Metal Use and Production among Coastal Societies of the Atacama Desert

ARTICLE *in* ARCHAEOMETRY · AUGUST 2014

Impact Factor: 1.33 · DOI: 10.1111/arcm.12119 archaeometry

Archaeometry **57**, 4 (2015) 687–703 doi: 10.1111/arcm.12119

METAL USE AND PRODUCTION AMONG COASTAL SOCIETIES OF THE ATACAMA DESERT*

V. FIGUEROA†

Instituto de Investigaciones Arqueológicas y Museo R.P. Gustavo Le Paige, Universidad Católica del Norte, San Pedro de Atacama, Chile

D. SALAZAR

Departamento de Antropología, Universidad de Chile, Santiago, Ñuñoa, Chile

B. MILLE

Centre de Recherche et de Restauration des Musées de France (C2RMF), Paris, France

and G. MANRÍQUEZ

Facultad de Medicina, Universidad de Chile, Santiago, Chile

*In this paper, we focus on the study of metal objects associated with populations living on the northern coast of Chile in the Late Intermediate and Late periods (*c. AD *1000–1550). Our contribution is based on morphometric and physico-chemical (ICP–AES, PIXE and metallographic sections) analyses of the quintessential coastal metal object: the fish-hook. This study is part of a broader investigation that seeks to understand the organization of mining – metallurgical production systems and their relation with coastal economies and ways of life. We distinguish at least two different traditions, one associated with the Western Valleys area and one with the Arid Desert Coast. These findings expand our understanding of Andean metal making. Furthermore, the presence of a metallurgical tradition within the highly mobile hunter–gatherers of the most arid coast of South America is of great anthropological significance.*

KEYWORDS: METALLURGY, NORTHERN CHILE, LATE INTERMEDIATE PERIOD, LATE PERIOD, HUNTER–GATHERER–FISHERS, FISH-HOOK

INTRODUCTION

The Atacama Desert coast in northern Chile consists of a narrow coastal terrace flanked on the east by the Coastal Range and on the west by the Pacific Ocean (Fig. 1). While it is one of the most arid places on the planet, the marine ecosystem offers an abundant biomass, with its rich variety of fish, molluscs, marine mammals, birds and seaweed (Bittmann 1986; Llagostera 1992; Santoro *et al*. 2005).

Human occupation of this territory began approximately 12 000 years ago and has continued to the present, although the region's indigenous groups disappeared in the 19th century. Around 8000 cal BP, local societies achieved an efficient maritime adaptation, which included a varied

*Received 29 November 2013; accepted 28 March 2014
†Corresponding author: email vfigueroa@ucn.cl

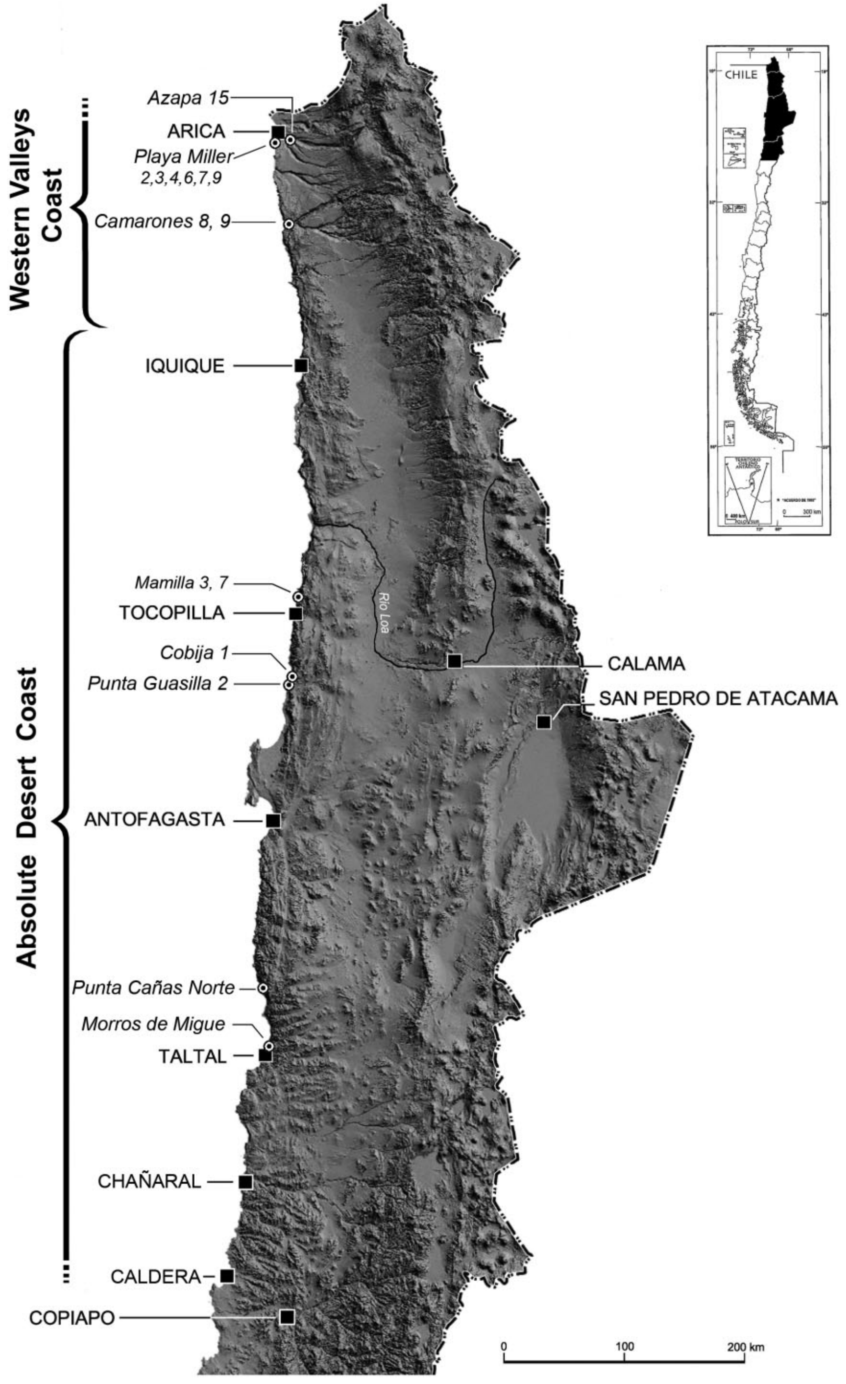

Figure 1 *A map of northern Chile, showing the location of the main sites studied.*

technology well suited for exploiting the coastal resources upon which they subsisted. It consisted primarily of simple and compound fish-hooks made from seashell (*Choromytilus chorus*), bone or cactus needles; stone, bone and/or shell fishing weights; bone *chopes* (shellfish openers); stone sharpeners; bone and wood harpoons, with stone heads and cactus needle or bone barbs; bone or stone fishing lures; and plant fibre fishing bags, known locally as *chinguillos*. While the raw materials and morphologies of some of these artefacts changed somewhat between 8000 and 1000 BP, this was a conservative technology, very efficient for capturing and processing coastal resources and well adapted to the needs of these mobile hunter–gatherer–fisher groups.

