Emergence of social complexity among coastal hunter-gatherers in the Atacama Desert of northern Chile

Pablo A. Marquet[a,b,c,1], Calogero M. Santoro[d,e], Claudio Latorre[a,b], Vivien G. Standen[e,f], Sebastián R. Abades[a,b], Marcelo M. Rivadeneira[a,g], Bernardo Arriaza[d], and Michael E. Hochberg[c,h]

[a]Departamento de Ecología, Facultad de Ciencias Biológicas, Pontificia Universidad Católica de Chile, Casilla 114-D, Santiago, Chile; [b]Instituto de Ecología y Biodiversidad (IEB), Casilla 653, Santiago, Chile; [c]Santa Fe Institute, Santa Fe, NM 87501; [d]Instituto de Alta Investigación, Antofagasta 1520, Universidad de Tarapacá, Casilla 6-D, Arica, Chile; [e]Centro de Investigaciones del Hombre en el Desierto (CIHDE), oficina 403, CP 1000007, Arica, Chile; [f]Departamento de Antropología, Universidad de Tarapacá, 18 de Septiembre 2222, Casilla 6-D, Arica, Chile; [g]Centro de Estudios Avanzados en Zonas Aridas (CEAZA) and Departamento de Biología Marina, Facultad de Ciencias del Mar Universidad Católica del Norte, 1781421 Coquimbo, Chile; and [h]Institut des Sciences de l'Evolution, Unité Mixte de Recherche 5554, Centre National de la Recherche Scientifique, Université Montpellier II, Place Eugène Bataillon, CC065, 34095 Montpellier Cedex 05, France

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The emergence of complex cultural practices in simple hunter-gatherer groups poses interesting questions on what drives social complexity and what causes the emergence and disappearance of cultural innovations. Here we analyze the conditions that underlie the emergence of artificial mummification in the Chinchorro culture in the coastal Atacama Desert in northern Chile and southern Peru. We provide empirical and theoretical evidence that artificial mummification appeared during a period of increased coastal freshwater availability and marine productivity, which caused an increase in human population size and accelerated the emergence of cultural innovations, as predicted by recent models of cultural and technological evolution. Under a scenario of increasing population size and extreme aridity (with little or no decomposition of corpses) a simple demographic model shows that dead individuals may have become a significant part of the landscape, creating the conditions for the manipulation of the dead that led to the emergence of complex mortuary practices.

climate variability | coastal desert | cultural evolution

The oldest known example of artificial mummification (AM) is dated at *ca.* 7–8 ka BP (thousands of calibrated ^{14}C years before 1950) in the coastal desert of northern Chile and southern Peru (1). AM involves the external and internal manipulation of recently deceased individuals, through different procedures (2–5). Since the discovery of artificially mummified bodies (now known as the Chinchorro cultural complex) in 1917 by Max Uhle, most scholars have concentrated on describing the different practices used in mummifying the dead rather than explaining its emergence as a social phenomena (Fig. 1). Suggested explanations for this practice range from an origin in the tropical lowlands of the Amazon basin (6, 7) to its emergence through in situ cultural evolution (3, 4, 8). The discovery of an early Archaic burial site in the same area where Chinchorro mummies are found [Acha (9)] and the recent analysis of its funerary patterns (10) reveal similarities with the Chinchorro culture as early as 10 ka BP, supporting the hypothesis that the Chinchorro culture was a local development. The emergence of such elaborate funerary practices raises several major questions. (*i*) What led these particular hunter-gatherer groups to develop this degree of cultural complexity? (*ii*) Why is this complexity manifested in an elaborate cult to the dead? (*iii*) Why did the nature of mummification take on several distinct forms? (*iv*) Why did this practice disappear by 4.4 ka BP? Cultural complexity in hunter-gatherers is here defined as the appearance of technological and socio-cultural innovations, including the emergence of sedentism or restricted residential mobility, increased population density, rituals, warfare and social differentiation (11).

Henrich (12) developed a simple model for cultural/technological evolution to explain the maladaptive loss of technologies in Tasmanian aboriginals before the arrival of Europeans. The model is based on known human cognitive capacities for social learning, reflected in the psychological propensity to imitate particularly skillful individuals within a group. Because imitation is a process of imperfect inference, large population sizes are required for a rare and skillful performance to spread and remain within a group; otherwise the skill would be lost due to imperfect inference [the so-called "Tasmanian effect" (13)]. Recently, Rogers and Ehrlich (14) found that symbolic cultural traits evolve faster than functional traits, supporting the interpretation of cultural change from an evolutionary perspective. To our knowledge, however, no study has investigated how shifting environmental conditions may, through their effects on population size, influence the emergence and loss of cultural innovations.

