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The evolution of projectile points and technical systems: A case from Northern Patagonian coast (Argentina)

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ABSTRACT

In this paper we present the results of the phylogenetic analysis of projectile points dating from the Middle-Late and final Late Holocene recovered from different sites along the coast of San Matías Gulf (Río Negro province, Argentina). In order to study the evolution of weapon systems we have used maximum parsimony phylogenetic reconstruction and tree based comparative methods. This allowed us to explore different evolutionary models addressing the technical systems used in the area.

The results suggest the existence of a robust phylogenetic signal that gradually evolved into at least two technical systems. One of the most important results however, was the evidence of a certain morphological continuity. In turn this suggests that, rather than a direct replacement, there was an adaptation of propellant-type weapons towards the bow and arrow.

We concluded that this pattern of metric and morphological continuity might be related to transitional forms between the different technical systems, with design types used in both systems. There would have been a degree of experimentation so as to produce performance effective projectile points, this would have occurred in a framework of trial and error in a context of low risk.

1. Introduction

Projectile points are special in that they constitute a lithic artifact type that has been used through time as a fossil guide for defining cultural entities, reconstructing ancient chronologies, understanding aspects of technological organization, and for identifying the chronological associations between different components (Tomka and Prewitt, 1993). The functional attributes of a given artifact, in this case projectile points (in the form suggested by Ratto, 2003), are directly related to the performance of the artifact in a given context and in relation to a particular task (Ratto, 1994; Tomka and Prewitt, 1993).

The characteristics that one looks for in the design of such a weapon include penetration, handle security, the size of the wound to be inflicted, its durability, the distance and velocity it is expected to achieve, its ease of transport and possibilities of recovering the piece (Nelson, 1997; Ratto, 1991, 1993). All these factors can be interpreted from the projectile point shape. For instance, the width of the piece bears on its sharpness, penetration and on the size of the wound to be inflicted; the general size of the projectile point also affects the size of the wound, its penetration potential, the use and possible re-use of the piece and the distance and velocity that the weapon can achieve (Hughes, 1998; Nelson, 1997). It therefore follows, that the morphology and size of the projectile point is the result of the selection of given variables that meet the needs for which the lithic point is required (Nelson, 1997; Ratto, 1994).

Consequently, we believe that a synchronic analysis of projectile point design can provide us with the tools with which to discuss processes of continuity and change in the subsistence strategies of human groups. Likewise this study will permit us to model the process of technological change through time.

2. Previous research and study area

The materials studied in this article come from the coastal strip of the Northern Patagonian coast, Argentina (Fig. 1). A great number of variedly formed and sized projectile points have been recovered from this area. The earliest archaeologists working on the area noted the degree of variability inherent in the projectile points from this zone (Bórmida, 1964), in turn they constructed the first chronological tables of regional change for these artifacts, albeit from a culture historical perspective (Bórmida, 1964; Menghin, 1952). Systematic archaeological research conducted between 2004 and 2014 has not only allowed us to generate a firmer chronological framework (Favier Dubois and Borella, 2011), but has also permitted us to contextualize the process of technological change (Alberti, 2012; Cardillo and Favier Dubois, 2011; Cardillo and Scartascini, 2007; Cardillo et al., 2010, among others).

The Northern coast of Patagonian Argentina is characterized by an abundant biodiversity, given that has easy access to marine species

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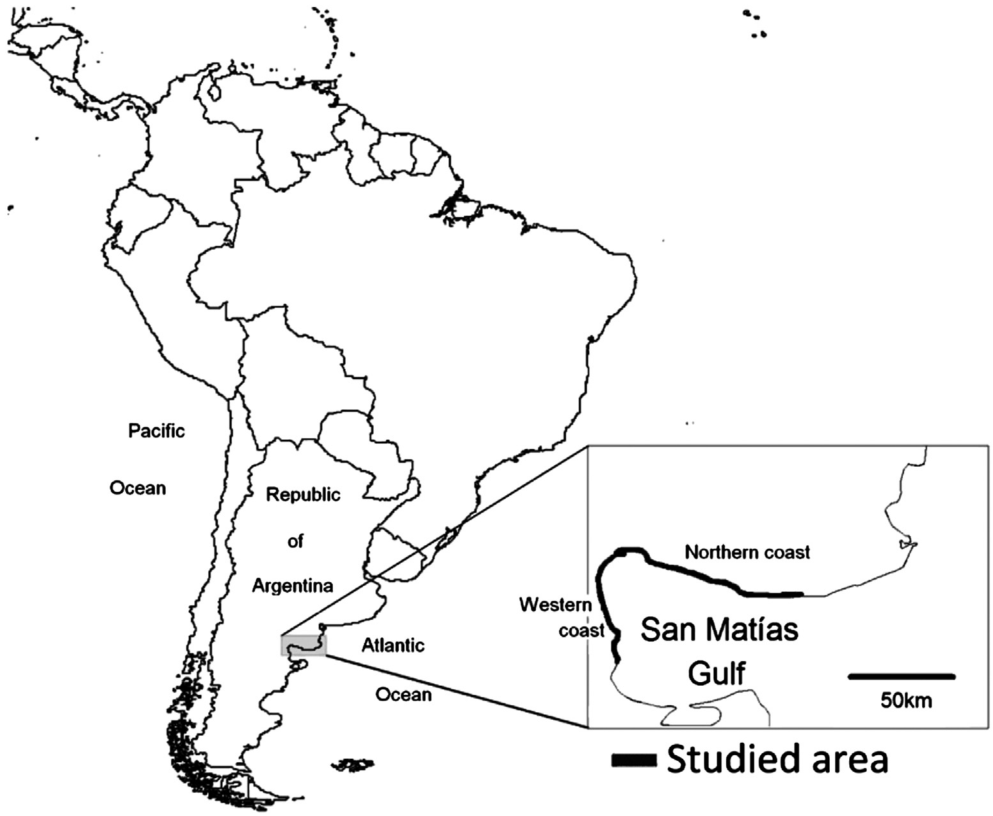

Fig. 1. San Matías Gulf coast, Río Negro province.

(mollusks, fish and sea lions), the availability of water in the dunes, the obtainability of rocks for tools and the existence of topographic shelters (Borella, 2006; Favier Dubois and Borella, 2011). To date more than 50 sites have been identified dating to between *ca*. 6000 and 450 ^{14}C years BP (Favier Dubois et al., 2009). Isotope analysis of human skeletal remains, among other evidence, shows that this area of the north Patagonian coast was exploited in a variety of ways from the Middle Holocene onwards (Favier Dubois et al., 2009).

During a first phase of occupation, from 6000 ^{14}C years BP, the groups in this area principally consumed marine resources, which exploitation did not require complex tools (Cardillo and Favier Dubois, 2011; Favier Dubois and Scartascini, 2012; Favier Dubois et al., 2009). A great number of medium- and large-sized lanceolate points have been recovered from these sites, especially from the earliest contexts (Fig. 3). In a second phase (between 1500 and 450 ^{14}C years BP), the evidence suggests a mixed diet, with a greater presence of plant and land resources (Favier Dubois et al., 2009), coinciding with the appearance of ceramic, small stemmed and triangular projectile points as well as an increase in grinding tools (Favier Dubois et al., 2009). This was a period of increased risk and climatic stress (Cardillo and Favier Dubois, 2011). Finally, sometime in the 18th Century historical evidence documents the virtual abandonment of the coast, perhaps as a consequence of the earlier introduction of the horse (Favier Dubois et al., 2009).

