cerro Pintado (CP), and in this case, the loss of this site would disconnect the network into two structures (one with Piedra Parada and Nahuel Huapi and the other one with Parque Nacional Los Alerces, Pilcaniyeu, and Comarca Andina del Paralelo 42°). In cluster 5 SN, the most connected nodes are Alero Las Mellizas (ALM) and Puerto Tigre (Pti), but they do not account for the connectivity of the network. Finally, in cluster 6 SN, the most connected node is Alero Lariviere (AL), while the loss of this node would not disconnect the regions in the network. Hence, although the importance of CP as a node is high, there are other nodes that are also important in the same region.

10 Conclusions

Our analysis has allowed us to formalize the Mutual Information Network between rock art motifs in Northwestern Patagonia. Rock art sites offer a "flattened" temporal dimension, recreating the idea of a palimpsest which Binford (1981) applied to the archaeological record. In a rock art site, time may be compressed. Hence, we have established a MIN among rock art motifs and considered different Site Networks as CTAPs. Since SN clusters are not explained by a territorial model (given the spatial overlapping between them), we have considered a MIN cluster's motifs as contemporaneous and/or representative of heritable continuity associated to CTAPs. Drawing on the rock art, we have determined CTAPs for a set of sites, by means of motif correlation. Probably these CTAPs will work also for the transmission of other kinds of information. Then, these CTAPs could be tested against other lines of evidence. In the future we will explore other conditions for the MIN (as changes in *u*) and SN requirements.

Furthermore, this analysis also allows us to relate rock art sites to Borrero's model for the population of Patagonia. We suggest that the strong connectivity between the middle and northern regions of the study area reveals a hypothetical nuclear region, well known and transited by the hunter-gatherer population who made the rock art. The few links with the extreme north and the extreme south regions allow us to maintain that those areas were in an exploration/colonization phase. Let us note that, as we have argued elsewhere (Scheinsohn et al. 2009, 2015), site proximity, in terms of geographical distance, did not ensure connections (in our case, motif sharing). So, another interpretation could be that the mix of high local connections and sparse regional connections is what sustained the information flux. Following White (2013), we can suggest that "the creation of a relatively sparse web of non-local connections is the most efficient way to engineer a significant improvement in the ease of information flow across a spatially-situated network (…) If the main purposes of maintaining non-local contacts is to facilitate 'over the horizon' information flow and secure access to assistance or resources in distant areas during times of stress, the cost of maintaining connections would be an incentive to have as few as necessary to serve the purpose of maintaining sufficient information flow" (White 2013: 20). The same has been proposed by Kauffman (1993), when investigating genetic networks. He suggested that genetic networks would have to be sparsely connected since densely connected networks seemed incapable of settling down into stable cycles. Nowadays, there is a good quantity of works from different fields (i.e., in biology Leclerc 2008, in sociology Granovetter 1973, etc.) which propose that a parsimonious network sparsely connected and not unnecessarily complex will be robust enough. Our results from rock art motifs fit this picture. Further research will be directed to exploring this issue and test whether these sites are best linked to other nuclear areas (North of the Santa Cruz province, for instance).

Acknowledgements We are grateful to Larissa Mendoza Straffon for inviting us to contribute to this volume. We would also like to thank Mercedes Salado Puerto (EAAF). This work would not have been possible without her. Sabrina Leonardt and Florencia Rizzo contributed to the database. Florencia Rizzo also helped with Figs. 1, 2, and 3. The Comarca Andina del Paralelo 42 Team (Cristina Bellelli, Mariana Carballido, Pablo Férnandez, Ana Forlano, and Mercedes Podestá) made their firsthand database available to us. Finally, we also thank the INAPL staff. Part of this research was funded by FONCYT PICT 2010 N° 1810 and CONICET.

Appendix 1

Before defining Mutual Information, we need to introduce the Shannon Information and the Entropy functions. In his classic paper, Shannon (1948) defined entropy (*H*) as a measure of uncertainty of a random variable. In a communicational process, a given source emits messages that can be stored in an *X* variable. Departing from probability distribution of *X* values, entropy quantifies the level of "surprise" the receiver experiences upon receiving each message. If there is no surprise, there is no Information content (Mitchell 2009), because the message is fully predictable.