Nevertheless, around 1000 BP the traditional raw materials used to manufacture some of the artefacts of this technology were suddenly replaced by copper and bronze (Salazar *et al*. 2010a,b; Figueroa 2012) (Fig. 2). While the shape of the fish-hooks did not change, from the Late Intermediate Period (*c*. AD 950–1200) they were increasingly made of metal, and the same trend was observed for shell openers, harpoon barbs, the heads of short harpoons, octopus hooks and hooks on fishing lures as well. Since then, and up to the arrival of the Incas and then the Europeans, coastal indigenous groups maintained their traditional fishing, hunting and gathering economy and at the same time developed strategies for accessing, producing and exchanging metal, which they used to manufacture traditional tools in copper and bronze. This development is of great anthropological importance, as it implies a significant technological shift for coastal societies, and especially for those highly mobile hunter–gatherer groups who inhabited the southern Atacama coast (22–25°S). Moreover, the adoption of metal had ample social and economic implications, associated with new provisioning systems and exchange alliances, as well as prestige connotations for those who could access and produce metal artefacts. Despite the importance of this phenomenon, metallurgy on the coast of northern Chile is a virtually unexplored topic; until we began our research, no investigations had focused on the reasons for this technological shift, its specific socio-economic implications or the particular features of this unique metalworking tradition.

In this paper, we will address these questions through the results of our archaeological and archaeometallurgical study of copper and bronze fish-hooks from the northern coast of Chile.

BACKGROUND: THE ECOSYSTEM AND SOCIETIES OF THE LATE INTERMEDIATE PERIOD

While some palaeoclimatic records of the southern coast of Peru and the highlands of northern Chile suggest that during the Pleistocene–Holocene transition the climate was more humid than it is at present (Betancourt *et al*. 2000; Moreno *et al*. 2009; Mächtle *et al*. 2010), since 8000 cal BP the territory has been extremely arid, with a few humid pulses (Santoro *et al*. 2005; Grosjean *et al*. 2007).

The aridity of the Atacama Desert contrasts with the rich faunal resources found on its coast. This is especially true for the intertidal and sublittoral zones, which are populated by a huge quantity of marine mammals, fish, molluscs and crustaceans, as well as permanent and migratory bird species (Bittmann 1986; Llagostera 1992). Owing to this abundance, the desert coast has been and continues to be a constant, highly reliable source of resources for the Andean societies of northern Chile, which throughout history has enabled the survival of local groups and led to complex systems for exchanging marine products with other ecological zones. The Atacama Desert coast can be separated into two different coastal environments: the Western Valleys (WV) and the Absolute Desert Coast (ADC). The Western Valleys or northern Atacama Desert coast (18–21°S) has reliable, year-round freshwater sources that owe their existence to run-offs from the Andes Mountains that flow in rivers from the foothills to the Pacific coast. There are five rivers

Figure 2 *Coastal metal objects: 1, harpoon (Azapa 15 (Arica), Inca); 2, short harpoon (Playa Miller 4 (Arica), Inca); 3, chope (shell opener) (Taltal, LIP–Inca); 4, fishing lure (Playa Miller 4 (Arica), Inca); 5, octopus hook (Playa Miller 3 (Arica), LIP); 6, fish-hook with cotton line (Playa Miller 3 and Playa Miller 9 (Arica), LIP); 7.1, ADC fish-hooks (a, Punta Guasilla; b, Antofagasta, LIP–Inca); 7.2, WV fish-hooks (a–c, Playa Miller 4 (Inca), d–f, Playa Miller 6 (Inca)). Abbreviations: LIP, Late Intermediate Period; Inca, Inca Period; LIP–Inca, Late Intermediate Period and Inca Period. Sources: 1, 2, 4, 5, 6 and 7.2, Museo Universidad de Tarapacá – San Miguel de Azapa (Arica); 3, Museo Augusto Capdeville (Taltal); 7.1, Schloss Gottorf (Schleswig).*

(the Lluta, Azapa, Vitor, Camarones and Camiña), all of which sustain agricultural landscapes and also are important circulation areas. On the other hand, the Absolute Desert Coast or southern Atacama Desert coast (22–25°S) is characterized by present-day hyper-arid conditions and the absence of permanent sources of fresh water, except for small springs dispersed along the coastal terrace and in the Cordillera de la Costa range. During the Late Intermediate Period (*c*. AD 1000–1450), the WV were populated by agricultural-maritime societies characterized by a growing social complexity. In the lower and middle reaches of the valleys that cut through the desert, there was significant agricultural production, with complex terracing and irrigation systems. In contrast, the absence of transversal valleys in the ADC and the vastness of the desert itself hindered agricultural development on the southern Atacama coast, thus encouraging the continuity of a way of life based on coastal hunting and gathering, and a high residential mobility of groups up and down the coast. These bands were less socially complex than their counterparts further north (Salazar *et al*. 2010c). Despite these social and economic differences, both areas show permanent interaction and circulation of goods throughout prehistory. Both areas also simultaneously adopted a metal technology for their artefacts, even though significant differences can be identified, as we will show below.

METAL IN THE SOCIETIES OF THE ATACAMA DESERT COAST

To date, archaeometallurgical studies in northern Chile have focused primarily on the oases of the Atacama region. Because the coast was *a priori* discounted as a region of metallurgical interest and fewer metal objects were recorded here, the place has developed a reputation as having 'few metal objects', with existing finds deemed to have come mainly from outside the area (Fig. S1).

However, and contrary to previous assumptions on this issue, Late Intermediate Period and Late Period residential sites and cemeteries on the northern coast of Chile tend to contain a large number of metal objects. We have identified this tendency both on the Western Valleys—at the sites Camarones 8 and 9, Playa Miller 2, 3, 4, 6, 7 and 9, and Azapa 15—as well as on the Absolute Desert Coast, in the cemeteries of Mamilla, Punta Guasilla, Cobija, Antofagasta, Paposo, Taltal, Chañaral and Caldera (Fig. 1).

In recent years, our interdisciplinary research has focused on characterizing and understanding this coastal metallurgy and its social and economic implications (Salazar *et al*. 2010a,b; Figueroa 2012). This paper systematizes and complements our findings to date, focusing on the fish-hooks, one of the most frequently represented types of artefact in the different Atacama Desert coast contexts studied, and one of the most important instruments for coastal economies and subsistence.

MATERIAL AND METHODS

We conducted a systematic study of all metal artefacts recovered from coastal sites in northern Chile held in the collections of several museums in Chile and abroad. Evidence of metal and waste from metal production was also gathered in our pedestrian surveys and archaeological excavations in the coastal sites of Camarones (WV), Tocopilla, Cobija and Taltal (ADC) (Fig. 1).

Up to now, we have studied and recorded more than 700 metal objects coming from different coastal sites between Arica and Caldera (Table S1). The vast majority correspond to artefacts associated with maritime activities, while the rest are status goods such as bells, pendants, rings, bracelets, weapons and other items. The most significant group of artefacts is associated with the extraction of marine resources, and among these, fish-hooks are the most common of all technological categories ($N = 254$).

We assumed that through an analysis of the variability in morphology, in technology and in elemental composition of the fish-hooks, as well as their geographical distribution, we would be able to determine whether one or more traditions existed for the production of metal on the coast of northern Chile. We also deemed that these results, coupled with a study of mechanical properties of the artefacts (microstructure, hardness), would enable us to determine their effectiveness as fishing implements. It is important to keep in mind that one of the primary objectives for the craftsmen who manufactured these fish-hooks was to obtain material that was adequate for fishing; that is, a metal that could withstand a considerable degree of stress.