The evidence to date stresses both continuity and a process of transition in subsistence strategies: during the first phase, these were strongly linked to the exploitation of marine resources, shifting at a later date to a strategy of consuming land-based resources, thus underlining a growing diversification in the diet (Favier Dubois et al., 2009). We contend that these shifts in subsistence can explain the changes observed in the chronological trajectories of lithic technology generally, and projectile points in particular, given that, as we mentioned previously, the design of these artifacts is linked to both the extractive strategies employed and the need for the technology to perform. Likewise, these changes suggest that there was an evolutionary process at work in weaponry assemblages during the course of the Middle to Late and final Late Holocene. On this basis, we support the use of phylogenetic methods in an attempt to model trajectories of change in these tools, and concurrently evaluate different hypothesis concerning the evolution of technical systems.

3. The technical systems of weapons

According to Ellis (1997), before the introduction of metal was better to use lithic projectile points than points made from other materials, given that they are by far the more efficient weapons for use in either war or hunting, their degree of lethality is higher due to the size and depth of the wounds they can inflict. The degree of lethality does not have solely to do with the particular type of lithic point, given that there is an ample variety of forms and sizes of projectile points that achieve the same functional end effect. In fact, great part of the metric variation in projectile points is related to the technical system of which it forms a part of – for example, spear, spear-thrower or *atlatl*, bow and arrow – that is to say, the tool in its totality. In relation to this and considering the ballistic performance of the projectile, there is a functional reason why arrowheads are smaller that spearheads. Arrows are relatively light projectiles in comparison to spears, therefore a change in the weight of the point can alter the center of gravity of the arrow; this in turn can affect the stability of its flight (Patterson, 1985; Ratto, 1993). Arrowheads also have a narrower stem given that they are hafted onto smaller shafts (Hughes, 1998; Patterson, 1985; Ratto, 1993).

In his 1993 article, Churchill undertakes a revision of the ethnographic data pertaining to the use of different weapon systems – throwing spear, dart, bow and arrow – employed by different human groups. The author suggests that among the groups studied, 95% of them used spears, although only 50% of them used it for hunting on land. The spear, as a technical system, was also important in the hunt of marine mammals, fishing, war, and as defense against other predators

(Churchill, 1993:16). In particular, spears are principally used once the prey has been placed at a disadvantage. Furthermore, spear use is associated with cooperative hunting methods, such as the use of domesticated animals – dogs – and other technologies such as boats (Churchill, 1993), nevertheless it is a less flexible weapon system than the bow and arrow (Nelson, 1997).

On the other hand, darts are linked to hunting methods that emphasis ambush and the need to get close to smaller prey (for example, Churchill, 1993:17). Ratto (2003) sustains that darts are normally employed in hunting marine animals and birds, although there is evidence of their use on land, for instance in Australia (see articles cited in Ratto, 2003).

Finally, bows and arrows are used in all hunting methods described above (Churchill, 1993:18). Even so, in marked difference to spears and darts, the bow and arrow adjusts the hunting method to the characteristics of the prey and not vice versa – in the other two technical systems the limitations of the weapon conditions the type of prey that can be hunted – (Churchill, 1993:18). In using a bow and arrow the hunter should aim at the chest cavity given that there is a greater chance of hitting a vital organ and thus killing the prey through hemorrhaging. Therefore, even in large animals the target tends to be small which in turn requires a higher technical skill on the part of the hunter (Churchill, 1993:18). It should be noted that ethnographic studies on this weapon system, and among those that use projectile points in general, the type of point did not have a major influence on the prey that was hunted (Ellis, 1997).

In Argentina, Ratto's (1991, 1993) research on the metric and morphological characteristics of projectile points allowed her to differentiate between technical systems on the basis of aerodynamics and size. The author stated that size and relative symmetry allowed one to assign certain projectile points to hand-held, non-thrown, weapons such as hafted knives. The use of knives is also supported by ethnographic evidence from Insular Patagonia (Tierra del Fuego) where these artifacts have been recovered, as they have been in the Argentine *puna* (Ratto, 2003).

Crucially, it has been possible to determine that in numerous cases more than one technical system were in use contemporaneously given that these systems covered different yet complementary functions (Hughes, 1998; Ratto, 1994, 2003). In other cases, the archaeological evidence suggest that there have been processes of change and replacement of technical systems linked to changes in hunting strategies (Martínez, 2003; Ratto, 2003; Restifo, 2013) and competition between human groups (Bettinger and Eerkens, 1999; Blitz, 1988; VanPool and O'Brien, 2013). For instance, there is the well-documented case of the replacement of the spear-thrower by the bow and arrow (Blitz, 1988; Hughes, 1998; Ratto, 2003). Although one should note that the *tempo* and mode of these varied processes of stasis, innovation and replacement were different depending on the context (see Bettinger and Eerkens, 1999; VanPool and O'Brien, 2013).

4. Objectives

Given that the empirical evidence of long-term technological change (Basalla, 1988; Foley and Lahr, 2003; Jordan and Shennan, 2009) suggests that technology follows a pattern of descent with modification on the basis of pre-existing designs, it is possible to use phylogenetic methods of analysis (Boyd et al., 1997; Collard et al., 2006; García Rivero, 2013; Harmond et al., 2006; Muscio, 2009, among others) to model trajectories of change and thereby generate plausible hypothesis concerning the evolution of technology. Henning (in Kitching et al., 1998) originally developed this concept, were he classified organisms using the criteria of ancestry embedded in either common or shared inheritance.

Phylogenetic reconstruction has been shown to be a useful tool in studying the emergence of adaptive strategies and technological change, given that it creates an independent comparative framework within which one can contrast historical processes (see García Rivero, 2013 for a comprehensive treatise on the method; O'Brien et al., 2013). This is because, when considered within a purely adaptive framework, the emergence of technological innovation forms part of phylogenetic flexibility, for example, as a response to risk (Fitzhugh, 2001). In this case, similarities between two technologies can be explained by functional convergence without the necessity of any process other than the maximization of performance. Nevertheless, we would expect some adaptive elements within the cultural toolkit to be retained within the system of information transmission, so that innovations do not emerge *de-novo* but rather as part and parcel of a knowledge base passed down the ancestral line (see for example Borrero, 2011; Boyd et al., 1997).

Another aspect that can affect technological change is the functional or structural restrictions inherent to technology; these can be understood as the artifacts function and design limitations (Cardillo, 2009; Hughes, 1998; Ratto, 1991, 1994). This can limit, or at least channel technological change trajectories. In this manner, a human populations adaptive response to, for instance, climate change, can only be partially understood by flexibility in their actions, given that they depend on the information available to them via their cultural toolkit and the structural restrictions (in the sense stated by Cardillo, 2009; Gould, 2002), such as the raw material properties available for knapping.

Phylogenetic reconstruction permits a study of *tempo* and type of technological change linking this to climatic and spatial concerns and other issues arising from the archaeological record. This is particularly important in the framework of the study area given that, as mentioned previously, there is a dietary shift from a marine based diet during the early part of the Middle Holocene, towards a mixed diet of marine and an increasing presence of land-based resources towards the later Middle and during the Late Holocene (Favier Dubois et al., 2009).

In this archaeological context, we would expect that these trajectories of change would leave their mark on the technology and in particular on the projectile points. If there is cultural transmission of preserved information pertaining to the relative design and functionality of the projectile points throughout time, then it would be possible to create a trajectory observable through cladistic analysis.

Consequently, the primary objective of this article is to estimate the phylogenetic signal of projectile points from assemblages of the Middle-Late Holocene from the northern Patagonian coast and to identify the pattern of change with modifications, as established by the Darwinian evolutionary inheritance model. Secondly, we are interested in modeling changes in technical systems and the generation of artifact lineages within a context of change and evolution in the subsistence strategies of the area.