As an example, we present a rock art case. Let us introduce variable *X*, which represents a particular motif, which can take two possible values: 0 means the absence of the motif in a particular site and 1 its presence. Let us suppose that we have assessed 8 sites for this particular motif (see Table A1.1).

This motif is present in sites 1, 2, 3, and 4, and it is absent in the rest of the sites. From the data, we can compute the probability that *X* takes value 0 (which we will call $P(X=0)$) and the probability that *X* takes value 1 (which we will call $P(X=1)$). The probability of X taking a particular value is the frequency of this particular value with respect to the total number of observations. In this example, $P(X=1)=\frac{4}{8}=\frac{1}{2}$ (because in 4 of the 8 assessed sites the motif is present) and $P(X=0)=\frac{1}{2}$. Let us note that $P(X=1)+P(X=0)=1$ because *X* can take only two values in this example. The Shannon Information contained in the outcome value 1 of variable *X* is defined as

$$h(X=1)=-\log_2 P(X=1).$$

The entropy of the variable *X* is defined as the average of the Shannon Information contained in the possible outcomes, thus:

$$H(X)=P(X=1)h(X=1)+P(X=0)h(X=0).$$

The entropy of *X* for the example is $H(X)=1$, because

$$H(X=1)=-\frac{1}{2}\log_2\left(\frac{1}{2}\right)-\frac{1}{2}\log_2\left(\frac{1}{2}\right)=\frac{1}{2}+\frac{1}{2}=1$$

Let us note that:

- The entropy is always greater than or equal to zero. The particular case of entropy zero occurs when the variable *X* takes a particular value with probability 1 and

Table A1.1 Example of variable *X* representing the absence (when *X* takes the value 0) and the presence (when *X* takes the value 1) of a particular motif in 8 different sites

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Motif (*X* variable)	1	1	1	1	0	0	0	0

Table A1.2 Example of variables X_1, X_2, X_3 and X_4 representing the presence (when variable takes the value 0) and absence (when variable takes the value 1) of four motifs in each of th3 8 assessed sites

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	*H* (Entropy)
Motif 1 X_1	0	0	0	0	0	0	0	0	0
Motif 2 X_2	1	1	1	1	1	1	1	1	0
Motif 3 X_3	1	1	0	0	0	0	0	0	0.81
Motif 4 X_4	0	0	1	1	1	1	1	1	0.81

Table A1.3 Example of two variables *X* and *Y* representing the presence (when variable takes the value 0) and absence (when variable takes the value 1) of two motifs in 8 sites

	Site1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Motif 5 (*X*)	1	1	0	1	1	0	0	0
Motif 6 (*Y*)	1	1	0	1	1	1	0	0

the rest of the values with probability 0. Then, the uncertainty of the variable is 0, because we are certain that *X* will take only one possible value.

- Entropy *H*(*X*) reaches its maximum value when the probability of the occurrence of the outcomes of *X* variable is uniform. For the particular case of two possible outcomes, *H*(*X*) is maximum when the probability of the two outcomes is the same, $P(X=1)=P(X=0)=\frac{1}{2}$, and it reaches the value $H(X)=1$. In this scenario, the uncertainty of the variable *X* is maximum.

Let us complicate our example a little bit further. We will continue with 4 motifs and 8 assessed sites (Table A1.2).

In the case of motif 1 and motif 2 (row 1 and row 2 of Table A1.2), the entropy takes the same value ($H(X_1)=H(X_2)=0$). This occurs because entropy is a function of the probabilities and not of the values of the outcomes. Entropy does not distinguish between two cases which are symmetric (if we change outcomes 1 for 0 and vice versa). The same happens with motifs 3 and 4 (X_3 and X_4) that reach the same entropy value, which results $H(X_3)=H(X_4)=0.81$.

Now let us compare two other motifs (*X* and *Y*) in the same 8 sites. Let us suppose that the observed values result in Table A1.3.