We recorded all metal objects available using a standardized form. We then selected 134 complete hooks (53%) for a morphometric study. We used traditional morphometric analysis (measuring the distance between landmarks to determine differences in size, length, opening and internal angle) and geometric morphometric standard procedures (using 2D matrices of landmark coordinates to analyse the pattern of shape and size differences).

Furthermore, 60 fish-hooks were subjected to physico-chemical analysis in order to determine the metal elemental composition. Thirty-eight analyses were performed by particle-induced X-ray emission (PIXE) using the AGLAE ion-beam facility located at the C2RMF in Paris (beam directly extracted in air, beam spot diameter 50 μm, surface scanning 0.5×0.5 or 1×1 mm). Spectra were acquired from 2 SiLi X-ray detectors and processed using the Gupix software to obtain quantitative results (details of the operating conditions can be found in Calligaro *et al*. 1998; Dran *et al*. 2000). This set-up has been adapted for copper alloys by the use of a 30-μm cobalt filter on the high-energy detector to attenuate the copper signal. The detection limits achieved a range of between 0.01 and 0.1%, depending on the element. The analyses were validated using Certified Reference Materials analyses (some copper alloys containing high levels of tin, zinc, lead, arsenic and antimony, some unalloyed coppers with impurities at 200–1000 ppm to control trace element composition). A good accuracy was achieved, since the relative deviation from certified values is around 10% for most elements. Twenty-two analyses were performed by inductively coupled plasma – atomic emission spectrometry (ICP–AES), using a PerkinElmer model Optima 7400V Cyclonic, in the Laboratorio de Geoquímica of the Departamento de Geología, Universidad de Chile. The analyses were carried out following the protocol published by Bourgarit and Mille (2003). Lastly, seven pieces were chosen for metallographic examination. A section was taken from each object and the corresponding samples were then mounted in resin blocks and polished with diamond pastes up to 0.25 μm, according to Scott (1991). The sections were observed under the optical microscope (OM) and the scanning electron microscope (SEM). During SEM examination, micro-analyses were performed by energy-dispersive X-ray spectroscopy (EDX). The samples were also subjected to Vickers microhardness tests in order to assess the degree of hardness (HV) of the pre-Hispanic fish-hooks, and to determine whether the hardness values were similar for the same object and among different objects.

RESULTS

Morphometric analyses

In order to describe the pattern of shape variation of metal fish-hooks from archaeological sites located along a 900-km stretch of the northern Chilean coast between Arica and Caldera, traditional and geometric morphometric analyses were carried out. The raw data for these processes included inter-landmark linear distances and landmark coordinate matrices, respectively (Table S2 and Fig. S2).

After comparing the total length and the aperture of the fish-hooks from diachronic cemeteries, we found no statistically significant differences (Late Intermediate versus Late periods—total length, $F = 0.6957$, $gl = 1, 101$, $p = 0.406$; gap length, $F = 1.438$, $gl = 1, 101$, $p = 0.233$: Late Intermediate and Late versus Inca periods—total length, $F = 2.1556$, $gl = 2, 131$, $p = 0.119$; gap length, $F = 0.8316$, $gl = 2, 131$, $p = 0.438$). However, after comparing the geographical origin

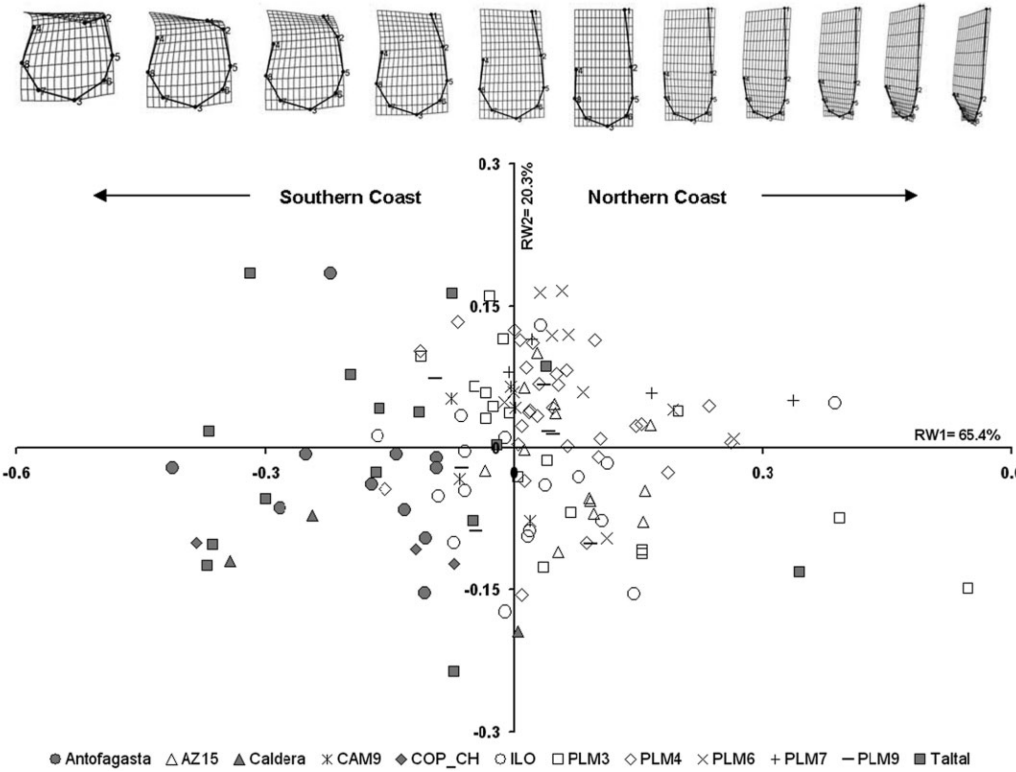

Figure 3 *The pattern of fish-hook shape variation from archaeological sites on the northern coast (Arica, AZ15, PLM3, PLM4, PLM6, PLM7, PLM9 and CAM9) and the southern coast (Antofagasta, Taltal, Caldera, Copiapó-Chañaral/COP_CH/). The grids indicate the direction of change in the shape along the axis of greatest variation, according to the geographical location of the sites of origin: (i) straight fish-hooks, with shanks, in the north and (ii) curved fish-hooks without shanks, in the south (x-axis, relative warp 1; y-axis, relative warp 2). After applying standard geometric morphometrics methods, the relative warp axes correspond to the principal components of the standard PCA carried out in the raw data matrices of the fish-hooks.*

(WV versus ADC) of the same sample, the fish-hooks belonging to the northern archaeological sites (WV) showed a statistically significant longer shank than the fish-hooks from southern sites (ADC) ($F = 4.21$, $gl = 1, 132$, $p = 0.04$) (Table S3).

The typological analysis showed that the variation in the shape and size of these fish-hooks is primarily related to differences in the shape of the bend and in the shank length, respectively. This morphoscopic observation was corroborated after applying a standard geometric morphometric analysis, showing the presence of two clearly differentiated groups: (i) straight fish-hooks with long shanks belonging to the WV sites; and (ii) curved fish-hooks with a short or absent shank, which are only present at ADC sites (Fig. 3).