In this contribution, we evaluate how environmental and demographic factors may have been central to the emergence, maintenance, and eventual loss of cultural complexity in the Chinchorro, as predicted by recent models of cultural and technological evolution in human groups (12, 15). Our hypothesis has two parts (Fig. 2). First, we hypothesize that Chinchorro cultural and technological complexity was brought about by an increase in population size driven by environmental changes that affected an increase in available resources. In turn, larger population sizes would make more likely the emergence of innovations and accelerate cultural evolution driven by social learning (12). We distinguish, for the sake of simplicity, two main types of innovations: tools and technologies permitting more efficient resource extraction, and those associated with the ideological world (13). The environment regulates both types of innovations through its effect on resources (e.g., coastal upwelling drives marine productivity, and aquifer recharge increases freshwater availability; see below), which, in turn, affects human population size and thus cumulative cultural evolution (12).

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[1]To whom correspondence should be addressed. E-mail: pmarquet@bio.puc.cl.

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Fig. 1. Chinchorro mummy from the red period. This style of AM involved, among other manipulations (8), evisceration, painting the body with red ochre, and the use of long human-hair wigs. This style was predominant *ca*. 4.5 ka BP. Photograph by Bernardo Arriaza.

The second part of our hypothesis (Fig. 2) is the emergence of a particular type of ideological innovation, which manifested as AM owing to the unique environmental characteristics of the Atacama Desert environment: hyperaridity resulting in natural mummification of all corpses. In this context, a large population size means that natural mummies increasingly became a significant component of the physical and cultural landscape. We hypothesize that this provided the essential context for the manipulation of the dead and the emergence of AM.

In the following section we present the evidence that bears on our hypothesis.

Holocene Environmental Change in the Atacama and Human Population Size. The Atacama Desert is one of the oldest and driest deserts on the Earth today (e.g., ref. 16) (Fig. 3). Whereas the main hyperarid "core" of the desert has remained thus for millions of years (but see ref. 17), the eastern and southern margins have fluctuated considerably during the Pleistocene and Holocene (18–21). Although exact chronologies vary, most of these records agree on two pronounced wet phases at the end of the Pleistocene, documented by higher lake levels, plant invasions into what is today absolute desert, and elevated groundwater tables between 17.5–14.2 and 13.8–10 ka BP (17, 22). These wet phases are collectively known as the Central Andean Pluvial Event, and the latter phase was coeval with abundant early Archaic and Paleoindian settlements throughout the central Atacama (e.g., ref. 23). Moreover, these records agree on the abrupt onset of extremely arid conditions at the beginning of the Holocene (at 9.5 ka BP), which drove humans out of the Atacama inland basins toward more productive areas at higher elevations and coastal valleys (24–26).

Intermittent periods of greater rainfall also occurred between 7.8 and 6.7 ka BP in the Andean highlands, as evidenced by the intermittent presence of perennial plants in areas of absolute desert during the Holocene (18, 19, 27). Increases in rainfall were coeval with increased aquifer discharge in the lowlands, causing the emergence of springs (*aguadas*) and watercourses along small creeks and ravines (28).

It is difficult to adequately characterize in detail the complexity and variability of hydrological change along the Pacific coastal desert of South America. No high-resolution hydrological proxies are known from this region, and current reconstructions from inland areas are temporally discontinuous or are associated with complex dating issues. To overcome this limitation, we take advantage of the amply demonstrated link between rainfall in the high Andes and aquifer discharge in the lowlands, discussed above (see also ref. 20).

We thus analyzed a long-term climatic series represented by the Sajama Ice core (29), located in the Bolivian highlands