Also, as mentioned before, a clear pattern of change in subsistence strategies was observed in the study area from different indicators (zooarchaeological record, site density and distribution and stable isotope analysis). Therefore, we believe that these analyses will assess the projectile point variation trends in relation to the hypothesis that technological change is linked to changes in subsistence strategies by human populations during the studied temporary span.

5. Methodology

5.1. Cladistic analysis

The basic assumption underlining the use of these methods is that culture like biology is circumscribed by a system of inheritance. Following from this, the copy and different learning methods permit the transgenerational transmission of information (see García Rivero, 2013 and O'Brien et al., 2014 for a summary of the basic principles of this from an archaeological perspective). Experimental studies and observations demonstrate that, in general, this system holds sufficiently well, maintaining culturally inherited information against replicative error and the horizontal transmission of information between individuals and groups (Muscio, 2009; Nunn et al., 2010; see also Collard et al., 2006).

Therefore, if a given culture creates an information inheritance system that is more or less coherent it is then possible, through the use of biological methods, to map paths of change, appearance or extinction of cultural elements (Boyd et al., 1997; O'Brien and Lyman, 2003; O'Brien et al., 2001). In the case of Archaeology, the analysis of different bodies of data provides sufficient evidence that can be used to run different models of cultural change (through mimicking, innovation or a combination of both) utilizing various phylogenetic reconstruction methods to this end, albeit appropriate adjustments measures (see discussion in Muscio, 2009).

In cladistic analysis each type is taken as an evolutionary unit or HTU (*Hypothetical Taxonomic Unit*), in effect, a theoretical type generated according to a paradigmatic classification as stipulated by Dunnell (1971), the result of a non-hierarchical intersection of elements that describe them (or characteristics in cladistics usage). If the instrument types contain character aggregates that are relatively stable in time and space, then these have enough integrity for them to be used as valid units containing phylogenetic information in their characters (see discussion in Boyd et al., 1997; O'Brien et al., 2014). These characters (elements selected for phylogenetic analysis), when shared by two forms derived from a common ancestor (or synapomorphy) are known as homologous. We would expect a pattern of gradual divergence as long as new characters emerge from the ancestral forms; this is in keeping with the evolutionary principle of descent with modification (Felsenstein, 2004).

This pattern can be represented via a tree diagram known as a cladogram, where, according to the characters, the branches reconstruct the historical relationships between the units studied (Felsenstein, 2004). The most parsimonious cladograms thus created engender hypothesis concerning the historical relationship between the classes analyzed. Nevertheless, within a culture, different technological lineages and traditions can share information between them, thereby interchanging characters or following similar trajectories on the basis of information transferal between each other. Characters shared in this manner violate the principle of descent with modification given that they do not share a common ancestor and are known in the phylogenetic context as homoplasy.

On the other hand, as the origin of these changes are in occasion impossible to detect, homoplasy can introduce uncertainty into the evolutionary interpretation impacting on the simplicity of the phylogenetic hypothesis of descent with modification (Muscio, 2010; Nunn, 2011). Due to this, different methods have been applied with the aim of evaluating the consistency of the cladistic hypothesis and towards measuring the quantity of homoplasy (or uncertainty) within the cladogram tree (Collard et al., 2006; Muscio, 2010). The selection of characters and their construction forms the primary homology hypothesis that is then tested through cladistic analysis.

As mentioned above, if projectile points constitute a class with phylogenetic information, then changes in their construction would constitute shared evolutionary novelties (synapomorphy) between the individuals that form a group. This would then constitute empirical proof of a shared history of the characters, or secondary homology (Hawkins et al., 1997). The most robust trees are those that have the highest number of synapomorphies or evolutionary novelties shared only by members of a given group. Contrariwise, if characters vary repeatedly at random within distinct groups then they are considered homoplasic. Homoplasy is the result of convergence (independent evolution towards the same combination of characters), reversion or parallelism (Felsenstein, 2004). Identifying the type of homoplasy occurring in tools also provides important information on the evolutionary dynamic at work and may be modeled using different methods. Nevertheless, we do not deal with this facet of tool evolution in this study.

5.1.1. The phylogeny of projectile points

Since the beginning, cladistics in archaeology has focused on the study of projectile points because they are relatively complex artifacts with well established design elements. As Shott (2011) remarks (2011) if points evolve they do so in relation to a combination of functional and social factors, as requirements of performance (penetration capability, flight stability, durability, among others). Also projectile points found in archaeological assemblages are complex compounds of different averaged mechanism as cultural transmission information, individual replication error and/or cultural replication rules in each time (see also Okumura and Araujo, 2014). The interaction of different factors through time and space results in a complex mosaic that compounds observed variation. Cladistics could be useful to determine if similar technological traits emerge for common decent or convergence due similar selective environments or technological design space constraints. For example, Jennings and Waters (2014) apply cladistics to compare Clovis and Pre-Clovis technological traits using the lithic assemblage of Debra L Friedkin site in Texas, and conclude that the shared technological attributes could be related to Pre-Clovis ancestral position and not to an early Clovis assemblage.

Different approaches have been proposed to take into account projectile point change in time and space, as has been shown by the work of Buchanan and Collard (2007, 2008) and Cardillo and Charlin (2014) among others. Buchanan and Collard (2007, 2008) used cladistics to contrast hypothesis analyzing the evolution of the first hunting technologies of North America in relation to mobility and space occupation patterns during the Paleo-Indian period. This allowed them to evaluate, among other themes, hypothesis related to the ancestry of early North American technologies and to discuss patterns of change and design diversification (Buchanan and Collard, 2007, 2008; O'Brien et al., 2014). Also, O'Brien et al. (2014) by means of cladistic analysis of early Paleoindian fluted projectile point models biogeographical processes of innovation and relates them to cultural transmission processes related to design change. Other authors like Prentiss et al. (2014) use cladistics and network methods to explore cultural macro evolutionary patterns (under branching *vs*. blending/borrowing processes) in the Pacific Northwest (see also Jordan and Shennan, 2009). In a wider spatiotemporal context, Lycett (2007) uses phylogenetic derived hypothesis to discus the lack of Mode 3 Levallois technologies in East Asia. In a similar manner, Okumura and Araujo (2014) made a significant contribution to projectile point evolutionary analyses combining geometric morphometrics and evolutionary simulation to study the evolution of stemmed projectile point in southern Brazil between Pleistocene-Holocene transition and Early/Middle Holocene. Authors observe low trait variation over time as much as expected related to random processes, and relate them with cultural conservatism and stability. In Argentina, phylogenetic methods have been used to show cultural continuity in the Middle Holocene of the *puna*, as well as for modeling the pattern of design change of projectile points in relation to functional restrictions (Cardillo, 2009). Likewise, Cardillo and Charlin (2010, 2014) use geometric morphometric and phylogenetic comparative methods to model the pattern of regional change in projectile points during the Middle and Late Holocene. The evidence here based of phylogenetic reconstruction suggests that spatial distance was a structuring pattern in technological diversification.

The cladogram trees with the greatest consistency can be used in comparative analysis. Comparative methods rely on the existence of a tree that reconstructs the emergence of functional elements or adaptations that cannot be directly estimated through phylogenetic methods, while taking into account the lack of independence between elements related by common descent (Nunn, 2011; Pagel, 1999). In this article, we are interested in studying changes in the technical systems of projectile points as shown on the cladogram tree.

