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ISSUES

Living in poisoning environments: Invisible risks and human adaptation

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This article describes the hidden natural chemical contaminants present in a unique desert environment and their health consequences on ancient populations. Currently, millions of people are affected worldwide by toxic elements such as arsenic. Using data gathered from Atacama Desert mummies, we discuss long-term exposure and biocultural adaptation to toxic elements. The rivers that bring life to the Atacama Desert are paradoxically laden with arsenic and other minerals that are invisible and tasteless. High intake of these toxic elements results in severe health and behavioral problems, and even death. We demonstrate that Inca colonies, from Camarones 9 site, were significantly affected by chemical contaminants in their food and water. It appears however, some modern-day Andean populations resist the elevated levels of arsenic exposure as a result of positive selection mediated via the arsenic methyltransferase enzyme and display more tolerance to high chemical doses. This article further debate the effects of natural pollution and biocultural adaptation of past populations.

KEYWORDS

archeology of the invisible, arseniasis, natural contamination, poisoning environments

1 | INTRODUCTION

Humans settled in a myriad of environments, some may have experienced hidden chemical hazards to their health and survival. Arid lands contain toxic environments due to poisoning by mineral accumulation, such as arsenic, lead, lithium, and boron, among others.[1–6] However, people are often unaware of endemic contaminants because they are dissolved in natural water as ions and molecular species, which are only detectable with sensitive analytical instruments (Figure 1). Arsenic threat has a global dimension as many aquifers are contaminated (Figure 2).[7–44] For example, in Bangladesh alone, approximately 50 million people suffer from waterborne arsenicism.[3] In Latin America, about 4.8 million people are affected.[3,5] In northern Chile, around 500,000 people suffer from natural arsenic exposure.[3] In antiquity, how many people could have been affected by this 'silent killer'? We debate the evolutionary biocultural consequences of unwittingly settling in the Atacama Desert toxic environments and consuming contaminated resources.

To better understand ancient cultures, one needs to explore the natural contaminants that affected them, such as arsenic. To be successful as a group, ancient populations must have adapted both culturally and biologically to the natural visible environment and to invisible contaminants. In this regard, particular attention must be paid to the type of toxic minerals that may have been present for thousands of years. Scrutiny of environmental exposure to toxic substances since antiquity is important to understanding social changes, and paleo-health, not only within complex societies but also in hunter-gatherer groups.[45,46]

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FIGURE 1 A narrow section of the Camarones river supporting vegetation in the desert, but laden with dissolved arsenic [Color figure can be viewed at wileyonlinelibrary.com]

Today, desert lands occupy about 20% of the world landscape.[47] In South America, a significant part of the landscape is dominated by the Atacama Desert,[48] covering about 180,000 km^2. There, arsenic levels in the water are often 10–100 times above the 10 μg/L or parts per billion thresholds defined by the World Health Organization.[1–6,12,45,49] Thus, we must wonder about the resilience of ancient humans to these hidden environmental risks and their impact on human health. Understanding the natural pollutants present in the soils and freshwater is fundamental to the natural history of ancient populations. Bioarcheological research, particularly in arid lands, needs to incorporate hidden environmental hazards and their biological consequences upon the trajectories of local cultures to complement economic and sociopolitical models. The analysis of sediments, plants consumed, hard tissues such as bones, teeth, and hair, as well as other tissue remains, can shed light on exposure to ancient contaminants and the archeology of the invisible in the Atacama Desert.

2 | THE ARSENIC RIDDLE

The natural occurrence of arsenic in surface and groundwater in South American countries is associated with the long-term volcanism of the Andes and dissolution of arsenic-bearing minerals (Figure 3). Arsenic toxicity affects up to 200 enzymes, most notably those involved in cellular energy pathways and DNA replication and repair.[50] Arseniasis (chronic arsenic poisoning) leads to dermatological changes such as hyperpigmentation, and skin lesions,[51] cancer,[52] slow development in children,[53,54] psychosomatic disorders, cardiomyopathy, and differential mortality.[1,54] Arsenic can pass through the placenta, predisposing spontaneous abortions, prenatal deaths, low birth weights, and teratogenic conditions.[1,55–57] The degree of arsenic poisoning correlates with the number of years consuming contaminated water.[1,54,56] Humans are easily poisoned by arsenic when this metalloid and other