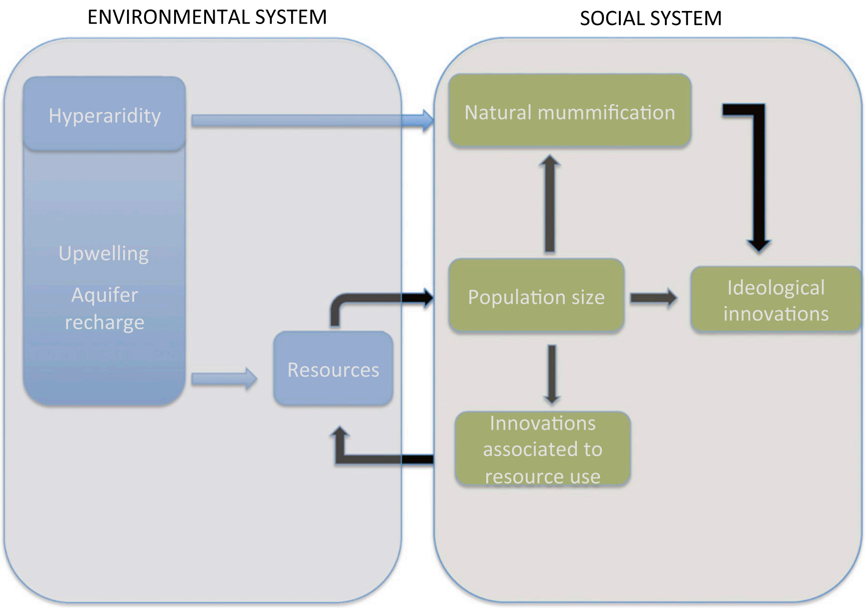

Fig. 2. Schematic diagram of our hypothesis for the emergence of AM in the coastal Atacama Desert.

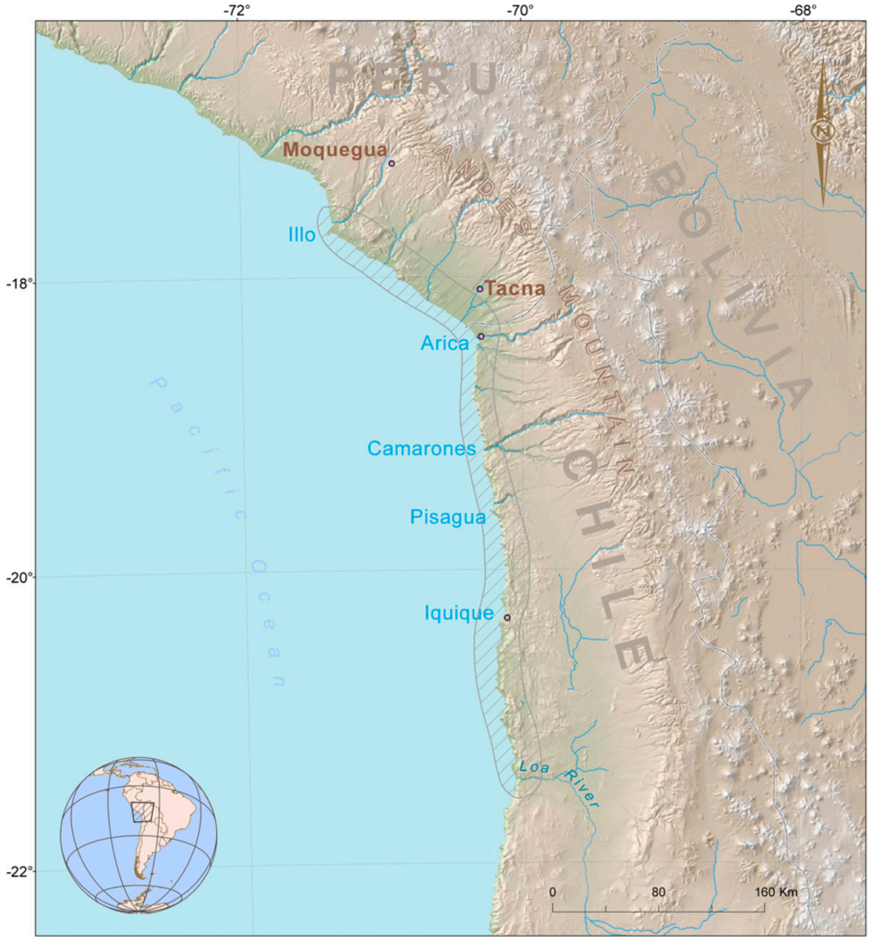

Fig. 3. Study area showing the location of the Chinchorro cultural complex in northern Chile and Southern Perú.

(Altiplano; *Materials and Methods*). The current consensus is that the Holocene Sajama $\delta^{18}O_{ice}$ record is a proxy of snow accumulation (and thus precipitation), which in turn seems to be a function of tropical Pacific sea surface temperature gradients (30). The Hölder exponent analysis (which allows for the characterization of regime shifts in time series; *Materials and Methods*) of the Sajama $\delta^{18}O_{ice}$ record suggests that between ~7 and 5 ka BP, prevailing conditions were more stable than today (Fig. 4).