We are interested in detecting if there is any type of correlation between these two motifs. Does information about motif 5 give information about motif 6, or are they independent variables? Mutual Information helps to answer this question by quantifying the information gain that we obtain from one variable when we know the other variable and vice versa. The Mutual Information is defined as:

$$I(X,Y)=H(X)-H(X\mid Y)$$

where $H(X\mid Y)$ is the conditional Entropy of variable *X* given that we know the variable *Y* (Cover and Thomas 1991). As we just mentioned, Mutual Information measures the difference in the uncertainty of *X* variable when we know *Y* variable and vice versa. When variables *X* and *Y* are independent, then the fact of knowing *Y*

Table A1.4 Example of two variables X and Y representing the presence (when variable takes the value 0) and absence (when variable takes the value 1) of two motifs in 8 assessed sites

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Motif 7 (X)	1	1	0	1	1	0	0	0
Motif 8 (Y)	0	0	1	0	0	0	1	1

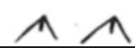
does not reduce the uncertainty of *X*. Formally, $H(X \mid Y) = H(X)$, because the uncertainty of *X* is the same (regardless of whether *Y* is known or not). Then $I(X,Y) = H(X) - H(X \mid Y) = 0$, reflecting that the knowledge of one of the variables (*X* or *Y*) does not say anything about the other. In the other extreme case, the uncertainty of variable X is fully reduced when we know Y variable, $H(X \mid Y) = 0$ (if we know the value of *Y*, then the certainty of *X* variable is complete, because we are sure of the value which *X* takes), then the Mutual Information is maximum $I(X,Y) = H(X) - H(X \mid Y) = H(X)$.

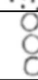
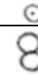
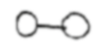
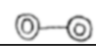
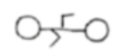
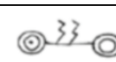
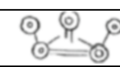
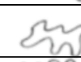
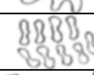
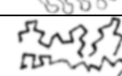
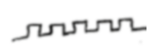
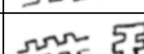
Returning to the example of Table A1.3, we compute $I(X,Y) = 0.548$. Thus, *X* and *Y* are not independent. We can observe that every time motif 5 is present ($X=1$), then motif 6 is present too ($Y=1$) (notice that the inverse case is not met: in site 6 although motif 6 is present, motif 5 is absent).

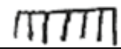
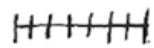
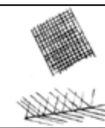
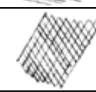
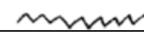
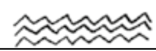
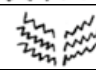
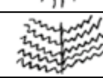
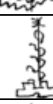
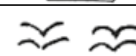
Finally, it is important to remark that Mutual Information does not say anything about the sense of the information gain. Hence, in Table A1.4 we present other example which leads to the same value of Mutual Information as the previous example ($I(X,Y) = 0.548$). But in this case, we can note that each time motif 7 is present ($X=1$), then motif 8 is absent ($Y=0$). Then, motif 7 gives us information about motif 8, but they are negatively correlated.

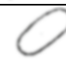
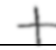
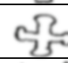
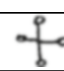
Appendix 2

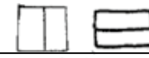
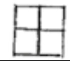
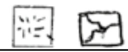
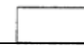
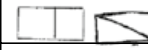
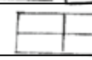
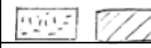
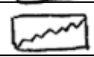
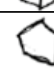
List of motifs and character states (Taken from Scheinsohn et al. 2009).

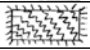
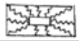
Motif	Character state	Description	Design
0	1	Dot	
	2	Aligned dots	
	3	Grouped dots	
1	1	Line stroke	
	2	Aligned strokes	
	3	Brush stroke	
2	1	V	
	2	Aligned Vs	
3	1	Tridactyl	
	2	Tridactyl in a geometric shape	
	3	Aligned tridactyls	
	4	United tridactyl	
4	1	Z	
	2	Aligned Zs	