5.2. Steps of the analysis

5.2.1. Selection of characters and construction of phylogenetic tree

The first step in phylogenetic reconstruction is the selection of characters. There are two types of characters, ones that have continuous values, and others that have discrete ones. Morphological characters tend to be discrete, while metric characters tend to be continuous. Depending on the method employed these characters can be discretized or transformed so that they adjust themselves to the preconditions of the method employed (Felsenstein, 2004). Through the use the maximum parsimony there has been the development of methods to analyze metric characters as such (Goloboff et al., 2006) combining these with discrete characters within the same matrix. These authors have shown, through their use of comparative data and simulations, that the combination of continuous metric and discrete data enhances the performance of the search algorithms and reduces the number of most parsimonious trees. On the other hand, the discretization of elements brings into play a subjective facet into equation, a subjectivity that is not necessarily methodologically justified (Goloboff et al., 2006; see also Shott, 2011). However, a number of possible change steps in continuous characters are related to scale; in this situation standardization or transformation prevents characters with extremely large numbers from having more influence than those with smaller values, as shown by Donato (2011). In cases such as this attempts to lessen the difference in the run of variables and the variation in the metric characters led to a transformation of the metric data into a logarithm. By these means we preserved the difference in magnitude in the transition between states of the character.

The discrete elements (including the blade angle) were changed into multistate characters (see Fig. 2). In deciding the character states (selection of the morphological elements) we employed a common typological procedure that described the projectile points, in this case we used the guidelines established by Aschero (1975, 1983). The final result was that we generated a matrix with seven discrete and five metric characters (see NPtree archive in Supplementary material).

In general, until one defines the root of the phylogenetic tree, it will have no particular orientation. The root of the tree is frequently an older ancestor; this ancestor will determine the direction of evolutionary change. This hypothetical ancestor establishes that all the changes observed along the tree are derived and constitute evolutionary novelties along this baseline, while all the reversions entail homoplasy. Moreover, ancestor definition is critical to recognize character convergence that leads to analogous structures due to functional or structural design constraints. In this case, we realized that a lithic lanceolate point belonged to an external group (see Figs. 3 and 4). We based this interpretation on the fact that this class was the earliest manifestation of this point-type given that it was uncovered in a context dated to *ca.* 6000 ^{14}C years BP. This early date for lanceolate points with a triangular blade was repeated across various contexts along the North Patagonian zone (Crivello Montero et al., 1993; Fernández, 1988-1990; Gómez Otero et al., 2011); therefore chronologically it was a morphological type that could be assigned to the Middle Holocene. Furthermore, our decision was also based on ontogenetic or developmental criteria, given that points with triangular blade or lanceolate forms are, in design terms, simpler forms that penduculate ones, these latter points require additional steps of manufacture. By establishing this class as an external group, the elements that involved an added complexity of the design, such as the shoulder or the stem, would have to appear as novelties derived from a simpler, primary design, this is congruent with one of the principles of parsimony.

Other similar morphologies to classes 7, 8 and 9 have been uncovered in contexts belonging to the final Late Holocene *ca.* 1000 ^{14}C years BP. On the other hand, stemmed forms seemed to be earlier, from around 2000 ^{14}C years BP. Large triangular and lanceolate projectile points were more widely distributed chronologically although they seem to be more common to the Middle Holocene, this might be a

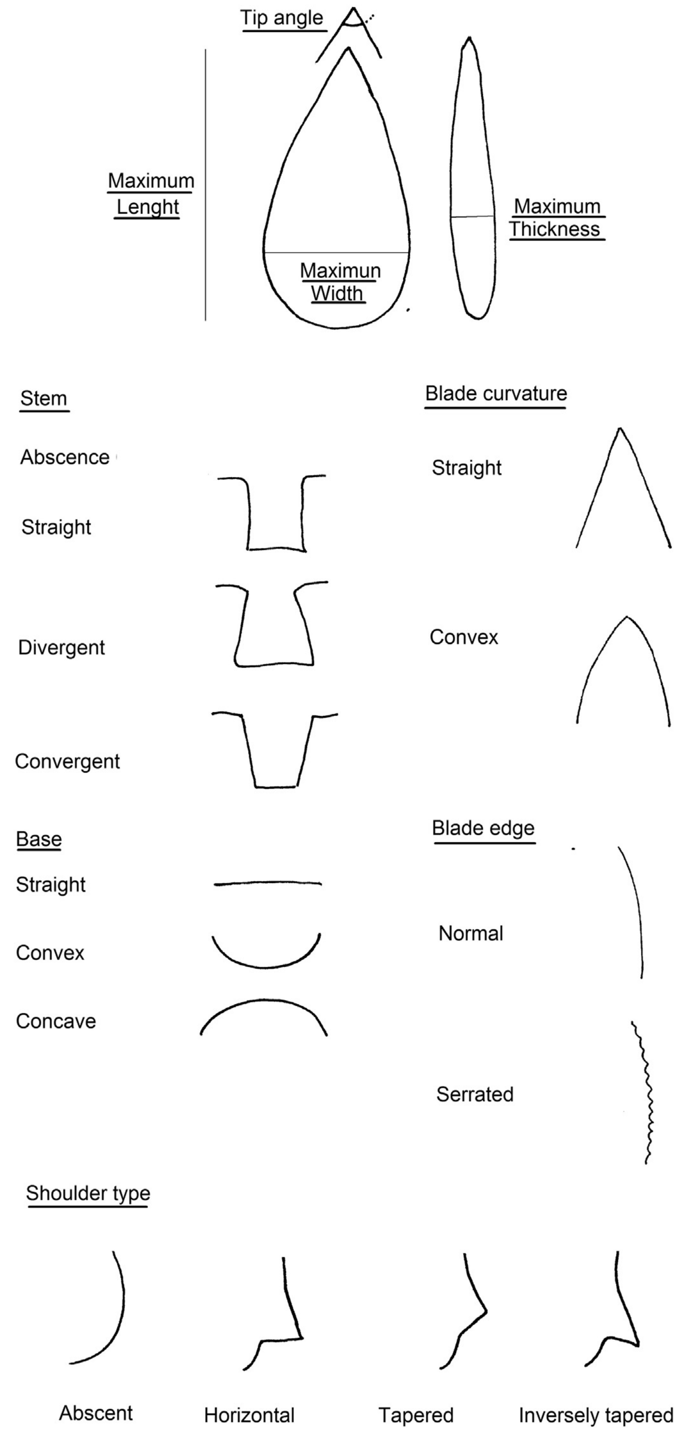

Fig. 2. Characters and character states used in this study.

consequence of function (see below). The phylogenetic estimation was undertaken using the TNT program (Goloboff, 2003), on the basis of the TBR (*tree bisection and reconnection*) algorithm, 10000 tree searches were conducted, with up to 1000 trees being retained each time. This process was repeated numerous times to prove the consistency of the results, resulting consistently in a single parsimonious tree. After this process we estimated retention and consistency indexes for this tree, after which we used the tree for comparative analysis.