Archaeometallurgical study of pre-Hispanic fish-hooks

Chemical composition Table S4 sums up the results of the elemental composition analysis. One notable finding is the generalized use of bronze (i.e., a copper-based alloy with the intentional addition of tin) to manufacture fish-hooks, especially in the Western Valleys (Fig. 4). This alloy

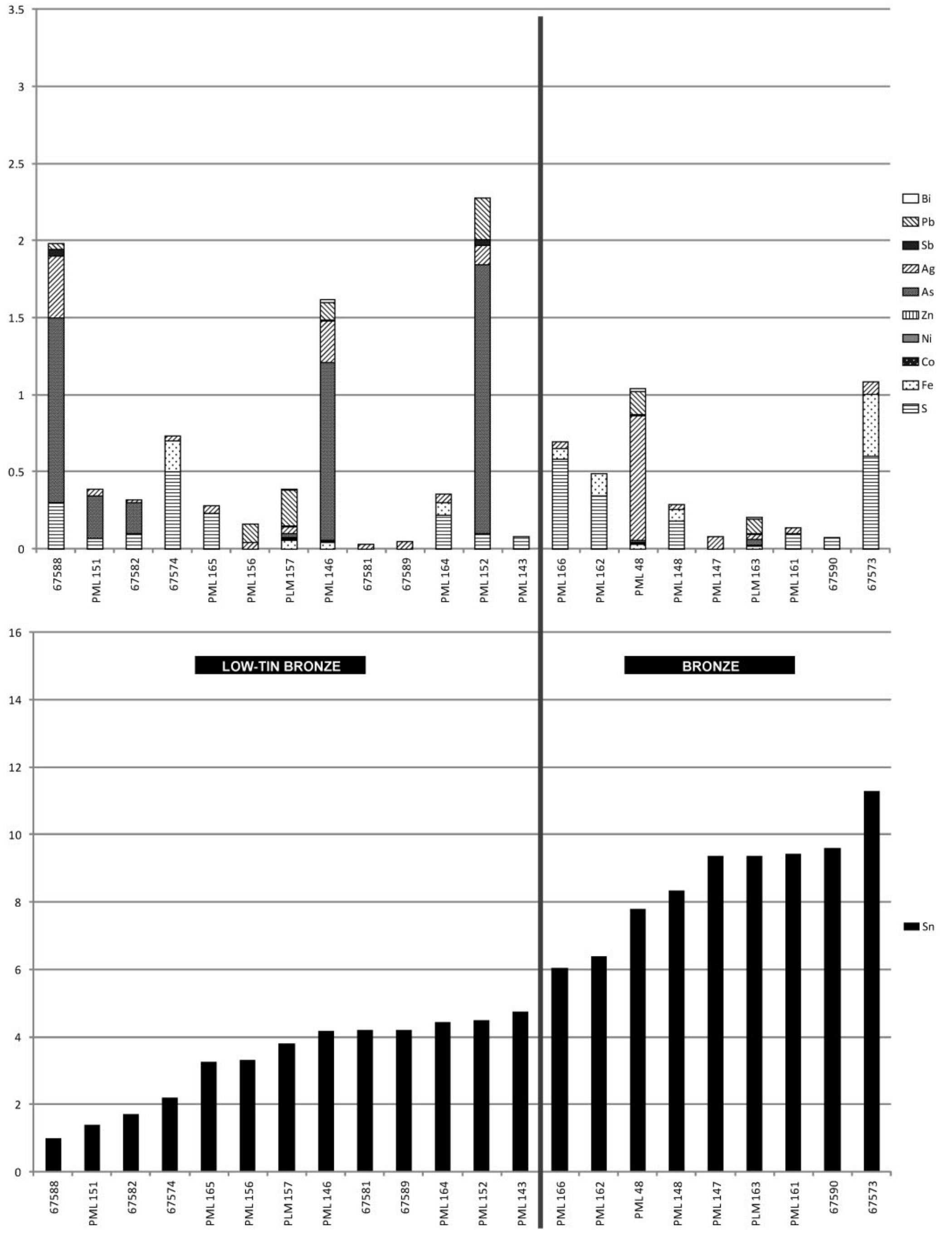

Figure 4 *The elemental composition (PIXE/ICP–AES) of fish-hooks from the Western Valleys: lower graph, the tin content; upper graph, the associated impurities pattern. Horizontal axis, fish-hooks by label; vertical axes, the elemental content in wt%.*

is also used for other kinds of coastal objects, such as harpoons, short harpoons, squid hooks and others. This result is even more interesting if we consider that the nearest sources of tin are found on the highlands of the Bolivian Altiplano and north-west Argentina, more than 250 km away from the coast (Keutscha and de Brodtkorb 2008).

The tin content of the fish-hooks varies widely, and as such, the 'mean value' of the alloyed element is of no significance. In one group of artefacts, the content is distributed almost evenly between 0.5 and 5% tin, while a second group displays higher tin contents (5–12%). The results of the composition analysis show unambiguously that all of the fish-hooks from the WV sites are made in bronze. On the contrary, along the ADC, similar bronze fish-hooks are recorded, but the use of unalloyed copper is also documented (Fig. 5). Looking at the alloy composition, therefore, at least two distinct metallurgical traditions seem to exist along the northern Chilean coast, with the dividing line being somewhere between Antofagasta and Tocopilla. These results correspond nicely with the groups segregated by the morphometric analyses.

It is thus possible to propose that during the Late Intermediate Period, there were independent economies of metal in the two different areas of the coast, the WV and the ADC. Current data indicate that these areas were producing most of their own metal fish-hooks. For example, the Camarones Terraza Sur site in the WV shows evidence of *in situ* metal production, including a significant amount of mould fragments with internal vitrification, waste from metallurgical activities and finished metal artefacts. Further north, at the Altos de Rosario site, additional metallurgical evidence has been reported, including slag, metallurgical waste and metal objects (Schiappacasse and Niemeyer 1989; Figueroa 2012). Analyses performed on the Camarones moulds show clear evidence for the production of bronze objects, and are thus coherent with our studies on the finished objects (Figueroa 2012). On the other hand, in the ADC, archaeological evidence of *in situ* metal production includes stratigraphic and superficial associations between copper ores, copper prills, slag, small ingots and metal fragments in diverse sites such as Mamilla, Cobija 1 Norte, Guasilla, Punta Tames and Caleta del Fierro (Salazar *et al*. 2010a). Significantly, all copper prills so far analysed have shown unalloyed copper (Salazar *et al*. 2010a).

While in the WV the fish-hooks show elemental composition and morphological uniformity indicating a single economy of metal, in the ADC a number of traditions seem to coexist, suggesting a more complex scenario. Therefore, even though there is good evidence to support a local production of unalloyed copper in the ADC, it still remains unclear whether the bronze fish-hooks found in this area were also manufactured locally or imported from the WV or elsewhere through independent distribution networks. Some of the impurities found in the bronzes of the ADC are similar to those in WV bronze, suggesting that they may have been imported from the northern valleys, whereas some specific impurities patterns were also noticed that could indicate yet another origin for these objects.