Estimation of Human Population Size. Fig. 4 shows that the period between 7 and 4 ka BP was one of high human population density, as evidenced by using the distribution of summed ^{14}C probability densities as a proxy. This reconstruction uses 460 dates from known archeological sites from coastal southern Peru and northern Chile (*Materials and Methods*). The resulting curve indicates that human populations increased dramatically at 7 ka BP and peaked by 6 ka BP. A strong decline is visible at ~4.9 ka BP, but populations recovered by 4.2 ka BP, only to decline again afterward.

We therefore assert that cultural complexity along the coastal Atacama emerged during a period when water was not limiting, population density was high, and fish and seafood were plentiful owing to strong upwelling conditions and a weakened El Niño-Southern Oscillation (31, 32). Chinchorro hunter-gatherers and fishermen would have probably been able to take advantage of freshwater runoff from the canyon and valley mouths, as well as exploit "paleo" springs and wetlands that outcropped along the endorheic coastline south of 17°S (e.g., perennial rivers cross the Atacama and reach the coast north of this latitude). Chinchorro mummies are typically found in these latter areas (e.g., sites Arica, Camarones, and Pisagua in Fig. 3).

Emergence of Complex Mortuary Practices. Elevated groundwater tables and offshore productivity along the otherwise harsh desert coast in southern Peru and northern Chile would have contributed to increased population size and fostered more sedentary lifestyles. These external factors promoted a demographic scenario for increased innovation and cultural complexity (12, 15). In fact, technological innovations associated with resource use diversified during this period, as seen in a wide range of fishing tools such as harpoons, hooks, and weights (3, 33–35) (Fig. S1). Although the above characteristics of the environment may have been key to the emergence of social complexity in the Chinchorro, this does not explain why innovations were manifested in the intentional manipulation of dead individuals. We hypothesize that this was due to the interaction between human cognitive abilities and environmental causes. In particular, the fact that little or no decomposition of the dead occurs in the barren, hyperarid coastal deserts of southern Peru and northern Chile leads to the natural accumulation of naturally mummified corpses through time, which soon become a significant component of the landscape, with a strong influence on the living population. According to Hertz (36), there is a correspondence between the decay of the corpse and the fate of the soul. On the basis of ethnographic evidence primarily from the Dayak agricultural society in Borneo, he points out that "Death is fully consummated only when decomposition has ended; only then

