The Rise and Fall of Wiñaymarka: Rethinking Cultural and Environmental Interactions in the Southern Basin of Lake Titicaca

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Abstract (150 words)

Investigations of how past human societies managed during times of major climate change can inform our understanding of potential human responses to ongoing environmental change. In this study, we evaluate the impact of environmental variation on human communities over the last four millennia in the southern Lake Titicaca basin of the Andes, known as Lake Wiñaymarka. Refined paleoenvironmental reconstructions from new diatom-based reconstructions of lake level together with archaeological evidence of animal and plant resource use from sites on the Taraco Peninsula, Bolivia reveal frequent climate and lake-level changes within major cultural phases. We posit that climate fluctuations alone do not explain major past social and political transformations but instead that a highly dynamic environment contributed to the development of flexible and diverse subsistence practices by the communities in the Titicaca Basin.

Keywords: Lake Titicaca, Human-environmental interactions, Lake-level change, Subsistence diversification, Environmental archaeology

Introduction

The study of past human-environmental relationships in different settings globally has been integral to defining the Anthropocene (Erlandson & Braje 2013) and informing decisions of how human communities might respond more effectively to the ongoing climate crisis (Barnes et al 2013; Redman *et al.* 2004). The first generation of large-scale, interdisciplinary archaeological and paleoenvironmental studies, while groundbreaking, often had low temporal and spatial resolution, which rendered their correlation imprecise. Moreover, sometimes the records were interpreted simplistically to suggest that climate variability was the major influence on the rise and fall of ancient societies (Contreras 2016; Rosen 2007). Increasingly collaborative projects amongst paleoscientists are improving the quality of data collection, synthesis, and interpretation of past human-environmental interactions, resulting to more nuanced, less deterministic interpretations that consider a variety of scales and tempos of climatic and societal change (Dincauze 2000).

The Lake Titicaca Basin (16°S, 69°W, 3810 m above sea level) in the Andes of South America has a long, dynamic history of study into human-environmental relationships. Beginning in the late 1980s, large-scale, interdisciplinary archaeological and paleoenvironmental studies produced the first generation of hypotheses about the relationship between regional climate change and human communities in this high and dry, yet productive, region (Abbott *et al.* 1997; Baker *et al.* 2005; Baker *et al.* 2001; Binford *et al.* 1997; Kolata 1993, 1996, 2003; Rigsby *et al.* 2003). Building on these studies, climate change was invoked to explain the appearance of agriculture here around 2000 BCE (Aldenderfer 2009; Marsh 2015), shifts in socio-political centers and economic practices in the Formative period (1500 BCE- 500 CE) (Bandy 2001; Capriles *et al.* 2014; Smith & Janusek 2014), and the rise in political strife and warfare during the Pacajes period (1100-1400 CE) (Arkush 2008). The role of climate change in the rise and fall of the Tiwanaku state, between 500 and 1100 CE, has received considerable attention. Some scholars argued that the success of this early state was rooted in an intensive agricultural system of raised-fields built along the sometimes-inundated shorelines and plains (*pampas*) of Lake Titicaca (Janusek & Kolata 2004; Kolata & Ortloff 1996; Ortloff & Kolata 1989). Based on paleoenvironmental data from the Quelccaya glacier in central Peru (Thompson *et al.* 1985) and sediment cores in the Wiñaymarka basin of Lake Titicaca (Abbott *et al.* 1997), Kolata and colleagues proposed that raised-field agriculture was supported by wetter climatic conditions between 500-1050 CE and subsequently undermined by a multi-decadal drought around 1050 CE, which ultimately contributed to the collapse of the Tiwanaku state (Binford *et al.* 1997; Ortloff & Kolata 1993).

Erickson (1988, 1999) criticized this narrative and argued that farmers in the region were adaptable and that climatic fluctuations were unlikely to be the only cause of the state's demise. He cited historical accounts of local Aymara farmers, who adjusted to lower lake levels in drought years by planting in the newly exposed and fertile lands. Additionally, studies of raised fields in Koani Pampa showed that they continued to be used during post-Tiwanaku times (Graffam 1990, 1992; Janusek 2004). The relevance and interpretation of the Quelccaya data were also questioned, including the distance of the site from the lake, the robustness of the dating and its calibration (Calaway 2005; Erickson 1999; Williams 2002), and the climate interpretation accorded by Thompson *et al.* (1985) to the proxy measurements (Arkush 2011; Baker *et al.* 2009; Vimeux *et al.* 2005). This debate illustrates the need for a careful and increasingly multicausal consideration of the dynamic interactions between socio-political entities *and* climate change that might have contributed to the decline of states, such as Tiwanaku.