Synapomorphy and evolutionary novelties were mapped on the tree with the object of studying the most relevant evolutionary transitions, focusing on the ones that determined the most important clades (Fig. 4). The tree's consistency (phylogenetic signal) was measured

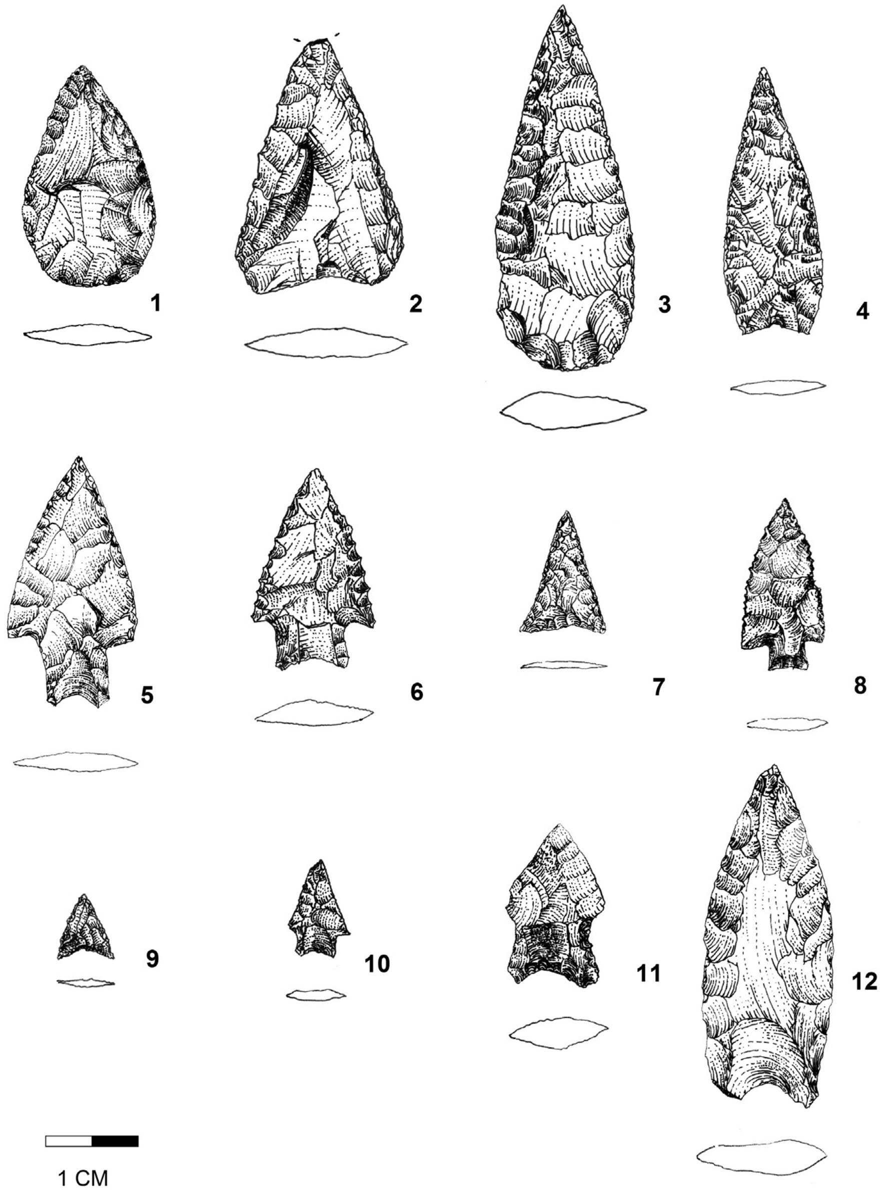

Fig. 3. Classes used in the phylogenetic analysis. Class number 4 corresponds to the external group.

using consistency and retention indexes; these measured the number of synapomorphs across the whole tree (Felsenstein, 2004) in variations between 0 and 1. The CI (Consistency Index) approaches one when there are no reversions or parallelisms in the characters, while the retention index takes into consideration the number of changes in each character in relation to the number of steps detected. In the absence of homoplasy, this index is 1. Collard et al. (2006), Muscio (2010) and Nunn et al. (2010) among others, studied the ability of these indexes to detect levels of homoplasy especially in respect to processes of horizontal transmission or borrowing of information between analytical units.

The resulting tree according to parsimonious estimation did not have branch length; rather all the branches were equally long without a measurable distance between nodes. Nevertheless, the length of the branch is required since this provides for an estimate of contrast and for the use of comparative methods, given that the distance between nodes contains information pertaining to time and the process of diversification linked to the total length of the tree from its roots to its terminal classes.

A procedure that can be employed to transform the length of the branches, involves the assignment of dates to the individual nodes to one less than the number of leaves that occur in each node. Branch lengths are then calculated as the difference between the height of the lower and that of the upper nodes. This is known as the Grafen method (Grafen, 1989). This method, based essentially on topology, was the preferred option given that with the other methods it was necessary to assume a particular diversification model. The total length of the tree thus obtained gave a value of 1, which also indicated the value of the node. This transformation permitted, among other matters, the direct comparison with trees of a similar length, whether actual or generated using simulations, so as to estimate diversification parameters.

5.2.2. Adjustment of evolutionary models for technical systems, metric variables and phylogenetic signal estimation

The most parsimonious trees can be used to map the evolution of elements so that the evolutionary history of these can be reconstructed. For example, Mace et al. (2003) used the method of maximum likelihood to estimate the pattern of change of the matrilineal system based on the constructed phylogeny of African languages. The maximum likelihood method allows us to calculate the evolutionary probability of different

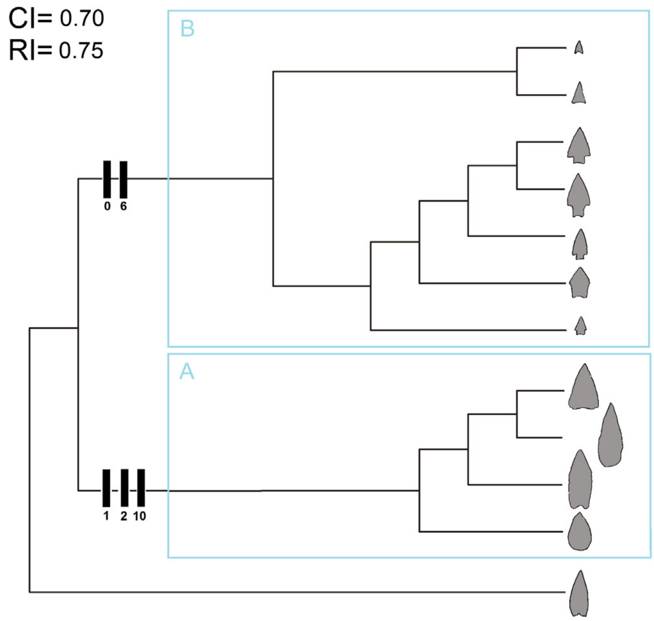

Fig. 4. Most parsimonious tree obtained. CI: Consistency Index. RI: Retention Index. Characters: 0: maximum lenght; 1: maximum width; 2: maximum thickness; 6: blade from; 10: blade angle.

characters on the basis of the phylogenetic tree and on the elements observed in the characters of the classes (Felsenstein, 1973, 1985; Schluter et al., 1997). The aim is to obtain the maximum fit (probability) in the estimate of ancestral characters, given the characteristics observed in the classes used for the phylogenetic reconstruction. In this case, given that our interest lies in studying technological evolution, we generated three different models on the basis of the assignment of studied classes to different technical systems using their metric and morphological elements. The values of likelihood for the different nodes can be understood as a measure of the uncertainty in the technical systems evolutionary patterns.

The first two models were based on weight to determine the type of technical system. Hughes (1998) proposed the first model in which weight was used to differentiate between a bow and arrow and a spear-thrower; if the lithic point weighed less than 11 g then it was an arrow, and if between 11 and 70 g then it was identified as a spearhead. Fenenga (1953) developed the second model that considered projectile points of less than 3.19 g to be from a bow and arrow arrangement and those between 3.19 and 20 g to be from a spear-thrower. Within Fenenga's range a large number of the projectile points would be categorized as arrows (Fig. 6). The third model combined the Hughes (1998) model with criteria that consider symmetry, section form and the regularity of workmanship to determine aerodynamics, as employed by Ratto (1994, 2003). This third model allowed the identification of a third technical system, one that selected for artifacts with low aerodynamics that included low-range handheld throwing weapons, or non-throwing weapons such as lances and hafted knives.