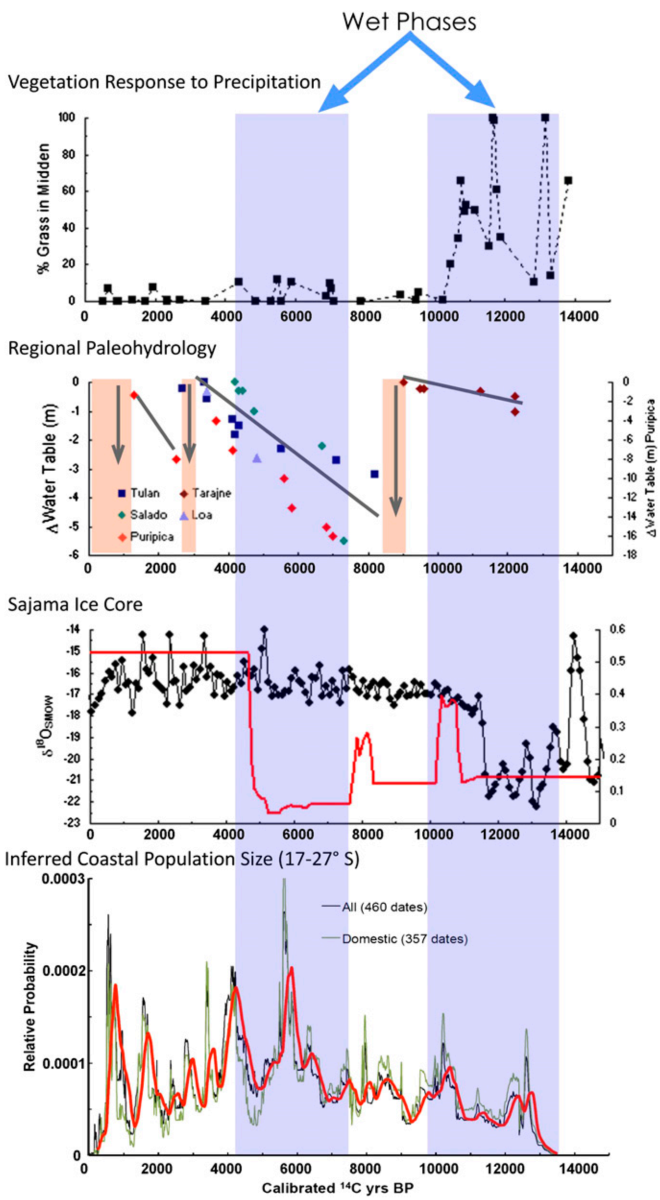

Fig. 4. Summary of past climate change in the central Andes and Atacama Desert for the last 14 ka BP. *Top* to *Bottom*: Paleoecological reconstruction of past plant productivity based on rodent midden data (after ref. 19); paleohydrological reconstruction of ground water levels (after ref. 28); Sajama ice-core data (after ref. 29) and associated Hölder exponent analysis (in red); and changes in the summed probability density of all radiocarbon dates (460 dates) from coastal sites known between 17° and 27° South latitude. *Bottom*: Red curve is a 500-y moving average (64). Also depicted is the summed probability of a subset of 357 dates taken from domestic contexts (green curve). The overall pattern between the two curves is very similar and provides strong evidence against a potential bias of overrepresentation of burial or other funerary sites.

does the deceased cease to belong to this world so as to enter another life" (36). Thus, the lack of decomposition may have had a profound influence upon the living population, because the dead would have been still among them, albeit in a different state of existence. Hertz's point could apply beyond agricultural societies. In fact, complex mortuary practices are known in hunter-gatherer societies, such as those involving primary burial and secondary skull removal in the Late Natufian and the Prepottery Neolithic in the Levant (37). Another interesting example is the Batek hunter-gatherers in Malaysia (38): mourners carry the body of the recently deceased on a stretcher inside the forest, and the body is then put on a platform where family members return to visit the corpse and observe the full process of decomposition. The impact of dead bodies upon the living population is further emphasized by Boyer (39, 40), who points out that religion and religious thoughts are an emergent property of our standard cognitive capacities in interaction with social and natural phenomena, such as dead bodies. Boyer (39) suggests (p 226) that "religious phenomena are around because of a conspiracy of relevance. That is, once a particular theme or object triggers rich inferences in a variety of different mental systems, it is more likely to be the object of great cultural attention and elaboration. This certainly seems to be the case of dead bodies." According to this author, corpses generate salient cognitive effects that may underlie the emergence of supernatural concepts and religion. This highlights the important role that the natural accumulation of dead bodies in the hyperarid Atacama coast may have had as a driver of social complexity, manifested by AM.

The lack of decomposition of human corpses implies a long residence time for dead individuals, and an increased rate of contact, hence a considerable presence of natural mummies among the living population. We developed and parameterized a simple population model based on hunter-gatherer demography (*SI Materials and Methods*). The model suggests that highly productive groups attaining a maximum size of approximately 100 individuals (which is representative of known hunter-gatherer groups) will yield *ca.* 400 corpses every 100 y. This means that when AM emerged ∼7 to 8 ka BP, a typical individual was potentially exposed to a "population" of several thousand naturally mummified individuals as coastal settlements started ∼10 ka BP. Our hypothesis emphasizes that the increasing contact rate through time between living and dead individuals provided the basis for the manipulation of the dead that led to the emergence of complex mortuary practices. The model demonstrates an increasing contact rate between living and dead individuals over the 5,000 y of the existence of the Chinchorro people. This could have provided the basis for a cultural innovation resulting in the manipulation and further elaboration of complex mortuary practices.

Fig. 5 presents the effects of population growth rate on total living population numbers and on the total mummy population for three different points in time. We see that, as expected, population size increases both as a function of time and maximum growth rate (Fig. 5). Numerical studies indicate that for a founding population of 10 individuals it will take approximately 130 y to attain 90% of carrying capacity when growing at a relatively high rate of 3.5% per annum and approximately 880 y to reach the same level if growing at a more moderate rate of 0.5% per annum. Whereas the time to attaining carrying capacity is sensitive to the maximum rate of population increase (F), the total number of mummies per living individual is relatively insensitive to F values above 0.5% after 1,000 y and 0.1% after 5,000 y (Fig. 5 *A* and *B*).