Here, we contribute new insights into human-environmental studies in the Lake Titicaca basin through interdisciplinary collaboration to examine both previous and new archaeological and paleoclimate datasets from the smaller, southern basin of Lake Titicaca, known locally as Lake Wiñaymarka, which translates as "eternal place" in Aymara. First, we review the regional archaeological chronology for the basin established by long-term interdisciplinary archaeological projects, including our own, the Taraco Archaeological Project (TAP). Then, we examine paleoenvironmental reconstructions for the Wiñaymarka basin, including the pioneering study of lake low-stands by Abbott *et al.* (1997) and a recent study of diatom assemblages by Weide *et al.* (2017). Our intent is to examine the *longue durée* of environmental change experienced by people in the Wiñaymarka basin over the past 4,000 years and to examine variability in climate and lake level within major periods that archaeologists consider to be culturally continuous (Ramón Joffré 2005; Swenson and Roddick 2018). Finally, we consider archaeological plant and animal data of taxa that are sensitive to environmental change from the Formative and Tiwanaku periods on the Taraco Peninsula. While it has long been recognized that residents of the Titicaca Basin employed diverse economic strategies, including farming, fishing, and herding (Browman 1987; Bruno 2014a; Stanish 2003), few archaeological studies have utilized direct zooarchaeological or archaebotanical evidence for these practices (Bruno 2008). Through integrating this recent paleoenvironmental and archaeological evidence, we track the persistence of diversified subsistence practices in relation to climatic changes in the Wiñaymarka Basin over the last 4,000 years.

Regional chronology and human occupation in the Wiñaymarka basin

Over 40 years of archaeological research on human occupation of the Wiñaymarka basin has produced a detailed radiocarbon-derived chronology of major shifts in settlement, economic practices, ceramic styles, and social and political organization. In particular, long-term, interdisciplinary projects in the Tiwanaku and Katari valleys (Albarracin-Jordan 2007; Janusek 2008; Kolata 1996, 2003; Ponce Sangines 1981), Desaguadero River valley (Smith & Janusek 2014), and Taraco Peninsula (Bandy 2001; Browman 1978, 1981; Hastorf 2003a, 1999) provide data to generate a comparative framework.

The regional archaeological chronology developed by Janusek (2003), Bandy (2001), and Hastorf (Bandy & Hastorf 2007; Hastorf 2008; Roddick & Hastorf 2010) for the Wiñaymarka Basin is the most widely used today (Table 1). Each period is defined based on observable changes in ceramic types and technologies, settlement patterns, architectural, and iconographic styles associated with major socio-political trends (Janusek 2003; Marsh *et al.* 2019). The materials dated, the technology used (radiometric or AMS), and calibration procedures varied based on the generation of the projects (Capriles & Hastorf 2021; Marsh 2012; Marsh *et al.* 2019). Paleoclimatologists working in South America have relied on the southern hemisphere calibration curve (recently updated to SHCal20, Hogg *et al*. 2020) but its applicability to the tropical Andes, where the atmospheric circulation results in contributions of carbon from both hemispheres remains unclear (Marsh *et al.* 2018).

While it is advisable to use the same calibration protocols when comparing different datasets, it is beyond the scope of this paper to recalibrate the hundreds of dates from multiple projects that have contributed to the regional Wiñaymarka chronology. Instead, we present the most recent modeled age ranges for each archaeological phase (Table 1). To represent the limits of the archaeological phases of settled village life in the Wiñaymarka basin, known as the Early and Middle Formative periods, we use dates from the site of Chiripa, Bolivia (Capriles & Hastorf 2021). For the final era of pre-state development, known as the Late Formative period, we use dates from multiple sites that designate major changes in the use of regional decorated ceramics styles (Marsh *et al.* 2019). The end of the Tiwanaku state is based on radiocarbon dates from Proyecto Wila Jawira (Janusek 2003; Janusek & Kolata 2004). The final two periods of pre-Columbian life, designated as Pacajes and Inka, are based on historical records of the timing of the Inka and then the Spanish conquests.