When calculating the evolutionary trajectory of each technical system, each was dealt with as a different character state, and coded accordingly. In this manner, in models 1 and 2 the spear-throwers where designated as 0 and the arrows as 1. In model C, spear-throwers were designated as 0, handheld or thrown weapons as 1 and arrows as 2 (see System.txt file in Supplementary materials).

Given that the method of maximum likelihood as applied to phylogeny is based on evolutionary models of the transition between characters (Felsenstein, 1985; Pagel, 1999), the most simple possible model covering the transition of characters is the one that assumes that each ancestor divides into two at each moment of diversification (appearance of new classes), and that this probability maintains itself constant for all classes. Given that this method takes into account the length of the branches, the transitions between states of character – in this case technical systems – are more likely in the longer branches. By these means the probability that a technical system will emerge from another is both constant and symmetrical throughout the whole tree, this does not hold necessarily true, but we assumed this as it provided us with the simplest evolutionary scenario possible (Felsenstein, 1973, 1985).

Two possible estimates of the different characters are obtainable from the nodes, marginal or joint estimates. In the first case, the likelihood values are estimated using only the information from the classes and their branches. On the other hand, in the joint estimation all the available information is used to estimate each node, the results are checked twice over taking into consideration the values assigned to the different nodes in the first instance, in this way the adjustment achieved is more global (see Felsenstein, 2004).

The probability of one or another technical system for each node was compared by pairs and was presented as a proportion of likelihood for each node from the root to the tips (Fig. 6). Likewise, we established a global likelihood value that measured the relative adjustment in each of the three evolutionary models generated by the phylogenetic trees. Although the value of likelihood cannot be directly utilized in terms of statistical significance, the adjustment of each model can be compared in pairs via a contrasting of hypothesis using the Chi^2 test with one degree of freedom for each one (see Paradis, 2006). In a complementary manner we estimated the Akaike information index as a measure of relative complexity in each model in relation to the adjustment parameters while using the maximum likelihood method (see Script1 in Supplementary materials).

Equally, we estimated the phylogenetic signal of the variables studied; this included the three technical system evolutionary models and the metric variables not used directly in the estimation of phylogeny, such as the shape of the projectile points (see Appendix file) and the weight in grams (Shape.txt and Weight.txt files and Script2 in Supplementary materials). The procedure undertaken followed the same logic as the evolution of discrete characters adjustment model mentioned previously.

However, it is possible that although classes have been constructed taking into account only classes with minimal signs of resharpening, is possible that this process affects the characters studied, as well as weight measure. This could be problematic, because the latter could carry information related to descent and life history. Therefore, a next step will be to control the effect of reactivation on weight, using the residuals generated by means of regression between weight and different measures of reactivation.

In this case, we compared the value of maximum likelihood obtained in the adjustment of each of the evolutionary models of the technical systems with that generated by the adjustment of the same with a tree without phylogenetic structure (Pagel, 1999), in effect a tree with branches of a length close to 0 (0.01). In this model, the elements evolved independently of phylogeny (model of independence); this was done by changing an original tree under the parameters specified above and adjusting each model by the maximum likelihood using the ER model; the values of likelihood of the original tree and under the independence model were compared using the procedure described above. In all cases, the signification value was $\alpha = 0.05$.

The adjustment of continuous characters, such as weight or shape, was estimated using the Blomberg K (Blomberg and Garland, 2002; Blomberg et al., 2003). This model assumes the constant variance models from the roots to the terminal classes (Browian model). That is, the expectation for a trait that evolved by Brownian motion along a particular topology with defined branch lengths. A null variance model under this principle is obtained through a simulation of the states of character along the tree and its comparison with the observed value for the classes. The K statistic of phylogenetic signal as well as the p-value is based on the variance of phylogenetically independent contrasts relative to tip shuffling randomization, where high K values

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(more than 1) suggest significance (Blomberg and Garland, 2002; Blomberg et al., 2003) because grouping of closely related taxonomic units is bigger than expected under the null model. On the contrary a value of 1 is expected under the Brownian model and small K values (lower than 1) suggest low phylogenetic signal (Blomberg et al., 2003). The application of this randomization statistic to simulated datasets, suggests that the test has low power in small datasets (less than twenty classes) so the pylogenetic signal could't be detected in these cases even when it is present (Blomberg et al., 2003). However K parameter remains a reliable indicator even though the p-value can not be determined at the desired power level (Garland et al., 2005). The phylogenetic signal is a measure of the correlation between the pattern of observed diversification for the continuous character given the model tree used, and the tree observed under the stochastic model generated via randomization of 1.000 permutations. The stochastic model was generated using the R program (R Development Core Team, 2009) where the phylogenetic signal was calculated for the weight of the artifacts and an estimate of maximum likelihood was undertaken (see Scripts1 and 2 in Supplementary materials for further details).

6. Results

The phylogenetic analysis on the matrix of discrete and continuous characters yielded a single most parsimonious tree with a length of 34 steps. The tree had a consistency index of $RI = 0.72$ and a retention of $CI = 0.76$. This suggested a consistent phylogenetic signal among the data analyzed, given that 76% of the observed changes were derived and only 14% were homoplasic (Fig. 4)

The analysis revealed the existence of two large clades (Fig. 4), the first (A) composed of large and medium sized lanceolate projectile points (Fig. 4A) and a second (B) composed largely of stemmed designs and, in smaller quantities, small triangular points, these formed a separate group at the base of this clade (Fig. 4, B). The group of stemmed points is made up of all classes of this type analyzed, with those of the smallest size at the base of the clade and the larger ones in the more derivative positions (Fig. 4, B). This clade possesses larger size classes given that two of the synapomorphs that support it are width and maximum thickness, which tend to be greater for these classes. Likewise, the blade angle tends to be relatively higher than in the clade of stemmed types (Fig. 4 A). The presence of the stem was an important derived synapomorphy or novelty that separated both clades, together with the length, width and thickness of the points. The base of clade B was supported by two synapomorphies: the form of the blade and the maximum length, given that there was a relative diminution of size within the whole group. The more triangular types (equilateral) tended to appear on ancestral nodes, while the more elongated ones appeared as derivatives, such as character 6. This, in part, was in accordance with the external group selected for analysis.

Another interesting aspect that was observed on the tree was that size in general tended to show a change that was more or less directional along the whole tree. Using the topography of the tree we undertook a correlation of the distances between each class and the weight used, using a Blomberg (see above) evolutionary model of continuous elements, this showed a significant correlation between the pattern of diversification and weight ($K = 1.22$, $p = 0.011$). This meant that the closest phylogenetic classes tended to have similar weight and that the general tendency was a reduction in weight that might well have been linked to the weapon technical systems. This will be considered below.

6.1. Shape

The correlation between morphological space and phylogeny supports the hypothesis of morphological diversification for the chronological block under study. This was linked to the slow displacement towards new design spaces in relation to the first component (PCA1 $K = 0.83$, $p = 0.003$, PCA2 $K = 0.35$, $p = 0.27$). As seen in Fig. 5, which represents the phylogeny within the space of coordinates of the first two PCA's, we observed that the most derived classes, together with the most recent nodes, tended to displace themselves from the root to the left of the morphological space (Fig. 5). In clade A (Fig. 4 A), they were distributed to the right of the morphological space, presenting more elongated forms. The space to the left was occupied by clade B classes (Fig. 4 B) these being shapes that tended towards being equilateral and less long. In part this might be linked to design restrictions and the changing imperative of performance throughout the evolutionary history of the artifacts. This performance imperative might also have had an impact on the correlation observed between phylogeny and the weight of the projectile points.

Fig. 5 also shows the temporal assignment of the different projectile points; in general these corresponded with their distribution along the length of the first axis of the PCA coordinates. This suggested that there was a temporal tendency to the projectile points that involved morphological and metric change as well as the displacement towards new design spaces.