We can use the model to estimate the number of natural mummies a typical living individual will encounter in a given time frame. Natural mummies may either be deceased members of the group who an individual knew when the former were alive, or those that died before the birth of the individual. It is not known to what extent natural mummies were actually exposed to observation by the living, or whether the probability of exposure is related linearly or nonlinearly to their actual density. Assuming that living individuals were exposed, per annum, to only 1% of the habitat where mummies were located, then our model predicts that the average person would encounter *ca* 1, 35, and 190 mummies at 100, 1,000, and 5,000 y after the founding of the group, respectively (Fig. 5). These figures are probably an underestimation of the true contact rates, because the exposure

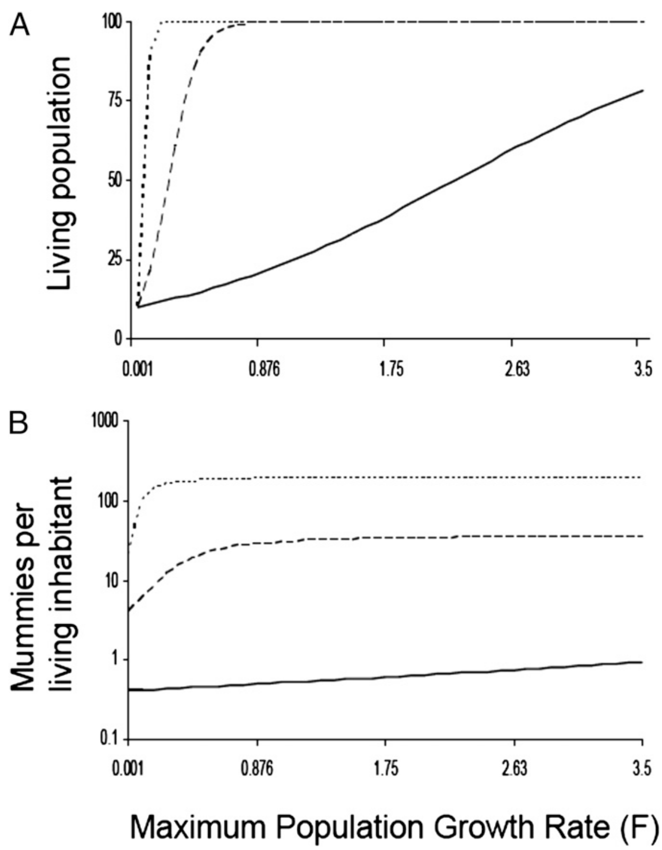

Fig. 5. Effects of population growth rate (F) on total population numbers (*A*) and the total number of mummies per living inhabitant (*B*) at 100 (solid line), 1,000 (dashed line), and 5,000 (dotted line) years after population founding. In these simulations, the net birth rate, *b*, is fixed at 4%.

estimate is likely higher than 1% considering that people buried their dead within the living areas, meaning that Chinchorro cemeteries were not separated from domestic areas (3, 41). In Camarones 14, for instance, with the oldest evidence of AM, bodies were buried within the shell midden (41). Chinchorro cemeteries have horizontal rather than vertical stratigraphy (42); burials were usually shallow (less than 50–60 cm), and bodies were interred in close proximity to one another. This implies that (*i*) corpses could have become exposed due to erosion, human removal while performing daily day activities, or both, and (*ii*) living group members would have seen existing mummies at least at burial time and possibly more often if the upper stratum was exposed for some time after placement, owing to long rituals (4). Further, our parameterized demographic model suggests that a typical living individual would have been exposed to tens of deaths during his or her life (roughly 50% of a group of a total size on the order of 50–150 individuals). All of these interrelated facts provide a strong case for Chinchorros experiencing an increased scale of previous deaths, the mummies of which would have accumulated over many generations, and the resultant emergence of complex mortuary practices as per our hypothesis (Fig. 2). Once the practice of AM began, it is possible that the location of mummies was marked, as has been observed in pre-pottery Neolithic societies of the Levant, where secondary burials were associated with the removal of the skull, whose location was marked at the time of the initial burial (37).

Discussion

What led hunter-gatherer groups along the coastal Atacama Desert to develop such a high degree of cultural complexity? Why did this complexity become manifested in such an unprecedented and elaborate cult to the dead? We postulate that the main environmental drivers of cultural complexity were an increase in water availability and high environmental (coastal/near shore) productivity, which led to larger population sizes. As previously stated, paleoclimatic conditions were favorable for population growth and closely coincide with the AM period (Fig. 4). These larger populations made possible, in turn, cultural innovations along with the maintenance and evolution of elaborate cultural practices (12). Interestingly, socio-cultural complexity manifested in elaborated architecture and art in hunter-gatherer populations in the near East [e.g., Gobekli Tepe (43)] has also been linked to increased productivity and population size (44). Similarly, socio-politically complex hunter-gatherer societies usually developed in highly productive coastal areas and were often associated with near-shore upwelling systems (45). Our hypothesis for the emergence of AM assumes an increased sedentism or low rate of residential mobility in the Chinchorro. Reduced mobility is not an unusual phenomenon among hunter-gatherers. Indeed, complex hunter-gatherers (reviewed in ref. 46) are characterized by, among other things, relatively high degrees of sedentism and high population densities, as for example the hunter-gatherers of the Northwest coast of North America (e.g., ref. 11) and the California Channel Islands (e.g., ref. 46). Sedentism has also been reported for groups in coastal Ecuador [Las Vegas culture (47)].