Metallographic examination and manufacturing process We observe a high degree of mechanical deformation of the fish-hooks. A first indicator of the major plastic deformation is the elongated shape of some non-metallic inclusions present in the metal. These inclusions in several objects correspond to copper sulphides, grey on a bright field or black on a dark field under the optical microscope. They are distributed across the entire surface area observed. These inclusions are oriented in the direction of the shank, which is also the direction of deformation of the metal. The degree of deformation of the metal is above 90%, estimated by calculating the aspect ratio of the elongated sulphide inclusions (i.e., the ratio of the length to the diameter of the cross-section). Some objects also contain inclusions of tin oxide (identified by SEM–EDX as SnO_2);

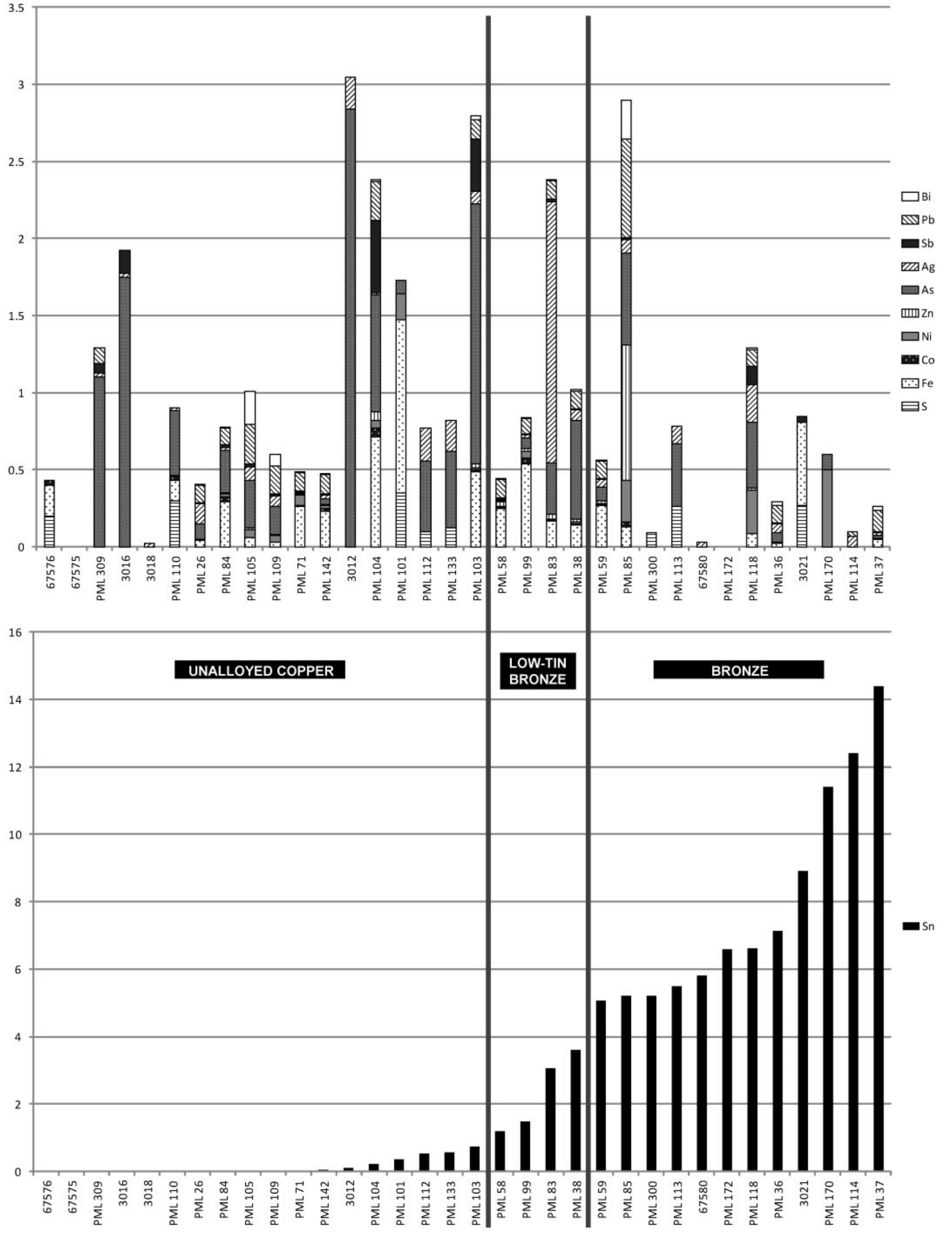

Figure 5 *The elemental composition (PIXE/ICP–AES) of fish-hooks from the Absolute Desert Coast: lower graph, the tin content; upper graph, the associated impurities pattern. Horizontal axis, fish-hooks by label; vertical axes, elemental content in wt%.*

these are usually present as alignments of small angular inclusions that correspond to the fragments of larger inclusions that were broken up through deformation of the metal.

A second indicator of the major deformation undergone by the metal is a fibred structure encountered in most of the microstructures of the bronze fish-hooks. These bands indicate segregation, or local variations of the tin content within the metallic matrix (Fig. S4). Like the inclusions, the segregated metal undergoes compression when hammered, which ultimately produces a crystallographic anisotropy characterized by elongated bands of alloy, the tin concentration of which varies.

Bronze fish-hooks from the WV included intermittent stages of annealing, since annealing twins have been systematically observed, leading to small polygonal grains (equivalent diameter 10–25 μm). The only copper fish-hook from the ADC that was examined showed very different features, with a metal let in its final stage as intensively hardened by hammering, and where the use of annealing cannot be proved.

Lastly, the high degree of mechanical deformation—which indicates that the material has undergone intense stages of hammering—has been established by measuring the microhardness of the metal, using a Vickers microhardness testing instrument. We then compared our data with the experimental results achieved by H. Lechtman on copper alloys (Lechtman 1996). When copper is in an annealed, recrystallized state, it is soft and very ductile and its hardness only reaches 50 HV. But plastic deformation will cause structural hardening of the metal, which profoundly changes its mechanical properties. It is, for example, possible to increase the hardness of a metal by a factor of two or more when subjected to intense plastic deformation (e.g., H. Lechtman achieved 125 HV by cold hammering unalloyed copper to 50% of the reduction thickness; see Lechtman 1996, fig. 20). The results of the Vickers microhardness tests on the metallographic sections of the fish-hooks are presented in Figure S3. The values are quite variable among the objects from the WV region, but generally fall between 125 and 175–200 HV. Some samples fall outside of this range and are extremely hard, such as fish-hook number 67590. The only unalloyed copper fish-hook analysed (number 67576) displays evidence of very strong hammering and, most importantly, was not reheated to avoid its softening by recrystallization after being subjected to that intense stage of plastic deformation, which enabled the hook to achieve a hardness of 125 HV, equal to that of some of the bronze hooks. The results display high rates of hardness across all samples, regardless of their tin content. Thus, the low tin content is compensated for by the intense work hardening of the metal, which considerably increases its hardness.

These data prove that the manufacture of metal fish-hooks on the northern coast was aimed at producing objects suitable for fishing, which meant that they had to be able to withstand considerable tensile stress. Hardness was achieved both by adding tin to produce tin bronze and by intense hammering when unalloyed copper or low-tin bronze was preferred.

DISCUSSION

During the Late Intermediate Period, both the agricultural-maritime populations of the Western Valleys and the hunter–gatherers of the Absolute Desert Coast adopted metallurgy as a technology to manufacture artefacts (especially fish-hooks) for extracting and processing coastal resources.

Bronze would probably have been chosen for its exceptional mechanical properties (high malleability, which allows items to be manufactured by hammering; good mechanical resistance to tensile stress; and good toughness, so that it is therefore not too brittle). Meanwhile, the manufacturing of fish-hooks from unalloyed copper or low-tin bronzes also produced pieces that were hard enough, as a result of the intense hammering.

The adoption of metallurgy is probably related to the fact that metals are better adapted to fishing activities, as they exhibit greater mechanical strength and durability than other raw materials (bone, seashell or cactus). Compositional analysis and microhardness tests reveal that the pre-Hispanic metallurgists of the Atacama Desert coast found diverse ways to achieve in the fish-hooks the mechanical properties adequate for their day-to-day activity—the capture of ichthyological resources.