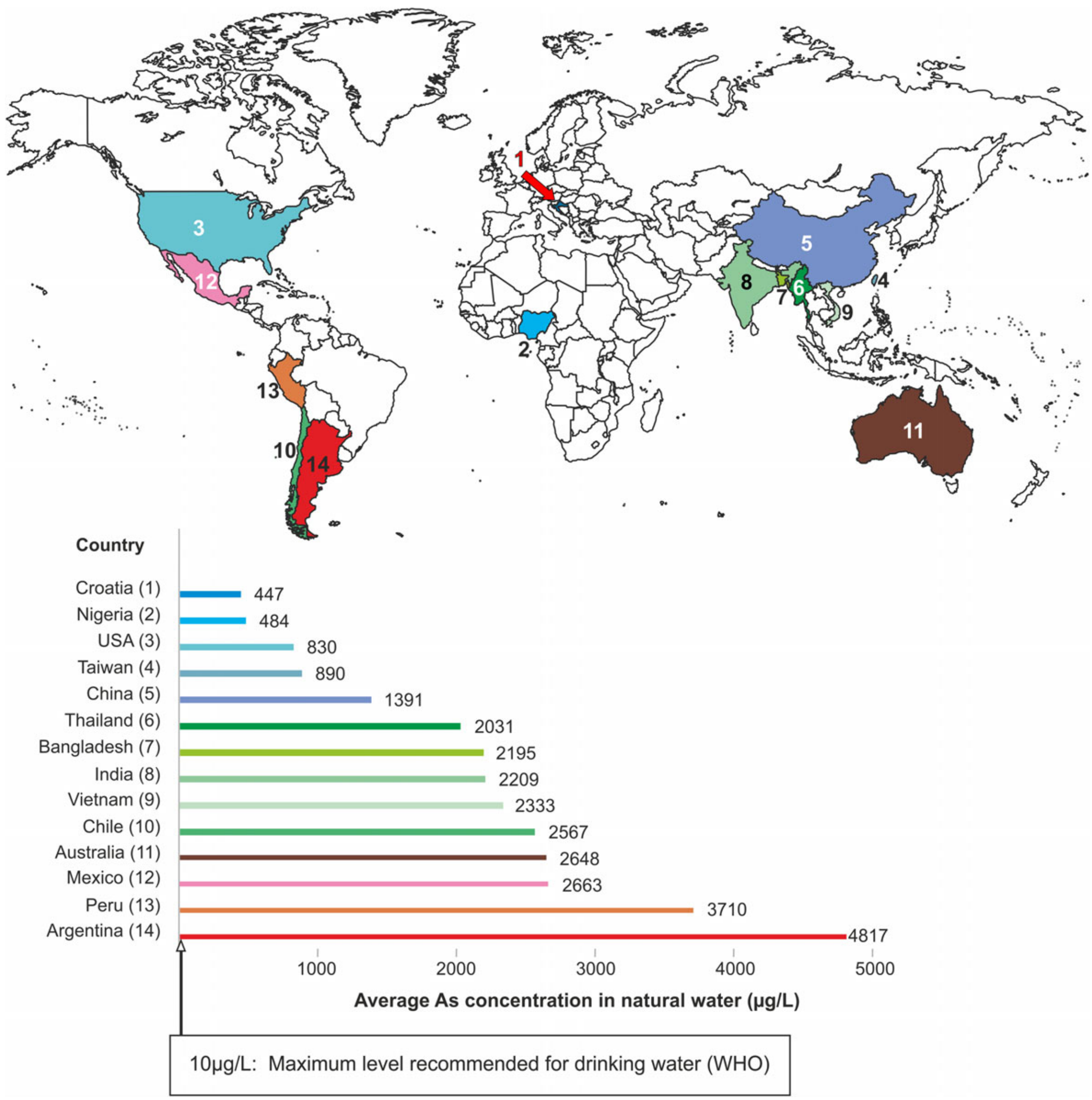

FIGURE 2 Arsenic is an endemic and global contaminant in natural water. Values are averaged from the literature data[7–44] [Color figure can be viewed at wileyonlinelibrary.com]

toxic elements are dissolved in water. They are not obviously detectable partly due to these natural contaminants do not have any particular smell, taste, or color. As such, arseniasis has a socioeconomic and health burden upon a population.[1–3,5,6]

2.1 | Arseniasis in the past

To what extent did natural contaminants exist in the Andean past? The remarkable preservation of mummies and skeletons allows for in-depth studies on this topic. This is particularly true considering that Atacama Desert populations have continually lived in mineral-rich environments that affected, are affecting, and will continue to cause suffering on local populations.[58–60] We propose that endemic pollutants permanently affected ancient Andean populations.

