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Materials and Methods

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Human Occupations and Climate Change in the Puna de Atacama, Chile

Lautaro Núñez,[1] Martin Grosjean,[2*] Isabel Cartajena[3]

Widespread evidence for human occupation of the Atacama Desert, 20° to 25°S in northern Chile, has been found from 13,000 calibrated ^{14}C years before the present (cal yr B.P.) to 9500 cal yr B.P., and again after 4500 cal yr B.P. Initial human occupation coincided with a change from very dry environments to humid environments. More than 39 open early Archaic campsites at elevations above 3600 meters show that hunters lived around late glacial/early Holocene paleolakes on the Altiplano. Cessation of the use of the sites between 9500 and 4500 cal yr B.P. is associated with drying of the lakes. The mid-Holocene collapse of human occupation is also recorded in cave deposits. One cave contained Pleistocene fauna associated with human artifacts. Faunal diversity was highest during the humid early Holocene.

Initial Paleoindian occupation of southern South America is found in the temperate rain forest at 14,600 calibrated ^{14}C years before the present (cal yr B.P.) (*1*, *2*), but apparently 2000 years later at ~13,000 cal yr B.P. (*3–5*) in the arid Atacama Desert and on the coast of Peru. Does this reflect migration lags, prohibitive late Pleistocene environments, or an incomplete archaeological survey of the vast desert? Was Pleistocene fauna still present when the first people arrived? And did people respond to Holocene climate change?

Here we provide evidence that late glacial and Holocene human occupation in the Atacama Desert was associated with climate change. We surveyed the most arid part of the

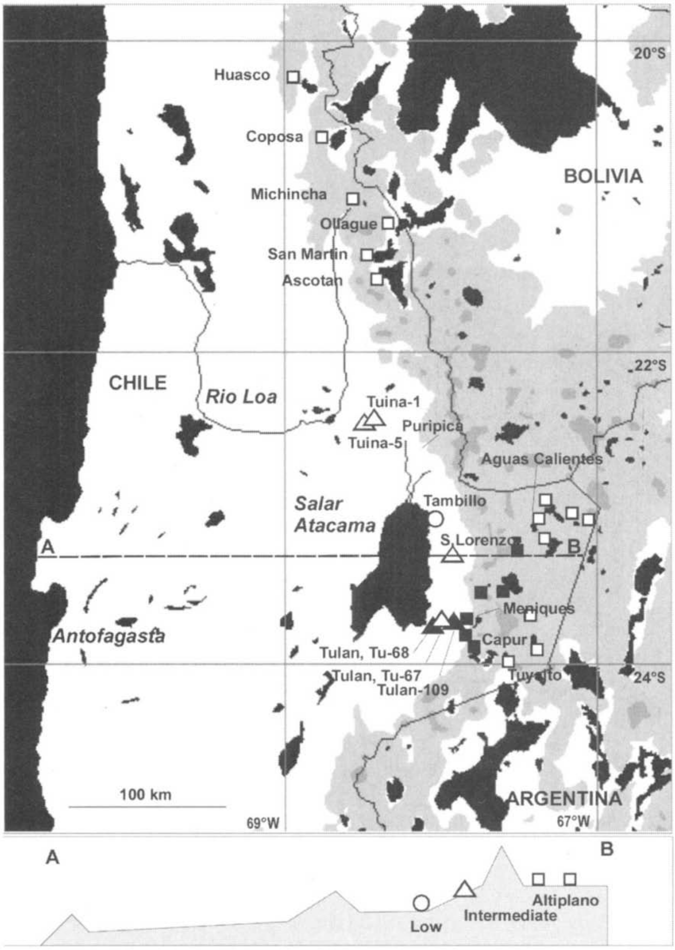

Fig. 1. Map showing the archaeological sites in high-elevation paleolake basins (squares), caves and shelters at an intermediate elevation between 3000 and 3600 m (triangles), and paleowetland sites at low elevation (2400 m) (circles). Lakes and salt flats in black shaded areas are above 4000 m. Open symbols are sites with triangular projectile points.

Atacama Desert, 20° to 25°S at elevations between 2400 and 4500 m, where humidity was critical to early societies. This area is located between the Salar de Atacama and the high-elevation plateau, the Altiplano, in northern Chile (Fig. 1). Modern precipitation, mainly during austral summer, ranges between <20 mm year^{-1} in the Salar de Atacama and <200 mm year^{-1} on the Altiplano. The annual 0°C isotherm is at 4400 m, and vegetation is extremely sparse, with a maximum of $\sim$30% cover between 3800 and 4000 m. Springs and a few perennial creeks are focal points for any life present.