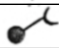
5	1	Empty circle	
	2	Filled circle	
	3	Circle with a point	
	4	Concentric circle	
	5	Circle with a cross	
	6	Dotted circle	
	7	Dotted concentric circles	
	8	Aligned empty circles	
	9	Aligned filled circles	
	10	Aligned circles with a point	
	11	Attached empty circles	
	12	Circle with a stroke	
	13	Concentric circles with a point	
6	1	Empty circles with a rod	
	2	Concentric circles with a rod	
	3	Empty circles with a zigzag rod	
	4	Empty circles with attached elements in a rod	
	5	Concentric circles with attached elements in a rod	
	6	Many Concentric circles with a rod	
7	1	Irregular closed figure	
	2	Grouped irregular closed figures	
8	1	Open irregular fret	
	2	Open regular fret	
	3	Double regular fret	
	4	Closed filled fret	
	5	Double opposed regular fret	
	6	Closed empty fret	
	7	Closed empty fret with an inner figure	

9	1	Hollow ladder	
	2	Staggered semicircle	
10	1	Parallel staggered truncated pyramid-like lines	
	2	Staggered truncated pyramid-like line	
11	1	Comb-like figure	
	2	Double comb-like	
12	1	Reticulated figure	
	2	Reticulated rhombus	
13	1	Zigzag	
	2	Aligned zigzag	
	3	Zigzag strokes	
14	1	Open arc	
	2	Aligned open arcs	
15	1	Undulated “tree”	
	2	Totemic post	
	3	Straight “tree”	
16	1	Zigzag circle	
	2	Zigzag circle with inner “sun”	
	3	Irregular zigzag figure	
17	1	Flying birds	
18	1	drumhead	

19	1	Sun	
	2	Circled sun	
	3	Sun with inner point	
	4	Concentric sun	
	5	Filled sun	
	6	Partial sun	
20	1	Oval figure	
	2	Oval with inner point	
	3	Oval with inner strokes	
21	1	Simple cross	
	2	Hollow cross	
	3	Filled cross	
	4	Concentric crosses	
	5	Greek hollow cross	
	6	Trefoil hollow cross	
	7	Staggered hollow cross	
	8	Greek cross with inner filled cross	
	9	Fretted inner cross	
	10	Aligned simple crosses	
	11	Aligned filled crosses	
	12	Aligned concentric crosses	
	13	Aligned fretted inner crosses	
	14	Linked aligned simple crosses	
	15	Aligned Greek cross with inner filled crosses	
	16	Cross with ovals at their ends	
	17	Others	

22	1	Square	
	2	Subdivided square	
	3	Square with two subdivisions	
	4	Concentric squares	
	5	Square with inner strokes	
	6	Filled square	
23	1	Rect angle	
	2	Subdivided rectangle	
	3	Rectangle with two subdivisions	
	4	Concentric rectangle	
	5	Rectangle with inner strokes	
	6	Filled rectangle	
	7	Rectangle with inner figure	
	8	Rectangle with inner zigzag	
24	1	Rhombus	
	2	Rhombus with inner strokes	
	3	Concentric rhombuses	
	4	Aligned rhombuses	
	5	Linked rhombuses	
	6	Rod linked rhombuses	
	7	Rhombus with attached element	
	8	Staggered rhombus with inner circle	
25	1	Polygon	
	2	Irregular polygon	
	3	Polygon with inner rectangle	
26	1	Guanaco footprint	

27	1	Hollow clepsydra	
	2	Clepsydra with inner strokes	
	3	Framed Clepsydra	
	4	Staggered clepsydra	
	5	Clepsydra with i9nner points	
28	1	Matra	
	2	Matra with attached lines	
	3	Matra with crenellated interior	
	4	Matra with inner rectangle	
	5	Matra with inner rhombuses	
29	1	Spot	
	2	Spot with inner point	
30	1	Crenallated cross and rhombus	
31	1	Ñandú	
32	1	Lion skin	
	2	Others	
33	1	Rosette	
	2	Aligned rosettes	
34	1	Schematic lion	
35	1	Guanaco	
	2	Grouped guanacos	
36	1	Human footprints	
37	1	Human hands	
	2	Negative human hands	