6.2. The evolution of technical systems

We used the three hypothetical models of technical systems to address the relationship between the design evolution of projectile points and the technical systems. These models considered the weight of the points (models 1 and 2), while model 3 analyzed weights and relative aerodynamic. The three models were adjusted using the process of maximum likelihood and evaluated on the basis of their relative adjustment (Fig. 6).

Fig. 6 reconstructs the transitional states of the different technical systems according to the three models employed. An important point to consider was that the three models proposed very different states for the root of the tree, as well as for the percentage of likelihood for some of the ancestral nodes that separated the clades. In the first model (Fig. 6, 1), the nodes are deeper, near to the root and had an adjustment of 50% when estimating the ancestor in respect to two possible technologies: spear-thrower or bow and arrow. This suggested that that under this model it was equally probable that the ancestor belonged to either of the two technical systems. Likewise, the clade which grouped the stemmed points had a homoplastic signal linked to the transition between one technical system and the other, given that we could observe reversions between the bow and arrow and the spear-thrower.

In model 2 (Fig. 6, 2), we defined two large groups, with the bow and arrow probably being the ancestor with the deepest nodes, close to 70%, or more, likelihood for this technical system. It is highly probable that this was related to the fact that the majority of the classes analyzed and the external group belonged to this category. The spear-thrower projectile points appeared here as a small group close to the base of the tree.

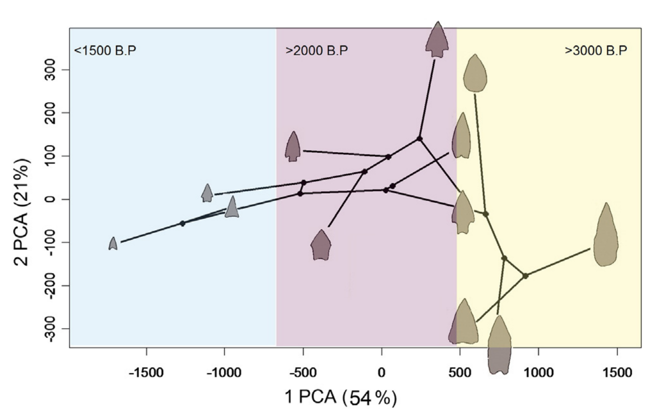

Fig. 5. First two components of the PCA obtained from the form coordinates generated through the elliptic Fourier analysis.

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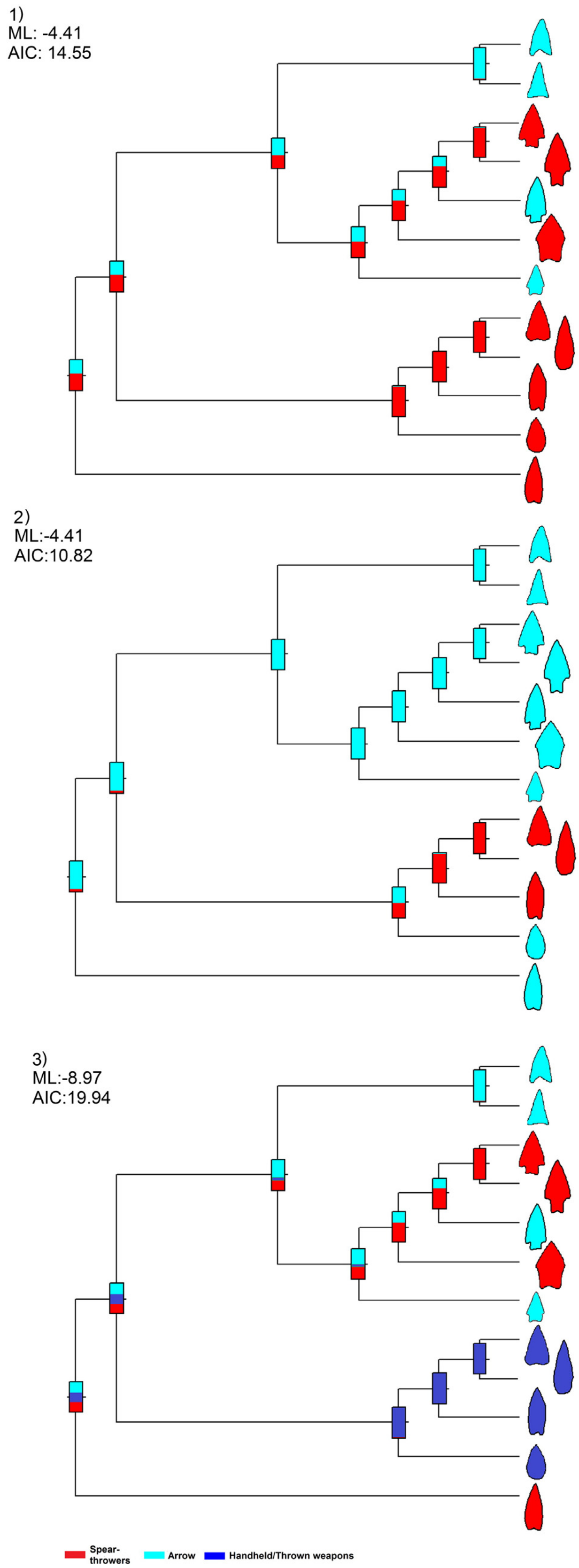

Fig. 6. Independent contrasts of the three technical systems evolutionary models. ML: maximum likelihood value for each model. AIC: Akaike information criterion for each model.

Model 3 (Fig. 6, 3) showed the existence of at least three weapons systems, including spear-throwers, bow and arrow, and handheld or thrown weapons all with similar likelihood percentages – *ca*. 30% for each type – as the ancestors of the two greatest clades. Within the handheld weapons clade there was great consistency in the prediction of the states for all the nodes, with values approaching 100%. The clade encompassing the stemmed points possessed a similar probability value for the bow and arrow, and spear-thrower technical systems. There was less resolution in respects to ancestors in these two classes, achieving close to 50% in both technical systems, this could be a consequence of shifting between different types of points within this clade.

Therefore, it would seem that models 1 and 2 adjusted themselves towards phylogeny. As can be seen in Fig. 6 the values of maximum likelihood and Akaike information criterion, pointed to the first two models being the most parsimonious given that they had the least number of changes in the tree. Meanwhile, model 3 proposed the transition between three different technical systems. Finally, the Chi^2 test on maximum likelihood values for each model showed that the first two models were marginally different when compared against each other, with both of them being significantly different to model 3 ($A = B\ p = 0.05$, $A = C\ p = 0.02$, $B = C\ p = 0.002$).

To conclude, we estimated the phylogenetic signal of the three models by comparing them to the adjustment derived from a tree without phylogenetic signal. The likelihood of model 1 (Fig. 6, 1) was −7.56, model 2 (Fig. 6, 2) −6.72 and for model 3 (Fig. 6, 3) −12.08. The comparison between the likelihood using the Chi^2 test with one degree of freedom suggested that the value of the first model was the same as the adjustment tree without phylogenetic signal $p = 0.10$, while model 2 with ($p = 0.03$) and model 3 with ($p = 0.01$) (Fig. 6, 2 y 3) did show significant variations. This was due to model 1 showing evidence for reversions in its technical systems as we indicated above, with the percentage of likelihood remaining relatively constant throughout the whole tree. Models 2 and 3 on the other hand had less uncertainty relating to the assignment of the nodes to one or another technical system. Even if model 3 also has reversions, it did have significant consistency in assigning one of the clades to handheld and short distance thrown weapons systems. On the basis of the trees generated, models 2 and 3 were the most likely. Although these two models (2 and 3) were statistically different, they were equally probable and could be considered complementary. Model 2 was a simpler and more parsimonious model of technical system evolution, while model 3 was less parsimonious but more informative.