Terminal Archaic: Evidence for Archaic period activity in the Wiñaymarka basin is scant and, to date, no Archaic components have been directly radiocarbon dated (Capriles & Albarracin-Jordan 2013). Research in the western lake basin and southern Altiplano, however, shows that mobile hunting and gathering groups occupied the region, starting as early as 8,000 BCE, with increased use and management of resources, such as camelids, chenopods, and potatoes between approximately 3,000-1,000 BCE (Aldenderfer & Flores Blanco 2011; Haas & Llave 2015).

Early Formative (EF): The more robust archaeological record of the Early Formative (EF) shows a shift from mobile hunting-gathering to a more settled agropastoral and fishing lifestyle, which sustained populations in the region hereafter. The initial transition (EF I) appears to coincide with the well-documented progressive flooding of Lake Wiñaymarka based on multiple lines of paleoecological evidence, which we discuss in more detail below. Scholars propose that the increase in regional moisture and environmental productivity in the Titicaca basin ~2,450 BCE years ago fostered the expansion of agriculture and more settled agropastoral communities (Hastorf 2008; Marsh 2015; Stanish 2003).

Table 1. Regional archaeological chronology for Wiñaymarka/southern Lake Titicaca basin. We retain the calibrations as presented in the original publications.

Regional chronology (Janusek 2003; Hastorf 2008).	**Refined Late Formative chronology (Marsh *et al.* 2019)**	**Refined Early and Middle Formative chronology (Capriles & Hastorf 2021)**
Sites in Katari and Tiwanaku valleys and Taraco Peninsula Dates calibrated using IntCal09 curve	Bayesian analysis of multiple sites with decorated ceramics. Dates calibrated with mixed IntCal13/SHCal13 curve.	Bayesian analysis within the site of Chiripa using stratigraphy and ceramics. Dates calibrated with SHCal20 curve.
Inka 1450-1532 CE		
Pacajes 1100-1450 CE		
Tiwanaku 500-1100 CE		
Late Formative 200 BCE- 500 CE	Terminal Formative 420-590 CE	
	Late Formative II 240-420 CE	
	Late Formative I 120-240 CE	
	Initial Late Formative 250 BCE-120 CE	
Middle Formative 800-200 BCE		Middle Formative/Late Chiripa 725-209 BCE
Early Formative 1500-800 BCE		Early Formative II/Middle Chiripa 1037-727 BCE
		Early Formative I/Early Chiripa 1379-1037 BCE
Terminal Archaic 3000-1500 BCE		

EF I communities were organized as dispersed hamlets near the lakeshore, supported by exploitation of lacustrine resources, which complemented early quinoa and tuber agriculture and camelid pastoralism (Bandy 2001; Stanish 2003). In the later Early Formative (EF II), the earliest communal architecture in the lake basin was built, specifically, trapezoidal sunken courts that included burials. These were likely associated with community-wide ceremonial rituals, including feasting (Hastorf 2003b), and may have paved the way for the first social differentiation within communities (Bandy 2004; Stanish 2003).

Middle Formative (MF): Populations grew across the Wiñaymarka basin, as farming and herding expanded, and use of lake resources diminished slightly in comparison to the EF (Capriles *et al.* 2014; Moore *et al.* 1999). Villages formed, expanded, and developed specialized community architectural spaces. The best known of these communities is Chiripa, on the Taraco Peninsula, with a mound, which was rebuilt over several generations, including a central court with small rooms around its perimeter (Hastorf 1999; Portugal Ortíz 1992). Although elaboration of some types of burials, carved stone, and architecture styles point to greater social and political differentiation within MF communities, each village appears to have been an autonomous political entity (Bandy 2004).