Chinchorro sedentism has been suggested by several authors (e.g., refs. 4, 41, 48, and 49), on the basis of the existence of dense and ubiquitous mortuary sites and large shell middens, which imply a continuous record of burial and habitation, but more importantly by considering the discrete occurrence of essential resources such as freshwater at valley mouths and aguadas (coastal freshwater bodies or springs) that restrict individual movement. The fact that most cemeteries are found near aguadas (4, 8, 49) indicates that Chinchorros were living in proximity to their dead. This pattern is repeated in Ilo, Arica, Camarones, and Pisagua (33, 41, 48–50). Although some degree of Chinchorro mobility is possible (51), the discrete nature of resources and habitats suitable for settling in the barren landscape of the Atacama Desert suggests that intersite visits were limited. This is also suggested by available paleo-pathological evidence showing a high incidence of infectious diseases (4, 52), which is at odds

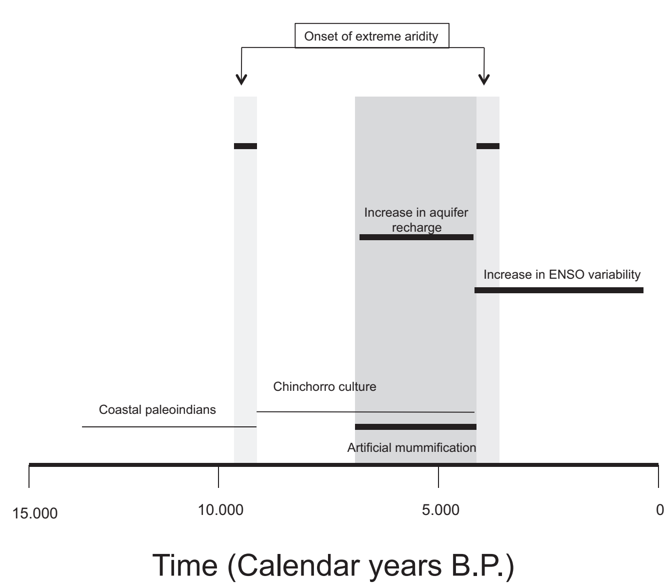

Fig. 6. Main cultural transitions and associated climate change regimes in the coastal Atacama Desert. ENSO, El Niño-Southern Oscillation.

with a nomadic lifestyle and suggests a low rate of mobility, hence a high contact rate among individuals. Finally, it is worth pointing out that Powell et al. (15) have shown that migratory activity can have the same effect on skill accumulation as increasing the size of a single population. Thus, our results would hold even if increased mobility were assumed.

The models proposed by Henrich (12) for cumulative cultural evolution have two main components: selective transmission of cultural practices via copying the behaviors of skillful individuals, and incomplete inference. The first component depends on the pool of social learners, which increases with population size, whereas the second is a measure of error in transmission due to imperfect copying. Our hypothesis entails that both processes operated in the Chinchorro after reaching a large population size, giving rise to the emergence of AM and explaining its variability in time and space.

Artificial mummification represents a complex and dynamic cultural practice. During the early period only infants and children were mummified (4, 8, 34), supporting the idea that they were considered full members of hunter-gatherer societies (53) and suggesting that AM was not originally intended for ancestor worship. Subsequently, adults also became mummified, and different AM variants emerged and evolved, including black, red, bandaged, mud-coated mummies, and corded mummies or mummies wrapped in reed cords (4, 5, 8, 34, 54). Other individuals were left without intervention to become naturally mummified corpses. There was some degree of overlap between these styles, suggestive of social differentiation (3, 34, 42). Although our hypothesis for the emergence of AM cannot explain why it started with juveniles, it does suggest that a temporal sequence of change can indeed reflect a pattern of cultural evolution driven either by fluctuations in population size, as suggested by our paleo-demographic analysis (Fig. 4) or by the selective transmission of fortuitous errors and experimentation. In the case of the Chinchorro culture, this could have been manifested by the existence of several mummification styles through time, thus contributing to answer the question of why AM takes on several distinct forms.