We conducted a survey for new archaeological sites in three complementary types of habitats: (i) open campsites along fossil Quaternary shorelines of Altiplano paleolakes above 3600 m, (ii) caves at intermediate elevations between 3000 and 3600 m, and (iii) low-altitude paleo-wetlands around the Salar de Atacama at 2400 m. We hypothesized that open lakeside sites would best indicate changes in the habitat due to regional climate change, whereas caves have always been a focus of attraction for human habitation, and occupation would have been recorded had humans been present in the region at all. In this sense, caves register fluctuations in human occupation.

Paleoecological data (*6–9*) show that this area changed dramatically from very arid environments at the Last Glacial Maximum (LGM) to relatively humid conditions during late glacial and early Holocene times. In northern Chile, this change began around 14,000 cal yr B.P. and culminated between 13,000 and 9500 cal yr B.P. Grass cover was extensive, and vascular plant diversity was high, particularly between 11,800 and 10,500 cal yr B.P. (*7*, *9*). The shorelines of late glacial paleolakes were up to 70 m above those of the current salt lakes and provided excellent habitats for mobile groups of hunters.

Along the paleoshorelines of 20 of these Altiplano lake basins (Fig. 1) we found 39 early Archaic open campsites. Four of them (San Martin, Aguas Calientes I, Tuyajto-1, and Tuyajto-2) (Fig. 1) contained charcoal dated between 9900 and 8800 cal yr B.P. (table S1). The presence of these 39 sites confirms the hypothesis that the early hunters lived in transhumant mobility with complementary resource use between the high-elevation lakes and low-elevation wetland areas of the Salar de Atacama (such as Tambillo). The high-elevation open paleoshoreline sites contain abundant lithic artifacts and bones of camelids (*Vicugna vicugna* and *Lama* sp.) and in some cases birds, including ñandu (*Pterocnemia pennata*). We found triangular projectile points that are diagnostic for the early period (*10*) at 25 of the 39 sites. At 30 of the 39 sites, microliths, ceramics, and other artifacts indicative of later cultures are absent, suggesting that these sites were never reoccupied. Instead, the sites reflect a particular habitat that was fit for human habitation only during a period of time when conditions were exceptionally favorable and paleolakes existed.

The youngest dated early Holocene fireplaces on the Altiplano (San Martin-4) (table S1) are located near the modern Salar, indicating that this paleolake reached modern low levels shortly before that time. The artifacts on the surface of this site were never covered with lake sediments; thus, the lake has not grown substantially above modern levels during the past 9000 years. This adds to the view, based on lake sediments and ice cores, that paleoclimates were generally dry during the mid- and late Holocene (*8*, *11–14*). This contrasts with interpretations of paleovegetation data (*7*, *9*).

This cluster of early Holocene lakeside sites is followed by a 4500-year-long hiatus. Exceptions are the sites Laguna Miscanti and Huasco (table S1), where paleolakes were replaced with mid-Holocene wetlands and grazing areas in the flat bottom area of the former lake, and thus more favorable habitats were created in a drier climate (*8*). Later reoccupation of the modern shorelines is shown by a cluster of 28 late Archaic sites. Three of them in Capur and Ollagüe were dated between 3700 and 3350 cal yr B.P. (table S1). This coincides with the lakes' recovery from the prolonged mid-Holocene low levels. Although 8 of the 28 modern shoreline sites show a purely preceramic pattern, diverse artifacts and ceramics give evidence of multiple reoccupations at most of the other sites.

As a reflection of the changing environmental conditions, sites that were occupied at different times are found at different locations. Early sites are located along paleoshorelines that are distant from modern resources, whereas late sites are found near the modern shorelines and subsistence resources. Mid-Holocene lakeside sites are rare.

Six early caves and shelters are known in this area: Tuina-1, Tuina-5, San Lorenzo-1, Tulan-67, Tulan-68, and Tulan-109 (Fig. 1, fig. S1, and table S1). They are located at intermediate elevation between 3000 and 3600 m.