Late Formative (LF): At the beginning of the Late Formative (LFI), communities continued to increase in population, but with a clear shift in settlement type. The numerous autonomous villages consolidated and grew into fewer, more centripetal multi-community polities, such as Kala Uyuni on the Taraco Peninsula, Lukurmata in the Katari Valley, Khonkho Wankane and Iruitu in the Desaguadero River Basin, and Tiwanaku in the Tiwanaku valley. A marked change in ceramic production occurred, with new forms of vessels across the basin (Marsh *et al.* 2019; Roddick & Hastorf 2010). Detailed Bayesian analysis of changes in LF decorated ceramics has enabled greater division of this long period. Other significant changes in community architectural practices also took place. In some cases, such as at Khonkho Wankane and Tiwanaku, sunken courts were elaborated and nested; in others, such as Sonaji and Kala Uyuni, sunken courts were closed, and raised platforms were erected (Roddick *et al.* 2014). There is scant evidence of social and political differentiation among community members, as noted in burials, although leaders likely became prominent figures in economic and religious activities. Competition between these solidifying polities apparently intensified over time (Janusek 2008, 2018; Stanish 2003). By the Terminal LF, approximately 420 to 590 CE, the center of Tiwanaku emerged as the primary political and religious entity in the region.

Tiwanaku: At approximately 500 CE, the large village of Tiwanaku became the center of the region's first state, serving as a population, political, and trade center, whose influence consolidated the integration of Lake Titicaca under a single polity. It eventually expanded as far south as the Atacama Desert of Chile, north and westward to southern coastal and highland Peru, and southeastward to the Cochabamba valley, Bolivia (Albarracin-Jordan 2007; Janusek 2008; Kolata 1993; Ponce Sangines 1981; Stanish 2003; Stanish & Vranich 2013). Tiwanaku political and religious leaders oversaw the construction of impressive monuments in the city center, made of earth and enormous cut stones that hosted elaborate ceremonies and feasts for locals and visitors. A large population grew within and around the city center, supporting the activities of the polity, particularly in trade and craft production, which included new forms of stone carving and construction, elaborate ceramic vessels utilized for ceremonial food presentations and ceremonial offerings. The Tiwanaku polity during its expanding stages was supported by both intensive agriculture, which included major expansion of raised-fields in the southeastern Titicaca basin and maize production in distant warmer regions, and large-scale camelid pastoralism that facilitated constant interregional trade. This polity and its ceremonial nature endured for approximately 600 years, until it lost local and far-distant control at approximately 1100 CE. This decline has been ascribed to multiple causes, including climate change in the form of an extended period of drought (Kolata *et al.* 2000; Arnold *et al*. 2021).

Pacajes and Inka: With the disintegration of the centralized Tiwanaku polity, populations in the Wiñaymarka basin again took the shape of autonomous villages and political entities. Although there were some fortified villages in the south (e.g. near Khonkho Wankane), fortified villages were more common in the northern Titicaca basin and farther north (Arkush 2011). In the Wiñaymarka region, populations apparently continued to live and produce food across the broader landscape as they had done before. Studies of the raised fields show scattered settlements throughout the pampas, as camelid herds were maintained on drier lands (Albarracin-Jordan 1996; Bandy and Janusek 2005; Pärssinen & Siiriäinen 1997).

The Inka made several attempts to bring this area under their influence and were finally successful in 1450 CE. Although they established a religious occupation at Tiwanaku itself, their most elaborate and well-known centers were built at Island of the Sun, Island of the Moon, and on the Copacabana Peninsula, where a formal pilgrimage center was established (Delaere 2017; Stanish & Bauer 2004).

Lake Wiñaymarka: Dynamics of Contemporary Climate and Lake Levels

The Wiñaymarka basin (Lago Menor or Huiñaimarca) is much smaller and shallower (>70% is <10m deep) than the northern basin of Lake Titicaca (Lago Grande or Chucuito) (Figure 1A) and includes the northeastern Chua and southwestern Taraco sub-basins (Figure 1B). The Chua sub-basin has a maximum depth of ~42 m, with a relatively steep face on its northern flank near Tiquina Strait and a gentler slope to the south and east. The much larger Taraco sub-basin has a maximum depth of ~20 m and a gentler slope on all sides. A wide, saddle-shaped sill that is <10 m deep connects the two sub-basins so that on interannual and longer timescales, substantial lake level declines will isolate the two sub-basins from each other (Wirrmann 1992).