38	1	Anthropomorphic figure	
39	1	Contoured painted natural holes	
40	1	Hollow star inscribed in dotted circle	
	2	Filled star	
41	1	Hook figure	
42	1	Hollow triangle	
	2	Filled triangle	
	3	Dotted triangle	
	4	Triangle with a hook	
43	1	T	
	2	I	
44	1	L	
45	1	Arc and circle	
46	1	Trident	
47	1	Bola with handle	
48	1	Horse and rider	
49	1	Horse	
50	1	Y	
51	1	Semicircle	
52	1	Fusiform	
	2	Fusiform with inner lines	
53	1	Undulated line	
	2	Parallel undulated lines	
54	1	8 figure	
	2	Axe	
55	1	Trapeze	
	2	Linked trapezes	
56	1	Other zoomorphs	
57	1	Pyramid	
58	1	E inverted	

Appendix 3: Simulation

In order to discard the possibility of obtaining the values of Mutual Information of Table 2 by chance, we performed a simulation in which we randomly assigned the same number of 1s and 0s (the amount of "presences" of motifs in the sites) from the database in the X_i variable. We generated 1000 random assignments. The obtained distribution of Mutual Information is shown in Fig. A3.1, where the threshold value *u* corresponds to a *p-value* (the probability of finding a case greater than the observed 0.093) of 1.56 % in the distribution of the Mutual Information obtained by random assignment. This means that, for the extreme case of less correlated pairs (on threshold value *u* 0.093), it is possible to obtain this correlation by random assignment with less than 1.56 (a low probability). Then, we performed another statistical test in which for each pair of motifs, the random assignment was made considering the same value as in our Table 2. For instance, comparing motif 50 with 15, we assigned 1 and 0 taking into account that motif 50 was present in 3 sites and motif 15 was present in 5 sites (see Table 2). We obtained a *p-value* less than 2 % for the three first cases corresponding to the threshold value *u* (the first three pairs of Table 2) and less than 0.2 % for the rest of the cases. Notice that these three cases, which are the ones with the greater possibility of being obtained by random, are also the ones with fewer information (given the small sample). Nevertheless we decided to include it on the Mutual Information Network, since in archaeology it is usual to deal with absence of information. In any case, with this exception, this test allows us to sustain that the probability of obtaining these values of Mutual Information correlation with the rest of the pair of motifs is low. These sets of correlated motifs above the threshold value *u* will be used to construct the MIN, in which nodes represent motifs and links represent the Mutual Information between them.

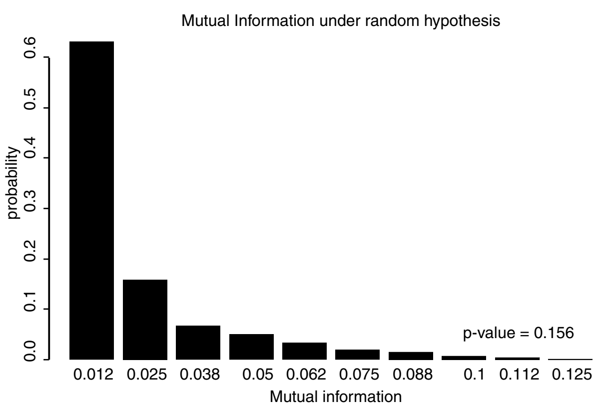


Fig. A3.1 Histogram of Mutual Information values obtained by assigning the amount of 1s and 0s observed in the database randomly in a matrix of 49 columns and 43 rows. The *p*-value of 0.156 for *u* means that the probability of obtaining a value of Mutual Information greater than the threshold value is 1.56 %

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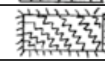
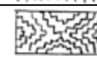
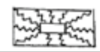
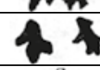
27	1	Hollow clepsydra	
	2	Clepsydra with inner strokes	
	3	Framed Clepsydra	
	4	Staggered clepsydra	
	5	Clepsydra with i9nner points	
28	1	Matra	
	2	Matra with attached lines	
	3	Matra with crenellated interior	
	4	Matra with inner rectangle	
	5	Matra with inner rhombuses	
29	1	Spot	
	2	Spot with inner point	
30	1	Crenallated cross and rhombus	
31	1	Ñandú	
32	1	Lion skin	
	2	Others	
33	1	Rosette	
	2	Aligned rosettes	
34	1	Schematic lion	
35	1	Guanaco	
	2	Grouped guanacos	
36	1	Human footprints	
37	1	Human hands	
	2	Negative human hands