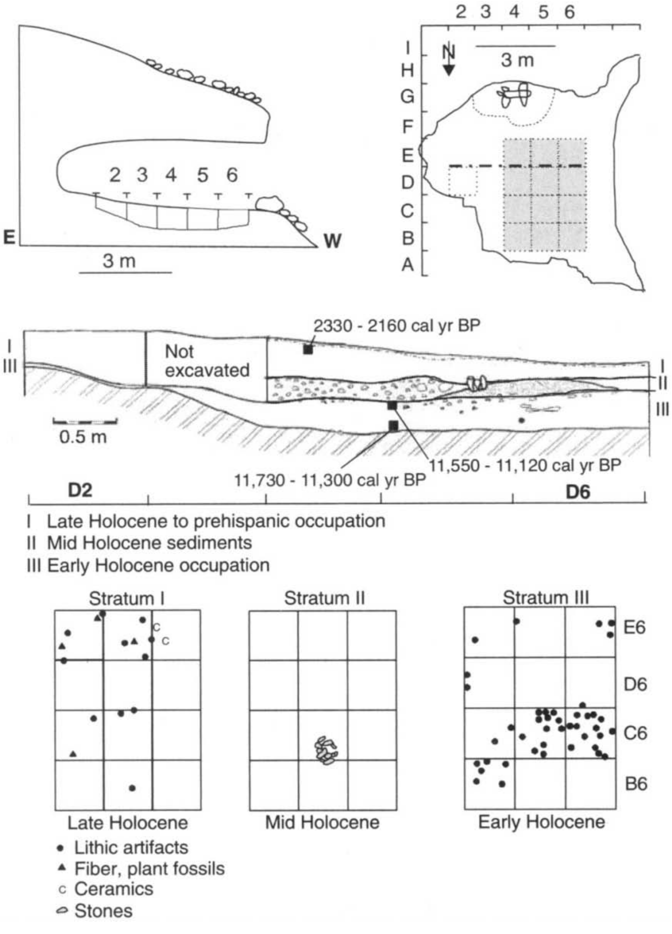

Fig. 2. Cross section and maps of Tuina-5, showing the very rich basal early Archaic cultural level (the plan view map shows artifacts of the basal 5 cm of stratum III); the mid-Archaic stratum II, indicating a very low density of cultural remains (5 cm of the middle section in stratum II); and the late Archaic (late Holocene) stratum I, with reoccupation and a high diversity of artifacts (the top 5 cm of stratum I). The basal stratum III lies directly on bedrock.

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[1]Instituto de Investigaciones Arqueológicas y Museo, Universidad Católica del Norte, Casilla 17, San Pedro Atacama, Chile. [2]National Centre of Competence in Research on Climate, University of Bern, 9a Erlachstrasse, CH-3012 Bern, Switzerland. [3]Departamento de Antropología, Universidad de Chile, Ignacio Carrera Pinto 1045, Santiago, Chile.

*To whom correspondence should be addressed. E-mail: grosjean@giub.unibe.ch

These sites all contain an initial cultural stratum rich in artifacts and bones. In four of the six caves, this stratum contained diagnostic triangular projectile points (fig. S2) that were also found in 25 of the 39 early lakeside sites on the Altiplano and the ^{14}C-dated site of Tambillo at low elevation. Initial occupation of the caves is dated between 12,900 and 9400 cal yr B.P. Four of the six sites are clearly older than 11,500 cal yr B.P. and predate initial occupation of the Altiplano lake sites by as much as 2000 to 3000 years. However, the typology of the triangular artifacts suggests that both habitats were occupied contemporaneously.

Excavation of a new cave, Tuina-5, revealed a stratigraphy (Fig. 2) that, with some modifications, applies to the other caves as well and intrinsically corresponds to the occupational history of the paleolakes: The top stratum (stratum I) shows an assemblage typical of late Holocene to late pre-Hispanic pastoral occupations, with various lithic artifacts, wool and fiber, feathers, copper minerals, charcoal and plant remains, and hearths and ash layers. The bones belong exclusively to camelids (Table 1). The underlying mid-Holocene (~3300 to 9000 cal yr B.P.) stratum (stratum II) reveals no lithic artifacts and reflects low cultural activity. Bones found in this stratum include those of camelids, rodents, and birds. The basal stratum (stratum III) lies directly on a bedrock floor and shows dense early Holocene occupation. It contains 3879 identified bones and 179 functional lithic artifacts, including two triangular projectile points (fig. S2). Lithic artifacts are mainly made of local macroporphyric andesites and dacites or basalt; only three of the specimens found were made of allochthonous obsidian. The bones indicate high biodiversity (Table 1).