From very early ancient Andeans actively moved between diverse territories such as the desert, the coast, and the highlands, always close to particular river water sources, exploiting the resources, and occupying land.[46,61] Rivers, however, present different degrees of arsenic concentration due to volcanic activity in the mountain range, geogenic arsenic transportation properties, and its bioavailability. Thus, arsenic pollution varies from area to area where ancient people transited or settled to obtain raw materials and complementary resources.[61–63] Thus, we expect populations to be differentially affected.

Ancient pristine and unique Atacama Desert environments that provided plenty of food resources were sometimes a lethal trap because water sources were contaminated with arsenic (Figure 1).[64] Environmental arsenic is incorporated into organisms via the food web, together with a bioaccumulation process, and by a direct consumption of surface water rich with dissolved arsenic (hydroarsenicism), which causes acute and chronic health problems.[1,3,5,6] As contaminated rivers cut across the Desert and drain into the Pacific, crops, as well as fish and shellfish, also accumulate toxic elements. Ancient people, particularly those living in desert areas, were constantly poisoned by their environment, independently of the time and cultural development. This ancient poisoning hypothesis is testable in

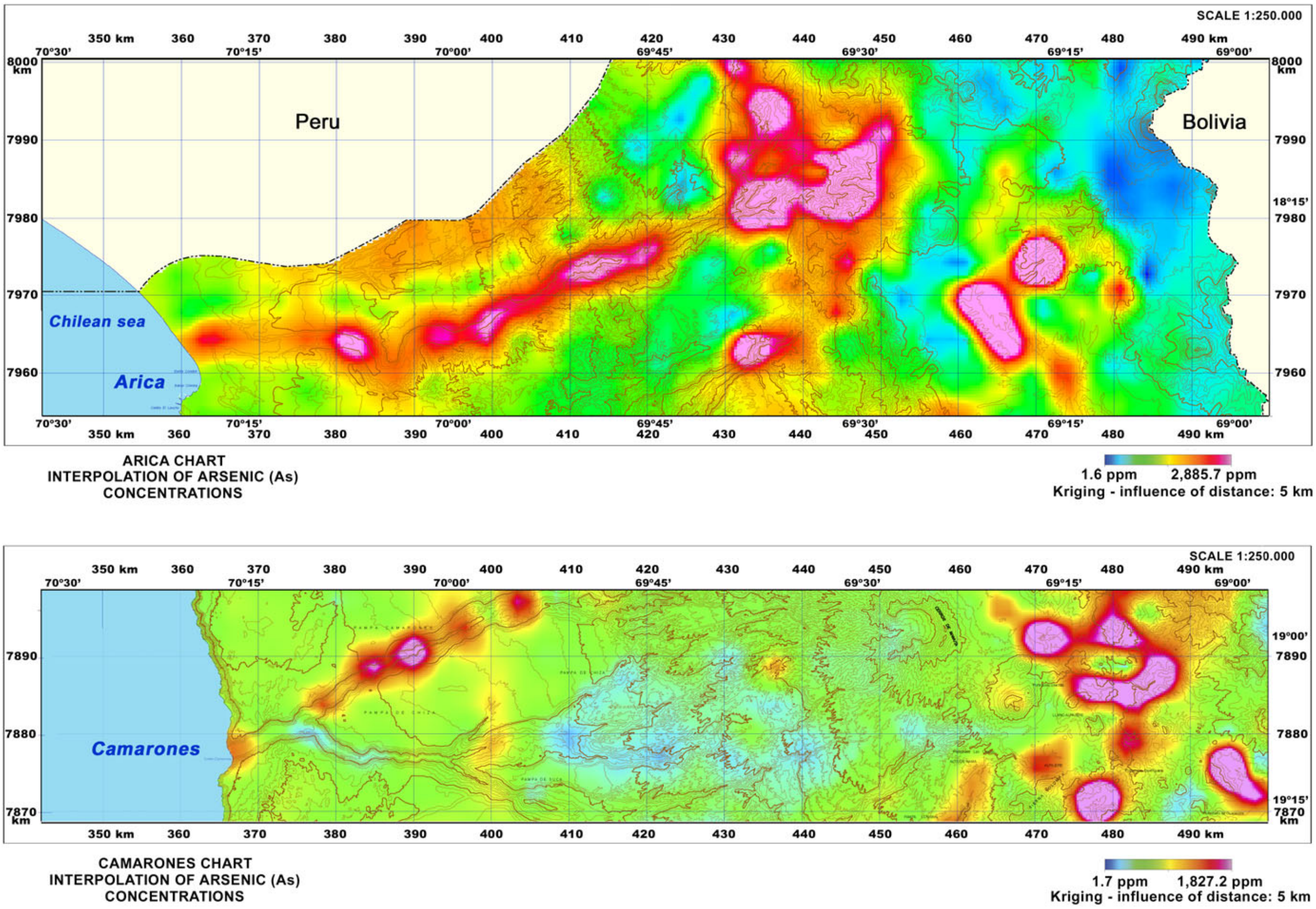

FIGURE 3 Mosaic distribution of arsenic concentration in northern Chile (courtesy of SERNAGEOMIN). The image was composed by the authors. Arica (top) and Camarones (below) map charts [Color figure can be viewed at wileyonlinelibrary.com]

bio-archeological remains because even though some of the chemical elements are eliminated from the body through urine after being ingested, a significant amount is stored in both the soft and hard tissue of the body.[5,45,65–67] Thanks to sensitive modern techniques for elemental analysis such as Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS), it has been possible to investigate the burden of toxic chemical elements upon the lives of ancient populations.[2,4,65–67] The environmental exposure to arsenic of the first coastal settlers of Northern Chile has been determined using teeth[65] and individual hair strands[45,68] by LA-ICP-MS.

It has been found that ancient Andean populations were severely affected not only by one chemical element but by several of them because many elements are present simultaneously in the water. Arsenic, lithium, and lead have been identified in the soft and hard tissue of ancient Chilean mummies.[2,45,65–67] However, each causes a different health problem. Arsenic, as stated, causes systemic damages. Lithium, produces severe nausea and gastrointestinal problems, and lead is associated with neurobehavioral and cognitive problems, among others.[4,6,58]