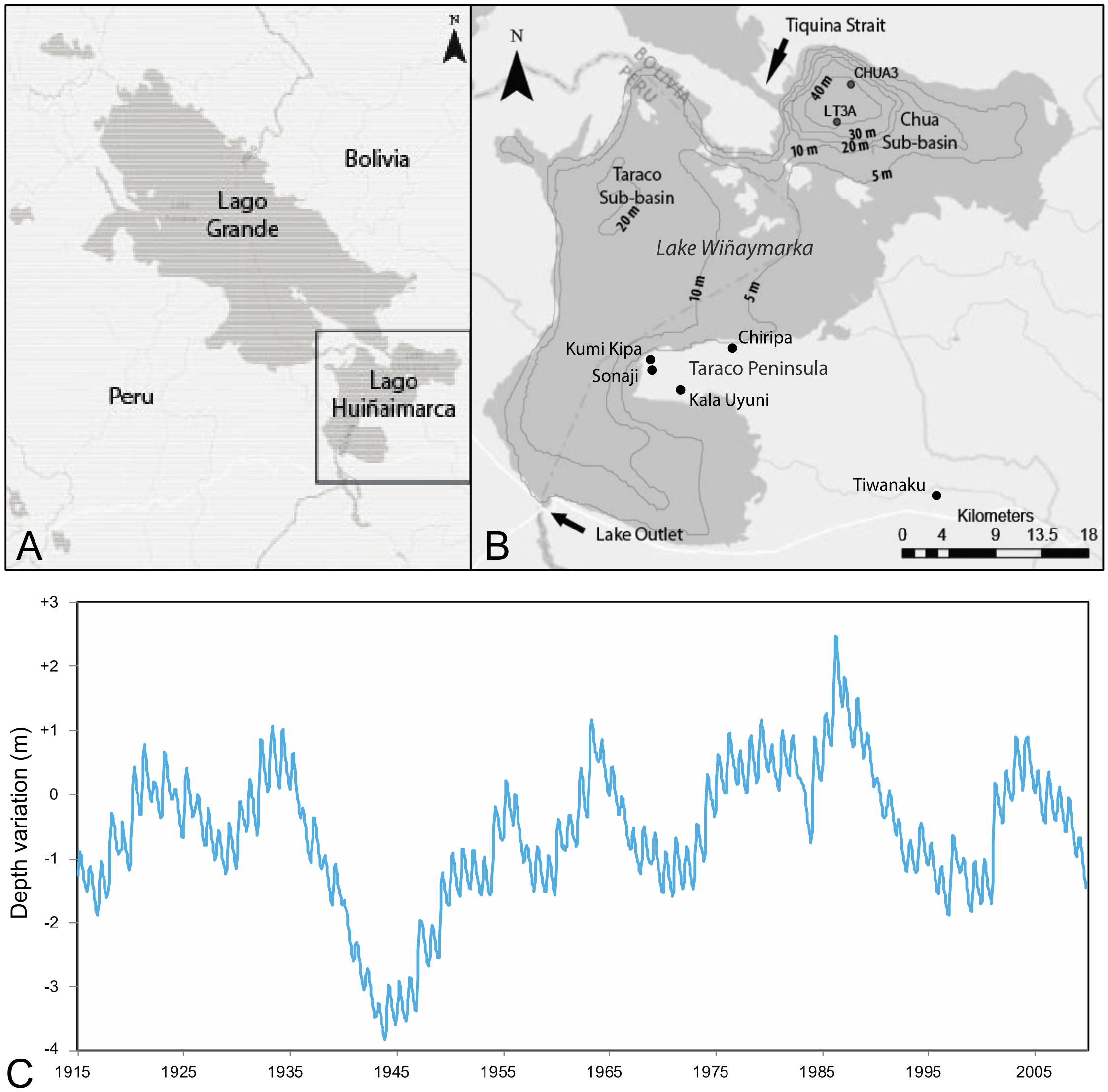

Figure 1. (A) Lake Titicaca showing its two basins. (B) Detail of the Wiñaymarka basin today, including the locations of major archaeological sites mentioned in text and two cores (CHUA3 and 3A) raised from the Chua sub-basin. (C) Historically documented lake-level variation measured at Puno, Peru, relative to the 3810 m above sea level elevation datum (SENAMHI 2019).