In that sense, the development of a local metallurgy beginning during the Late Intermediate Period allowed them to increase the production of coastal resources (dried and/or smoked fish) for exchange with inland populations (and later as a form of tribute to the Inca state). We believe this to be true since the coastal populations have used imported metal ornaments since at least 500 BC, and therefore the sudden replacement of local raw materials with metal produced locally and/or traded from other areas seems to be the outcome of a new social-economic condition, like the one mentioned above.

While the development of metallurgy and the use of these metal instruments were linked to the production of surplus marine resources, the instruments themselves became prestige goods among the pre-Hispanic fishing groups. In fact, metal artefacts associated with fishing, hunting and gathering were included in the tombs of males and were a major element of the marine ergology (Horta 2010).

It is possible that in some areas metal implements did not completely replace the cactus needle fish-hooks and compound hooks made of bone (Muñoz 1989). This hypothesis must be tested with further studies and a more precise look at chronologies and contexts; but it would support our claim that metal fish-hooks performed complementary social and symbolic functions: if only some fishermen had access to metal fish-hooks, then significant social differences would have arisen, based on both the opportunity to generate more coastal surpluses for exchange with highland populations and the symbolic importance and prestige that would accrue to those who manufactured and used such artefacts.

Apart from the economic, social and symbolic implications arising from the adoption of copper and bronze fish-hooks, their manufacture on the coast testifies to the fact that these groups had knowledge of metal technology. One indication of this specialized knowledge is that they worked with alloys that contained raw materials sourced more than 250 km away, while another is the control they displayed in the hammering and heating processes that produced very hard implements with or without the addition of tin.

Our results further indicate that the Atacama Desert coast had at least two different metallurgical traditions associated with the knowledge needed to produce metal artefacts. The first is that of the Western Valleys and the second that of the Absolute Desert coast. The WV metallurgical tradition was characterized by an exclusive bronze metallurgy, while the ADC technology was characterized by copper and bronze metallurgy. However, in the ADC only unalloyed copper seems to have been locally produced (see below), while bronze artefacts seem to have been imported through independent economic systems.

Shape differences found in the hooks from WV and the ADC could eventually be related to different fishing strategies employed by prehistoric populations of the southern and northern Atacama Desert coast and/or different fish captured. On the coast of California, for example, variability in hook types has been interpreted from such a functional perspective (Tartaglia 1976). Further research is needed on the mechanical properties of the fish-hooks, as well as archaeological experiments aimed at reconstructing local fishing technologies before we can adequately assess the functional and structural properties of these fish-hooks. Nevertheless, the fact that similar fish species exist in both the WV and ADC, and that the same taxa have been reported for Late Intermediate Period habitational sites (Bravo 1985; Schiappacasse and Niemeyer 1989; Salazar *et al*. 2010b), suggests the possibility that the variation in the shape of these artefacts has more cultural than functional significance, as has been also suggested for other coastal areas worldwide, including California (Salls 1989). Furthermore, this interpretation seems more coherent with the remaining data presented in this paper, especially the fact that there are also differences in the elemental composition of the fish-hooks from the WV and the ADC.

The complex exchange systems occurring during the Late Intermediate Period, coupled with these groups' own mobility, undoubtedly led to a certain flexibility and a geographical blurring of these two metallurgical traditions, especially in WV hooks that were adopted by ADC fishers. In fact, a more in-depth look at our results allows us to propose that these two metal-making traditions were integrated in at least four different 'economies of metal' among the Late Intermediate societies of the northern Chilean coast; in other words, four systems of production–distribution and use of these artefacts.

The first is for the Western Valleys region, where metal production appears to have been concentrated mainly at the mouth of the Camarones canyon. Records of this site suggest that it was a regionally significant metalworking place that produced artefacts for most of the WV coast. It is also possible that some metal ingots were produced at this site and then distributed along the coast. Both the artefacts and the ingots were made of bronze, and therefore would have required a supply of tin from the Bolivian Altiplano or north-west Argentina, more than 250 km away. The tin could have arrived as ore (cassiterite, for example) or in the form of metal ingots, but bronze was undoubtedly worked at the coastal site: the first possibility would involve the local smelting of the ore, whereas the second one would only imply melting, which constitutes a huge technological difference. This topic needs further research, and is currently being studied by the authors (Figueroa 2012).

For the Absolute Desert Coast region, the situation is different and at the same time more complex. Here, we can distinguish at least three distinct economies of metal during the Late Intermediate Period. The first corresponds to metal fishing technologies (fish-hooks, barbs, short harpoons and curved bars) made of bronze that came ready-made from the Western Valleys, most likely produced at the Terraza Sur site in Camarones. A subvariant of this model could be that not only finished objects but also bronze ingots were imported into the Absolute Desert Coast region, where they were melted down locally to produce the artefacts. The possibility that bronze prills were also circulating along with the ingots cannot be ruled out. At the same time as bronze objects, ingots and/or prills from the WV were beginning to appear on the ADC, the area was witnessing a second economy of metal, characterized by its own brand of metallurgical activity—short-lived efforts to smelt high-grade copper ore. These activities were performed directly on a hearth, without the use of elaborated smelting structures. They were limited events, perhaps even single attempts to produce metal, carried out by local populations at their base camps and in work camps, and leaving scant stratigraphic evidence (Salazar *et al*. 2010d). Such evidence includes the association of copper ore, metal prills and, in some cases, small pieces of slag. Additionally, at the site of Punta Cañas Norte (Taltal area), dated to the Late Intermediate Period, we have found preforms, the compositional analyses of which indicate that the material used was high-purity unalloyed copper, similar to the composition of some of the prills and artefacts found in the ADC. The fact that there are no known bronze preforms or bronze metal waste in the production sites of the ADC reinforces our hypothesis that only unalloyed copper was locally produced, while bronze artefacts were imported.

Considering that all known metallurgical sites in the ADC are short-lived events, it is likely that this local metal-making tradition would have consisted of small-scale production by these groups for their own internal consumption, and did not imply distribution of metal objects or preforms.

It is possible to identify a third metal economy that appears to support an early hypothesis of Latcham (1910), who suggested that the coastal fishermen could recast objects from the highlands into fishing implements for their own use. Although not yet strictly documented in the case of fish-hooks, a harpoon barb (PML98) from Caldera seems to support this hypothesis.

The analytical results of PML98 actually show an atypical elemental composition (copper with high concentrations of arsenic and nickel). The ternary Cu–As–Ni alloy is very infrequent in the Andes and generally associated with the Tiwanaku interaction sphere (Lechtman 1997, 2003a,b), including San Pedro de Atacama in the highlands of northern Chile (Lechtman and Macfarlane 2005; Maldonado *et al*. 2010; Salazar *et al*. 2011) (Table S4). The analysis of lead isotopes that was conducted by Lechtman and Macfarlane (2005) indicates that this alloy was made with material from Altiplano deposits and therefore that the objects were manufactured in the Bolivian highlands or in north-west Argentina. Its presence in fishing artefacts from the Absolute Desert Coast could therefore be explained as the result of local groups melting down used and/or broken objects manufactured in the highlands and manufacturing fishing implements by hammering and reheating the material—or else local groups could have re-hammered directly a newly produced imported artefact from the highlands, in order to shape it into the quintessential coastal metal object: the fish-hook.