2.2 | The antiquity of contamination and cultural development

When were Andean people first exposed to arsenic? Did their cultural practices increase the risk of toxic chemical exposure? In South America, long-standing pollutants are associated with the formation of the Andes ~20 million years ago and the resulting geochemistry. In comparison, the peopling of the Atacama Desert can be traced back to between 10,000 and 13,000 years ago.[46] Back then, the abundant but fluctuating water levels and different humid phases resulted in an increase in the food availability and adequate places for human settlements across a wide range of ecological zones, such as Los Burros, Quebrada Jaguay, and Tacahuay (Peru)[69] and the Acha, Morro, Tiliviche, and Quebrada Mani, among others (Chile).[46]

In Northern Chile natural contamination has a long history. For example, during the Archaic period, the ancient Chinchorro, a hunter-gatherer population (ca. 7000–1500 B.C.E.) ingested high levels of arsenic likely due to hydroarsenicism, in addition to consuming contaminated food such as cattail (*Typha* sp.) roots (rhizome). *Typha* grow in swampy areas, and their rhizomes store high levels of arsenic.[70]

In this area, arseniasis may have triggered social change. Arriaza[71] proposed an association between high levels of arsenic in the Camarones Valley, where the oldest anthropogenic mummies are found (the Chinchorro), and the development of complex artificial mummification practices. His proposition is based on the fact that Camarones Valley (Figure 1) has one of the highest levels of arsenic contamination in river water in the world (1,000 μg/L),[45,58,60,64] the oldest known anthropogenically mummified fetuses and newborns have been found in the Camarones Valley; and, it is known in modern context that pregnant women living in environments rich in arsenic suffer from high rates of miscarriages and premature births.[1,54] Therefore, for the Chinchorro people, preserving their children with colored earth, clay, pigments, and reeds could have been an emotional response to alleviate their grief (Figure 4a,b).[71]

A couple of Chinchorro mummies suffering from polydactyly,[72] a developmental malformation (i.e., six toes), have been found in Arica (Figure 5). Polydactyly of the hands and feet is also represented in the rock art of the macro region of late populations[72] and may have been an accurate representation of reality. It has been stated that polymetallic contamination can cause birth defects[57,73] and polydactyly.[74] Thus, the reported ancient teratogenic condition was probably associated with environmental pollution, among other key factors (i.e., genetic).