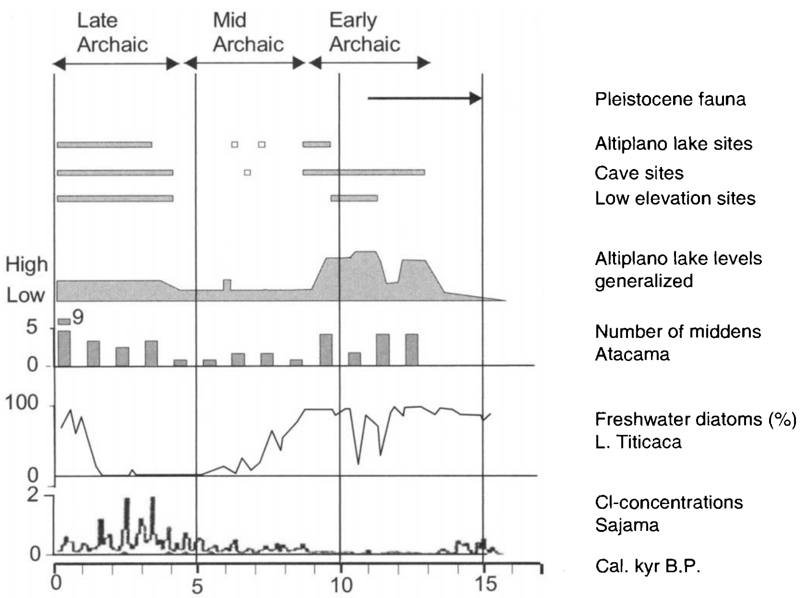

Fig. 3. Synthesis of late glacial Holocene environmental conditions (*8*, *11*, *13*, *18*) and human occupation at high-, intermediate-, and low-elevation sites.

Table 1. Lithic and faunal [number of identified specimens (NISP)] indicators in strata I, II, and III at Tuina-5.

	Surface and stratum I	Stratum II	Stratum III
Lithic artifacts			
Triangular points	0	0	2
Knives	0	0	77
Scrapers	1	0	52
Racloirs	1	0	22
Total	2	0	171
Other artifacts			
Ceramics	22	0	0
Copper minerals	14	0	0
Feathers	12	0	0
Faunal remains (NISP)			
Total weight (g)	413	349	2595
Total no. of fragments	271	583	3879
Camelidae	66	104	393
Cervidae	–	–	12
Chinchillidae	–	10	90
Abrocomidae	–	36	141
Sigmodontinae	–	90	85
Rodentia not identified	–	1	13
Tinamidae	–	4	15
Anatidae	–	–	4
Rallidae	–	–	1
Columbidae	–	4	15
Passeriformes	–	–	3
Aves not identified	–	1	7
Amphibia	–	–	1
Pleistocene fauna	–	–	1
Scrap bones	205	333	3098

One bone fragment in stratum III was of Pleistocene fauna, probably from an Equidae (*15*, *16*) (fig. S3), and was found in direct association with human artifacts. At all other sites in the south-central Andes where Pleistocene fauna has been documented [such as (*17*)], it occurs in layers below those showing human occupation. This is different from the Paleoindian sites in central Chile, where Pleistocene fauna is abundant and associated with typical fishtail projectile points (*5*).

Sites at a lower elevation of 2400 m show evidence of occupation at around 11,000 cal yr B.P. Obsidian flakes were found in wetlands at Tambillo east of the modern wetlands of the Salar de Atacama. Subsurface sites on nearby alluvial cones date between 10,200 and 9400 cal yr B.P. Both typology and lithology of the allochthonous artifacts correspond to the artifacts found in early cave deposits at intermediate elevations and at the sites around the paleolakes on the Altiplano (fig. S2). Obviously, the three altitudinal zones were used as complementary habitats within the same transhumant pattern.

Given that paleolakes and thus favorable environmental conditions became established after ~14,000 cal yr B.P. (*9–11*) (Fig. 3), initial human colonization is expected to have taken place up to 2000 years later than in south-central Chile, where humid conditions prevailed throughout late glacial times. This first phase of human occupation in the Puna de Atacama lasted until the paleolakes and subsistence resources disappeared. There is evidence for a significant decline and in some cases even a hiatus of human occupation due to aridity stress in all three habitats between 21° and 25°S, largely from 9000 to 4500 cal yr B.P. This time is known as the "Silencio Arqueológico" (*5*) and corresponds to low lake levels in the south-central Andes and the Titicaca basin, to low accumulation rates and elevated

Cl concentrations in the Sajama ice core, and to a number of other pedological and geomorphological features indicative of long-term dry climates (*8*, *11–14*, *18*). This decline in human activity around the Altiplano paleolakes is seen in most caves, with early and late occupations separated by largely sterile mid-Holocene sediments. However, a few sites, including the caves of Tulan-67 and Tulan-68, show that people did not completely disappear from the area. All of the sites of sporadic occupation are located near wetlands in valleys, near large springs, or where lakes turned into wetlands and subsistence resources were locally still available despite a generally arid climate (*7*, *8*, *19*, *20*).