This kind of metallurgy would appear to have been practised very infrequently on the Absolute Desert Coast; indeed, there is only one case with a sound chronological context—during the first half of the Late Intermediate Period, perhaps before the large-scale appearance of bronze from Camarones and the development of local metal-making using high-grade unalloyed copper.

Lastly, our compositional data also suggest that there may even be a fourth metal economy in the ADC, since our compositional data have demonstrated that some of the circular fish-hooks characteristic of the ADC and not present on the WV were worked in bronze. It is interesting to consider the possibility that the higher variability in metal economies in the ADC as compared to the WV was related to the different social organization of the two systems. Whereas we have more hierarchical agro-maritime societies in the WV that produced metal on a bigger scale, in the ADC highly mobile hunter–gatherer–fisher groups moved along the coast producing metal artefacts on a small scale, and thus were in need of importing artefacts in order to completely replace traditional raw materials with copper and/or bronze artefacts.

CONCLUSIONS

The ocean is a source of resources of considerable value, and this has been well known for the different human groups who have inhabited the coast since at least 12 000 cal BP. To take the most efficient advantage of this resource-rich space, very specific adaptations were required. The history of coastal marine techniques is fundamental for understanding the transformations that occurred in the equipment used by these hunter–gatherer–fishers. Even though metal industries appear around AD 1000, only four centuries before the arrival of the Spanish on the continent, this is part of a long technical continuum that began with the first human occupations of the northern coast of Chile.

The data presented in this paper suggest that around the beginning of the Late Intermediate Period, metals began to be used to manufacture traditional fishing and marine gathering artefacts, as their greater strength allowed local groups to maximize the energetic return and even to increase the size of the fish and other prey caught. Access to metal would have been achieved through a variety of economic mechanisms and strategies, including local production, trade and the melting down of objects manufactured in the highlands.

Together, the evidence confirms that metalworking took place on both the Western Valleys coast and the Absolute Desert Coast, with region-specific typological, compositional and technological differences, pointing to the presence of complex systems of consumption, use and distribution within the maritime ergologies of the coastal populations.

Moreover, it is important to mention the frequent occurrence of marine ergology in different burial contexts dated to the initial post-Contact period (16th century) in the Lluta, Azapa, Arica and Camarones valleys. Nevertheless, the grave goods recovered from such sites reveal a new form of coastal metallurgy that was centred on iron. Reshaped into fish-hooks, harpoon barbs and long-handled 'octopus' hooks, iron nails were of primary importance among the post-Hispanic coastal societies.

Most previous research on Andean metallurgy has highlighted its symbolic nature, emphasizing the 'non-utilitarian' aspects of the objects found—ornaments, power emblems and ceremonial artefacts. The symbolic dimension of Andean metallurgy resided in certain contexts as a *sine qua non* condition for the emergence of metallurgical production systems. Nevertheless, there are some exceptions in Andean metallurgy, in which the metal was adopted in other contexts and in accordance with other logics. Such was the case with the fishers, hunters and gatherers of the northern Chilean coast, among whom metallurgical production was focused on everyday items, linked to the subsistence activities of coastal societies, and developed within simple hunting–gathering societies with no social differentiation, as was the case in the ADC.

ACKNOWLEDGEMENTS

This paper was financed under Fondecyt Project 1080666, Proyecto de Investigación Asociativa Conicyt Anillo ACT-96 and ECOS-Conicyt C11H02. *[Correction added on 31 March 2015, after first online publication: In the preceding sentence, 'ECOS-Conicyt C11H02' has been added.]*. We would like to acknowledge Fondecyt 1100951, DI SOC 20-02 and Fondart grant 2008-60390. We would especially like to thank the Museo Universidad de Tarapacá – San Miguel de Azapa, Museo Augusto Capdeville de Taltal, Museo Rodulfo Philippi (Chañaral), Museo de Caldera, Museo Regional de Copiapó, Museo Nacional de Historia Natural de Santiago, Museo de Artes Visuales (Santiago), Museo Chiribaya (Ilo), Stiftung Schleswig-Holsteinische Landesmuseen Schloss Gottorf (Germany) and musée du quai Branly (France). Finally, we are grateful to the reviewers for their invaluable comments on this paper.

REFERENCES

Betancourt, J. L., Latorre, C., Rech, J. A., Quade, J., and Rylander, K. A., 2000, A 22,000-year record of monsoonal precipitation from northern Chile's Atacama Desert, *Science*, **289**, 1542–6.

Bittmann, B., 1986, Recursos naturales renovables de la costa del norte de Chile: modos de obtención y usos, in *Etnografía e historia del mundo Andino: continuidad y cambio* (ed. S. Masuda), 269–334, Tokyo University, Tokyo.

Bourgarit, D., and Mille, B., 2003, The elemental analysis of ancient copper-based artefacts by inductively-coupled-plasma atomic-emission spectrometry: an optimized methodology reveals some secrets of the Vix crater, *Measurement Science and Technology*, **14**, 1538; doi:10.1088/0957-0233/14/9/306

Bravo, L., 1985, Una proyección representativa de los recursos ictiotróficos del yacimiento Abtao-5 y sus implicancias socio-económicas, in *Actas del IX Congreso Nacional de Arqueología Chilena*, 95–104, La Serena.

Calligaro, T., Dran, J. C., Hamon, H., Moignard, B., and Salomon, J., 1998, An external milli-beam for archaeometric applications on the AGLAE IBA facility of the Louvre museum, *Nuclear Instruments and Methods in Physics Research B*, **136–8**, 339–43.

Dran, J.-C., Calligaro, T., and Salomon, J., 2000, Particle-induced X-ray emission, in *Modern analytical methods in art and archaeology* (eds. E. Ciliberto and G. Spoto), 135–66, John Wiley & Sons, Chichester.

Figueroa, V., 2012, *La métallurgie préhispanique des pêcheurs du littoral Pacifique dans le Chili Septentrional*, Unpublished Ph.D. dissertation, Université de Paris 1 Panthéon-Sorbonne.

Grosjean, M., Santoro, C., Thompson, L. G., Núñez, L., and Standen, V., 2007, Mid-Holocene climate and culture change in South Central Andes, in *Climate change and cultural dynamics: a global perspective on mid-Holocene transitions* (eds. D. G. Anderson, K. A. Maasch and D. H. Sandweiss), 51–115, Academic Press, San Diego.

Horta, H., 2010, *El señorío Arica y los reinos altiplánicos: complementariedad ecológica y multietnicidad durante los siglos pre-conquista en el norte de Chile (1000–1540 d.C.)*, Unpublished Ph.D. dissertation, Universidad de Chile.

Keutscha, F., and de Brodtkorb, M. K., 2008, Metalliferous paragenesis of the San Jose mine Oruro, Bolivia, *Journal of South American Earth Sciences*, **25**, 485–91.

Latcham, R., 1910, *Los changos de las costas de Chile*, Imprenta Cervantes, Santiago.

Lechtman, H., 1996, Arsenic bronze: dirty copper or chosen alloy? A view from the Americas, *Journal of Field Archaeology*, **23**, 477–514.

Lechtman, H., 1997, El bronce arsenical y el Horizonte Medio, in *Arqueología, antropología e historia en los Andes: homenaje a María Rostworowski* (eds. R. Varón and J. Flores), 153–86, Instituto de Estudios Peruanos, Lima.

Lechtman, H., 2003a, Middle Horizon bronze: centers and outliers, in *Patterns and process* (ed. L. van Zelst), 248–68, Smithsonian Center for Materials Research and Education, Washington, DC.