On the other hand of the cultural development spectrum, during the Inca period (1400–1536 A.D.) the expansion of agricultural areas occurred simultaneously with the application of new technologies for the more efficient use of water and inland and coastal resources.[75] Populations were no doubt tied to their chemically contaminated water sources. The amount of water consumed and the concentration of arsenic ingested daily, likely, significantly outweighed the contribution of arsenic ingested per day from plant or animal foods. Nevertheless, plants irrigated with contaminated water are good arsenic bioaccumulators.[76]

As part of their political and economic control, the Incas moved colonies of people (*mitimaes*) to newly conquered yet distant territories.[77–79] Some populations were relocated to harsher environments than they were accustomed to live[80] and this could have had an important effect upon their health. For example, the Inca period mummies of Camarones (Cam-9 site) present visible skin lesions (Figure 6) in addition to severe levels of arsenic in the inner organs including intestines and liver.[64] This Cam-9 inhabitants were more affected compared to other naturally mummified bodies from Arica. We hypothesize the Cam-9 people may represent a *mitimaes* colony that was unknowingly exposed to an arsenic-rich environment. It is known that many organs are damaged by arsenic poisoning, along with stomach pain, nausea, diarrhea, and partial paralysis among others complications.[3,5,50–53] Consequently, daily activities and productivity were likely reduced among ancient Inca settlers of Camarones. Thus, the longer these people consumed polluted water and food crops irrigated with arsenical water, the greater their health problems.

FIGURE 5 Polydactyly in an individual 10–12 years old mummy (case: M1/6 T28)

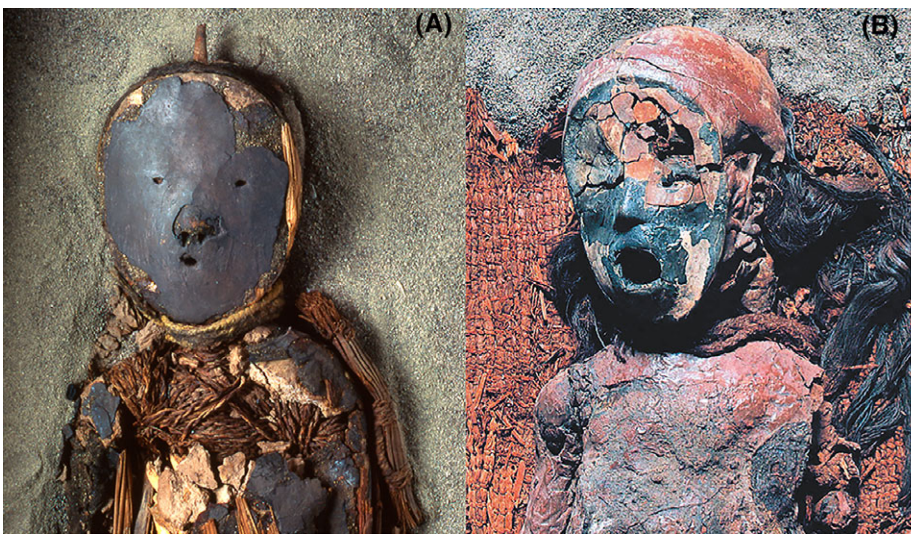

FIGURE 4 Chinchorro mummies (children) with artificial mummification. (a) Black mummy, (b) red mummy [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Skin lesions in the trunk (back) of an adult Inca mummy (case: Cam-9 T13) [Color figure can be viewed at wileyonlinelibrary.com]

3 | ADAPTATION

Ancient people drinking arsenic-contaminated water for thousands of years may have developed a physiological mechanism to eliminate the ingested arsenic.[60] Exposure to elevated concentrations of arsenic in drinking waters has been shown to enhance the methylation capability by the liver leading into a more efficient elimination of ingested arsenic through urine.[60] Recently, several scholars[81–83] have shown that modern populations exposed to high levels of arsenic over long periods frequently carry the Arsenic (III) methyltransferase (AS3MT) gene marker. This marker likely indicates a genetic protection against arsenic toxicity—a positive selection mechanism. AS3MT is a key enzyme involved in arsenic metabolism. The Camarones *mitimaes* may be less likely to have a protective genetic trait. They have been living in the area for a shorter period, and not exposed to dangerously high levels of arsenic for long enough to develop this adaptation yet.