7. Discussion

The results suggested that it was possible to generate good models of the evolution of projectile points and associated technical systems throughout this time period. A possible interpretation of the results in relation to the adjustment of the three technical change models is that designs potentially apt for use in different technical systems (particularly bow and arrow) might have been available before the actual appearance of these technologies. That is to say that a given technical system might not have required substantial design modification of the projectile points, at least not at the beginning.

Concomitantly, there is a tendency towards less weight and greater morphological diversification along the whole of the phylogeny, and not only in the more recent nodes. In particular this is important in the case of the bow and arrow, given that the archaeological evidence from northern Patagonia and southeast Buenos Aires province, suggests that this technology might only have been available towards the end of the Late Holocene (Prates, 2008). If certain technical elements that define arrowheads were present in other classes belonging to different technical systems, this might then have reduced the costs of invention or adoption of this technology, given that substantial technical innovations would not have been necessary in their initial creation.

This is particularly relevant considering the context and implications of the invention and dispersal of the bow and arrow among hunter-gatherer populations. For example Bettinger and Eerkens (1999) suggest that the adoption of this technology was via mechanisms of information transmission that limited the variation that would be produced through trail and error; this can be observed in the degree of design standardization found, at least in certain contexts. Within this framework in a context of risk, the dispersion of the bow and arrow limited variation linked to experimentation. While in contexts of less risk, more variation in design would have been possible (Bettinger and Eerkens, 1999). Furthermore, the existence of a phylogenetic signal for the technical systems, as well as the high retention of synapomorphs in the characters of the classes, implies that the elements that defined the technical systems developed throughout the Middle and Late Holocene within the studied lineages.

In respect to evolutionary models of the technical systems adjusted to phylogeny, we saw that model 1 had low probability, related to high uncertainty in deciding the ancestors for the terminal classes. This is due, in part, to the reversion of technical systems in relation to the nodes, especially within clade B. Model 2, on the other hand, has better adjustment given that all clade B is assigned to the same spear-thrower technical system. Model 3, that assumed the existence of three technical systems based on the size and relative symmetry of the edges as well as that of the section (including weight), also showed a good adjustment, although this model had the same uncertainty *vis-à-vis* deciding the ancestor for the nodes of clade B. We believe that this uncertainty could be an indicator of the high degree of similarity between the bow and arrow and spear-thrower technical systems, at least in respect to some classes, that could be classified in one way or another depending on what weight range was adopted.

Taking into account the pattern of morphological and metric continuity observed, as well as the change tendency linked to the most recent nodes, we believe that this might be related to transitional forms between different technical systems. It is possible that these designs might have been used in one or another technical system as an experimentation phase of pre-existing morphologies in an effort to achieve higher performance.

This could be related to the gradual adoption of the bow and arrow in the area, through a process of trail and error until it displaced other technologies such as handheld weapons and spear-throwers. This is supported by changes seen in the diet, in which during the Late Holocene larger quantities of land-based resources were consumed. Hunting with low aerodynamic and ranged weapons or weapons or hunting of a communal type – such as the use of corralling – such as that implied by handheld or thrown weapons, might have been the mechanism used to kill sea lions on beaches or rocky coastal ridges, given that a weapon with a high degree of thrust was necessary to harm these animals. The bow and arrow would have been more effective in the hunting of *guanacos* and other small mammals during the recent Late Holocene given that they are long-range weapons, adapted to killing highly mobile species. This last point is supported by the isotopic signal and the archaeofaunal record (Favier Dubois et al., 2009) of the different periods studied here.

This gradual innovation within the weapon systems used along the coast of San Matías Gulf serves to highlight low risk contexts among the groups in this area. Risk contexts would not have allowed such a practice given that it would imply having an efficient hunting system across the board *versus* suboptimal solutions. Other factors, aside from subsistence changes that could be associated to this change during the final Late Holocene (see Fig. 5), for instance the adoption of the bow and arrow, might well be associated to competition and the rise in socio-political complexity between human groups, as suggested by VanPool and O'Brien (2013). The evidence from northern Patagonia is interesting in this respect, given that it suggests a possible increase in competition between populations leading to interpersonal violence for the final Late Holocene (Gordon and Boscio, 2012).

In respect of the resulting phylogeny, a widening of the sample and the incorporation of materials from areas near to the study area allowed us to generate trees with a greater number of classes, which in turn allowed us to reconstruct the evolutionary history of these technologies at a larger scale. This enabled us, among other matters, to consider the role of the environment and space at the same time as deepening our temporal analysis. The increase in the number of classes analyzed allowed us to also undertake detailed morphometric analysis.

Finally, our study suggested that cladistic analysis on metric characters and projectile point morphology has great potential in the reconstruction of the evolutionary history of technology in the study area. Likewise, the identification of a clear phylogenetic signal in the projectile points supports what other phylogenetic studies have stated about this type of artifact (for example, Cardillo, 2002; Cardillo and Charlin, 2010; Charlin et al., 2014) and encourages the spread of this type of research within Patagonian archaeology.

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Appendix A. Morphological analysis

For the purposes of the morphological analysis each piece was photographed in grayscale with a digital camera mounted on a tripod at a focal distance of 30 mm and at 5-megapixel resolutions. The lens was kept perpendicular to the object so as to avoid distortion of the image. Each piece was orientated in accordance with its morphological axis, with the point upward and perpendicular to the framing of the image.

Afterwards each image was processed using the Tpsdig 2 program (Rohlf, 2006). Through the use of digitization, 100 regularly spaced points were located and these were set from the point in an anticlockwise direction. These points were registered as *landmarks* and later used for the elliptical Fourier analysis using the Past 2.17c program (Hammer et al., 2001).

The elliptical Fourier analysis (Kuhl and Giardina, 1982) is based on a coordinate count (X and Y) onto which are adjusted a series of harmonically related ellipses (harmonics) that incrementally increase their adjustment around the original contour. If more harmonics are used, then the adjustment to the contour function that is to be described will be better, so that the sum total of these represents an approximation of the form, as shown by Kuhl and Giardina (1982). The first harmonics describe the contour of the whole form (low order harmonics), while the last ones (high order harmonics) describe more localized aspects of the contour.

The optimum number of harmonics that should be used depends on the complexity of the contour and there are a number of methods to establish the minimum number of necessary parameters; in this case we employed a purely visual criterion and carried out 15 harmonics. Nevertheless, given that the harmonics are subject to a later PCA, we did not observe relative changes in the variance percentage described, or in the location of the points in the coordinate space if we had employed more coefficients. This is because in general the last harmonics trace only small amplitude variations and provide little information. Likewise, as the aim of this analysis was to capture the form of the artifacts, each contour was standardized by size, position and rotation used in the first ellipse, so that the information left was essential on shape. This procedure also serves to minimize error during digitalization, linked to position or to angle differences, during image capture. The procedure is standard and is comparable to Procrustes superposition usually employed in geometric morphometry (see Rohlf, 1990).

After the process of standardization, the first coefficient of the first harmonic was transformed into a constant and left aside. These harmonics could later be used in multivariate analysis. Multivariate analysis (in this case principal component analysis or PCA) reduced dimensionality and allowed us to extract general tendencies in shape variation or could be used for later analysis, such as here where it formed the body of a PCA based on a variance–covariance matrix. Using this method we retained the first two components, which entailed 54% and 21% of the respective variance. These two components were used as descriptors of the general contour form and to represent in a continual manner morphological change on the phylogeny, as well as testing the hypothesis of a phylogenetic signal in the form (see Supplementary material).

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jasrep.2014.11.005.

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