We hypothesize that AM was an ideological innovation reflecting the influence of the environment (i.e., the accumulation of natural mummies) on individual behaviors and the integration and evolution of these behaviors through the more than 100 generations over which the Chinchorros inhabited the northern coast of Chile and southern Peru. Our hypothesis assumes that the selective impact of these funerary practices on the fitness of group members, at least at its time of emergence, was neutral. This could not be the case if AM was also associated with signaling control over resources (55), or enhancing intragroup cohesion, cooperation, and identity (56) as a consequence of intergroup competition and warfare (57, 58). Currently, we cannot assess the relative contributions of these, or other factors, such as chronic arsenic poisoning (59), in the emergence of complex funerary practices.

AM in the Atacama practically disappeared by 4.4 ka BP. Our analysis could shed light on why this occurred. Records of hydrological change show that at this time there was a sharp drop in regional water availability (Fig. 4). The complex mortuary practices that define the Chinchorro culture completely disappeared from the largest settlement known along the coast (Morro-1 in Arica; Fig. 2). Rodent middens reveal the onset of extreme aridity in the central Atacama Desert between 4 and 5 ka BP (18, 19). This coincided with the loss of complex funerary practices in the Chinchorro culture (Fig. 6). Increased aridity in the highlands (and associated diminished groundwater tables) is a likely contributing factor to what would have been either the cultural transformation or migration of groups (60).

More importantly, increased frequency and intensity of warm water currents associated with strong El Niño events (61) began to extend their effects into northern Chile and precipitated the decline of the Chinchorro culture through a collapse of available marine resources, as suggested by Williams et al. (32), and likely in conjunction with other natural disasters, as has been suggested for north central Coastal Peru (62). These environmental events are consistent with the hypothesis that there was a decrease in population size (to levels before 7 ka BP; Fig. 4) and hence an increase in the likelihood that the skill of mummifying bodies was either lost by stochastic drift or by imperfect inference (12).

Materials and Methods

Statistical Analysis. We analyzed the $\delta^{18}O_{ice}$ time series for the Sajama ice core (29) by calculating Hölder exponents (also called Lipschitz-Hölder exponents). Hölder exponents are useful measures to characterize the continuity of a given function (63). A time signal $s(t)$ is Hölder continuous if there exists a constant C and a polynomial of degree m, such that for any t in the neighborhood t_0 the inequality

$$|s(t) - P_m(t)| \leq C|t - t_0|^{\alpha} \quad [1]$$

holds true, where α is the local Hölder exponent for t_0. Thus, the function is said to be Hölder continuous in the range [A,B] if **1** is satisfied for all $t_0 \in$ [A,B]. In other words, the signal under scrutiny can be considered stationary in the range [A,B]. Similar values of α repeated in time define windows of dynamically regular behavior, providing a valuable tool for stationarity testing and for the detection of time periods of similar variability regimes (and by complement burst of anomalous activity).

If the regularity of $s(t)$ at t_0 is n-1 < α_0 < n, with $n \in$ N, then $s(t)$ is (n-1) times continuously differentiable, but its derivative $s^{(n-1)}$ is singular. The Hölder exponent value characterizes this singularity: if $\alpha = 0$, the function is bounded and discontinuous; if $\alpha < 1$, the signal is continuous and non-differentiable. If $s(t)$ is Hölder with $\alpha < n$ in t_0, then we can approach the neighborhood of t_0 with a polynomial of maximum degree (n-1). In other words, $P_m(t)+E_{t_0}$ with $|E_{t_0}| \leq C|t-t_0|^{\alpha}$.

The Hölder exponent estimates for the Sajama time series suggest the existence of nonstationarity, characterized by abrupt changes between phases of regular temporal dynamics.

Past Population Size. We use the approach taken by Williams et al. (32) to infer past population sizes from coastal archeological sites along coastal southern Peru and northern Chile (17–25°S). The record sums the probability distributions of 460 calibrated ^{14}C dates published in the archeological literature spanning the last 14 ka BP. Our estimates incorporate methods used by Williams (64) to reduce biases when using the sum of radiocarbon distributions as a proxy for past human populations. The 460 radiocarbon dates from 131 archeological sites were converted to calendar years using CALIB 6.1.0 with the INTCAL09 (65) for dates ≥9.53 ^{14}C ka BP and SH04 (66) for dates <9.53 ^{14}C ka BP. Sites were also classified into "domestic" (357 ^{14}C dates) and "funerary" (103 ^{14}C dates) categories to evaluate the influence of archeological context on our analyses. The resulting distributions were achieved using the "summed probability" function available with CALIB 6.0.1. Following the recommendations of Williams (64), we use a moving average of 600 y to offset biases introduced by the calibration procedure and to describe overall population changes over the last 14 ka BP. Further, our sample size is within the range (200–500) that minimizes the biases associated with sample size.

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