Lechtman, H., 2003b, Tiwanaku Period (Middle Horizon) bronze metallurgy in the Lake Titicaca Basin, in *Tiwanaku and its hinterland*, vol. 2 (ed. A. Kolata), 404–34, Smithsonian Institution Press, Washington, DC.

Lechtman, H., and Macfarlane, A., 2005, Metalurgia del bronce en los Andes Sur Centrales: Tiwanaku y San Pedro de Atacama, *Estudios Atacameños*, **30**, 7–27.

Llagostera, A., 1992, Early occupations and the emergence of fishermen on the Pacific Coast of South America, *Andean Past*, **3**, 87–109.

Mächtle, B., Unkel, I., Eitel, B., Kromer, B., and Schiegl, S., 2010, Molluscs as evidence for a Late Pleistocene and Early Holocene humid period in the southern coastal desert of Peru (14.5°S), *Quaternary Research*, **73**, 39–47.

Maldonado, B., Rehren, Th., Pernicka, E., Núñez, L., and Liebbrandt, A., 2010, Early copper metallurgy in northern Chile, in *Metalla*, *Archäometry un Denkmalpflege* (eds. O. Hahn, A. Hauptmann, D. Modarressi-Tehrani and M. Prange), 96–8, Jahrestagung im Deutschen Bergbau-Museum, Bochum.

Moreno, A., Santoro, C., and Latorre, C., 2009, Climate change and human occupation in the northernmost Chilean Altiplano over the last ~11,500 cal yr BP, *Journal of Quaternary Science*, **24**, 373–82.

Muñoz, I., 1989, Perfil de la organización económica social en la desembocadura del río Camarones: periodo Intermedio Tardío e Inca, *Chungara*, **22**, 85–111.

Salazar, D., Figueroa, V., Mille, B., Manríquez, G., and Casanova, P., 2010a, La producción de metales en las sociedades costeras del norte grande de Chile, in *Actas del XVII Congreso Nacional de Arqueología Argentina*, vol. I, 135–40, Mendoza.

Salazar, D., Figueroa, V., Mille, B., Morata, D., and Salinas, H., 2010b, Metalurgia prehispánica en las sociedades costeras del norte de Chile: el caso de quebrada Mamilla, costa de Tocopilla, *Estudios Atacameños*, **40**, 23–42.

Salazar, D., Castro, V., Michelow, J., Salinas, H., Figueroa, V., and Mille, B., 2010c, Minería y metalurgia en la costa de la región de Antofagasta, extremo norte de Chile, *Boletín del Museo Chileno de Arte Precolombino*, **15**(1), 9–23.

Salazar, D., Figueroa, V., Morata, D., Mille, B., Manríquez, G., and Cifuentes, A., 2011, Metalurgia en San Pedro de Atacama durante el Período Medio: nuevos datos, nuevas preguntas, *Revista Chilena de Antropología*, **13**(1), 123–48.

Salazar, D., Palma, C., Salinas, H., Fuentes, F., Guendon, J. L., and Castellón, C., 2010d, Reconstrucción de la secuencia ocupacional de la quebrada Mamilla, costa de Tocopilla, norte de Chile, *Werkén*, **13**, 323–46.

Salls, R., 1989, To catch a fish: some limitations on prehistoric fishing in southern California with special reference to native plant fiber fishing line, *Journal of Ethnobotany*, **9**(2), 173–99.

Santoro, C., Standen, V., Arriaza, B., and Dillehay, T., 2005, Andean Archaic funerary pattern or postdepositional alteration? The Patapatane burial in the highlands of South Central Andes, *Latin American Antiquity*, **16**, 329–46.

Schiappacasse, V., and Niemeyer, H., 1989, Avances y sugerencias para el conocimiento de la prehistoria tardía de la desembocadura del valle de Camarones (Región Tarapacá), *Chungara*, **22**, 63–84.

Scott, D. A., 1991, *Metallography and microstructure of ancient and historic metals*, The Getty Conservation Institute in Association with Archetype Books, Marina del Rey, CA.

Tartaglia, L. J., 1976, *Prehistoric maritime adaptations in southern California*, Ph.D. Dissertation, University of California, Los Angeles.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Table S1 Analyzed samples and its geographical origin.
Table S2 Locality, archeological site/collection, sample size (N) and average value ± standard deviation of measurements of the archeological fishhooks from the southern coast of Peru and northern coast of Chile (PLM = Playa Miller, AZ = Valle de Azapa, CAM = Quebrada de Camarones, PGUA2 = Pta. Guasilla 2).
Table S3 Geographic origin (North = Arica; South = Antofagasta, Taltal, Caldera, Chañaral), sample size (N), average value and standard deviation of measurements of archeological fishhooks from the coasts of Peru and Chile. The differences in shank length (fishhooks from the North are larger than those from the South) were statistically significant (Anova, $p < 0.05$) (details in text).
Table S4 Elemental composition of the metallic fishhooks from the Western Valleys (WV) and from the Absolute Desert Coast (ADC), with results in wt percent; n.m. = not measured. Analyses made by: PIXE (Particle Induced X-ray Emission) using the AGLAE facility (Accélérateur Grand Louvre d'Analyses Elementaires) at C2RMF; ICP/AES (Inductive Coupled Plasma / Atomic Emission Spectrometry) at the Laboratorio Geoquímico Universidad de Chile; SEM/EDX (Scanning Electron Microscope / Energy Dispersive X-ray spectrometry) at C2RMF. Analyses of certified reference materials were also performed during the corresponding sessions of analyses. The results obtained so far are appended at the end of the table. Part a: elements from Chromium (Cr) to Silver (Ag); Part b: elements from Cadmium (Cd) to Bismuth (Bi).
Figure S1 Exogenous metal objects found in funerary contexts on the northern coast of Chile.1–2, Gauntlets (Isla Santa María (Antofagasta), LIP-Inca); 3. Tincurpa (Chaca 5 (Arica), Inca); 4. Armband (Taltal, LIP-Inca); 5. Spoon (Taltal, LIP-Inca); 6. Bell (Taltal, LIP-Inca); 7. Laurake (Playa Miller 6 (Arica), Inca); 8. Tupu (Azapa 15 (Arica), Inca) (abbreviations: LIP = Late Intermediate Period; Inca = Inca Period; LIP-Inca = Late Intermediate Period and Inca Period). 1, 2, 6: Schloss Gottorf (Schleswig); 3, 7, 8: Museo Universidad de Tarapacá-San Miguel de Azapa (Arica): 4: Museo de Artes Visuales (Santiago); 5: Museo Augusto Capdeville (Taltal).
Figure S2 Map of homologous landmarks (1–8) used in the geometric morphometric analysis of this study. Inter-landmark measurements correspond to gape and total lengths. Fishhook from site PLM6 (Tomb 23, piece 43050, Museo Universidad de Tarapacá – San Miguel de Azapa). The fishing line wrapped around the lashing device as revealed by X-rays is seen.
Figure S3 Vickers micro-hardness measurements of the fishhooks vs tin content (in wt%). The only unalloyed copper fish-hook comes from the ADC area (circular dot). The other fishhooks are from the WV area (square dots), and contain various amounts of tin.
Figure S4 Longitudinal metallographic section of the fishhook C2RMF67590 (provenance Caleta Camarones, average tin content 9.6wt%). The sample was taken in the point area. The very elongated copper sulphides inclusions indicate an intense hammering. The banded structure is related with local variation of the tin content. SEM backscattered images.