FIGURE 7 Details of legs painted with red ocher, adult Inka mummy (case: Cam-9 T16) [Color figure can be viewed at wileyonlinelibrary.com]

Molecular biology data indicates modern populations from San Antonio de los Cobres in Argentina and Camarones in Chile, areas, where arsenic levels in the water reach on average 300–1,000 μg/L, respectively, are able to metabolize and more quickly eliminate this semimetal from their bodies through urination.[81–83] Both populations present a 68% frequency of the AS3MT gene protective variant, which allows them to methylate arsenic and prevent poisoning.[81–83] This gene frequency value is very high compared with an 8% found in populations living in non-arsenical areas.[81] We expect that similarly high gene frequencies will be observed in other regions where extreme levels of natural multi elemental contamination are present in the water sources.[81,83] Thus, this gene most likely facilitated the peopling of endemic arsenical areas including the Andes.

Mummy studies should attempt to investigate the antiquity of this protective genetic variant to understand variation within burial sites and between regions. The mosaic type distribution of arsenic within a region (Figure 3), individual social interactions, and the frequency of a protective genetic trait may affect arsenic concentration values. Thus, a large data set, controlling for age, gender, location, chronology, and type of mummy tissue is necessary in order to shed light on ancient individual and population mobility, interregional variability, long-term exposure, and biocultural adaptation to natural pollutants.

Regarding cultural responses to environmental arsenic, the Chinchorro complex artificial mummification system was linked to arseniasis.[71] However, cultural adaptations to hydroarsenicism during the Inca time, have received minimal debate. Arseniasis has significant impacts on people´s daily lives and social interactions. Modern studies have shown that people suffering from arsenic poisoning are stigmatized by unaffected individuals.[84,85] In addition, affected women are socially the most vulnerable and often become ostracized. Housewives are divorced by their husbands and young woman are unable to marry.[84,85] As there is no cure, others may assume a fatalistic approach.[85] Certainly, many of these cultural issues are not visible in the archeological record, but they are worth to explore in future bioarcheological studies. Considering the decreasing health and socioeconomic impact of arseniasis upon modern populations,[3,50–54,56,57,84] the *mitimaes* populations living in Camarones area, most probably saw a decline in their quality of life, and a decrease in their economic activities. Despite this, the Camarones individuals affected by arseniasis received proper burial. They had many grave goods and bodies were painted with red ochre (Figure 7). Thus, the mortuary practices at Cam-9 reveal social caring and complex rites for those ill and departed.

4 | FINAL REMARKS

In summary, geogenic contamination is rarely considered in evolutionary and archeological models that debate ancient populations' health and cultural trajectories. It is important to shed light on this issue. This is especially true considering that arsenic is present in many regions of the world and not easily recognizable in water or the food systems (Figure 2).

The propositions we discuss are relevant because millions of people are affected worldwide by hydroarsenicism.[1,3,5,6,12] A similar poisoning situation could have occurred in other ancient sites from arid lands. Current analytical chemical technology allows us to gather in-depth data on each individual's biographical history and, in turn, generate information about morbidity and well-being of ancient populations. In other words, this type of study permits equal focus on both the health of an individual and that of the entire population. Data about chemical contaminants and protective gene markers can also be useful to further explore population mobility, social interactions, and biological adaptation of ancient populations living in contaminated environments. Today many chemical elements are widely used in the production of batteries, modern electronics, pharmacological, and pesticide products. Even today, the ongoing natural and anthropogenic contamination problem prevails in the same areas where ancient Andeans lived. For example, due to water demands, the naturally contaminated Toconce river (Northern Chile), carrying 800 μg/L of dissolved arsenic, was connected to the main drinking water supply.[53,54] Exposure to geogenic arsenic is continued among the contemporary people in the Atacama region.[60] Thus, learning as much as possible about past exposure events and evolutionary trends could provide insight into current and future environmental health exposure issues.

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