Archaeological data from surrounding areas suggest that the Silencio Arqueológico applies best to the most arid areas of the central Andes, where aridity thresholds for early societies were critical. In contrast, a weaker expression is to be expected in the more humid highlands of northern Chile (north of 20°S, such as Salar Huasco) and Peru (*21*). In northwest Argentina, the Silencio Arqueológico is found in four of the six known caves (*22*) [see review in (*23*)]. It is also found on the coast of Peru in sites that are associated with ephemeral streams (*24*). The southern limit in Chile and northwest Argentina has yet to be explored.

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Figs. S1 to S3
Tables S1 and S2

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Network Motifs: Simple Building Blocks of Complex Networks

R. Milo,[1] S. Shen-Orr,[1] S. Itzkovitz,[1] N. Kashtan,[1] D. Chklovskii,[2] U. Alon[1]*

Complex networks are studied across many fields of science. To uncover their structural design principles, we defined "network motifs," patterns of interconnections occurring in complex networks at numbers that are significantly higher than those in randomized networks. We found such motifs in networks from biochemistry, neurobiology, ecology, and engineering. The motifs shared by ecological food webs were distinct from the motifs shared by the genetic networks of *Escherichia coli* and *Saccharomyces cerevisiae* or from those found in the World Wide Web. Similar motifs were found in networks that perform information processing, even though they describe elements as different as biomolecules within a cell and synaptic connections between neurons in *Caenorhabditis elegans*. Motifs may thus define universal classes of networks. This approach may uncover the basic building blocks of most networks.

Many of the complex networks that occur in nature have been shown to share global statistical features (*1–10*). These include the "small world" property (*1–9*) of short paths between any two nodes and highly clustered connections. In addition, in many natural networks, there are a few nodes with many more connections than the average node has. In these types of networks, termed "scale-free networks" (*4*, *6*), the fraction of nodes having k edges, $p(k)$, decays as a power law $p(k) \sim k^{-\gamma}$ (where γ is often between 2 and 3). To go beyond these global features would require an understanding of the basic structural elements particular to each class of networks (*9*). To do this, we developed an algorithm for detecting network motifs: recurring, significant patterns of interconnections. A detailed application to a gene regulation network has been presented (*11*). Related methods were used to test hypotheses on social networks (*12*, *13*). Here we generalize this approach to virtually any type of connectivity graph and find the striking appearance of

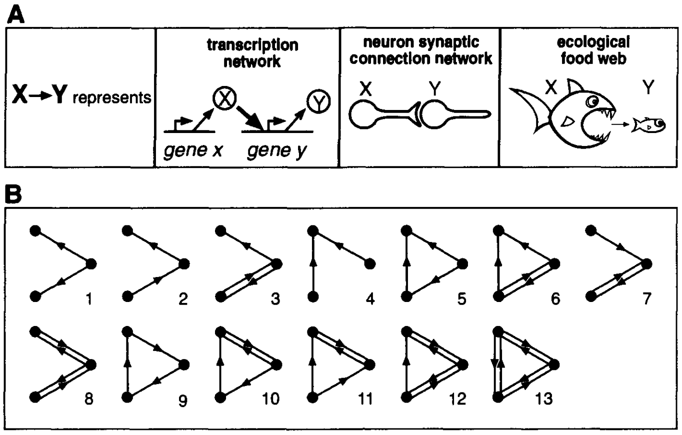

Fig. 1. (**A**) Examples of interactions represented by directed edges between nodes in some of the networks used for the present study. These networks go from the scale of biomolecules (transcription factor protein X binds regulatory DNA regions of a gene to regulate the production rate of protein Y), through cells (neuron X is synaptically connected to neuron Y), to organisms (X feeds on Y). (**B**) All 13 types of three-node connected subgraphs.

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[1] Departments of Physics of Complex Systems and Molecular Cell Biology, Weizmann Institute of Science, Rehovot, Israel 76100. [2] Cold Spring Harbor Laboratory, Cold Spring Harbor, NY 11724, USA.

*To whom correspondence should be addressed. E-mail: urialon@weizmann.ac.il