Lake Titicaca is surrounded by grasslands. Average annual rainfall for the watershed is 600-800 mm, although some areas receive up to 1300 mm (SENAHMI, 2019). The austral winter (April-October) is dry, with the lowest temperatures in July, whereas austral summer (November-March) has warmer temperatures and receives the majority of annual precipitation (>60%) (Roche *et al*. 1992). Precipitation variation is driven by the continental-scale South American summer monsoon (Garreaud & Aceituno 2001; Roche *et al.* 1992). Five major rivers feed the lake: the Ilave, Ramis, Coata, Huancané, and Suches. Inflow from these rivers accounted for ~53% of water inflow to the lake in the late 20th century (Roche et al 1992). The remaining ~47% of input was direct precipitation onto the lake surface. At the southern end of the Taraco sub-basin lies the sole outlet of Lake Titicaca, the Desaguadero River. Southward outflow from Lake Titicaca to the central Altiplano via the Desaguadero River averaged ~10% of annual water export from the lake, while the remaining 90% of water loss was evaporation from the lake surface (Roche *et al.* 1992). During low lake levels, flow of the Rio Desaguadero can reverse, as Lake Titicaca becomes a closed basin. During these periods of negative water balance, lake level begins to drop, shorelines move lakeward, exposing more land around the lake margin, and, if prolonged dry conditions persist (i.e. for centuries), the lake water becomes more saline.

In an observational time series of lake level recorded at Puno, Peru between 1914 and 2000 (SENAMHI 2019), the average seasonal rise and fall of lake level was 50 cm, with a total range of lake level variation of 6.3 meters (Figure 1C). The largest sustained drop in lake level was between 1935 and 1943, when 8 consecutive years of below-average precipitation brought about a 4.3 m lake-level drop and the lowest lake level ever recorded historically (3806.17 m)[1]. In contrast, the highest historic lake level was in 1986, when the level rose to 3812.49 m (Roche

[1] This long drought was produced by a combination of warm Tropical North Atlantic (TNA) sea-surface temperatures (cold TNA brings about high precipitation on decadal time scales), as well as an unusual occurrence of two-El Niño Southern Oscillation (ENSO) years in a row, 1940-41 and 1941-42, which also produce dry conditions in the *Altiplano*.

et al. 1992). Lowered lake levels, such as during 1943-1946, exposed large areas of Wiñaymarka's lake floor and increased the surface area of land available for human resource use (Binford *et al.* 1997). Although increased shoreline area can be beneficial to agriculture and grazing, during extreme cases, such as the 1935-1945 drought, there can be so little precipitation that agriculture and even pastoralism becomes almost impossible. In such cases, life-sustaining practices shift by necessity toward utilization of lacustrine resources for food and animal fodder. Conversely, during higher lake levels, such as in 1986, floods displaced over 100,000 people from agricultural lands on the lake margins and led to violence between neighboring communities (Sztorchv *et al.* 1989). These tensions persist in some regions to present day.

Records of past climate and lake-level change in the Wiñaymarka basin

Lake sedimentation and low stands

During the mid-Holocene (~8500-4500 years ago), a prolonged period of low precipitation and warm temperature caused the lake to fall below the outlet level, with the eventual desiccation of most of Lake Wiñaymarka and a minimum lake level of Lago Grande nearly 100 m below present day (Baker *et al.* 2001; Cross *et al.* 2000). Yet, at times during the mid-Holocene, a small lake persisted in the deep Chua sub-basin of Lake Wiñaymarka. After ~2450 BCE, water level rose in the main basin of the lake, rapidly flooding through the Straits of Tiquina into the Wiñaymarka basin. In the years that followed this flooding, the level of Lake Wiñaymarka rose and fell in response to variability in precipitation/runoff and temperature. Because of its shallow depth and nearly closed drainage, Lake Wiñaymarka is particularly well-suited for reconstruction of lake level and climate during the late Holocene.

In the first detailed study of lake level changes in Lake Wiñaymarka, Abbott and colleagues (1997) analyzed a series of sediment cores taken along a depth transect. By identifying hiatuses (gaps in sediment accumulation) in these cores using classical sedimentological observations and dating these hiatuses using radiocarbon analyses of sediments below and above the unconformities (erosional surfaces, in this case formed by lowered lake level), they deduced a multi-centennial history of lake-level change. Lake-level maximal elevations were constrained by the overflow level of the lake (assumed to be equal to the modern value); lake-level minimum elevations were deduced from the presence or absence of hiatuses at each depth along the depth transect. Five lake-level maxima (ranging between -3 to +5 m above modern overflow levels, with reported errors of elevation ranging between 5 and 15 m) and four lake-level minima (ranging between 6 and 10 m below modern outflow levels, with reported errors of elevation of 4 to 5 m) were identified (Abbot *et al.* 1997; Weide *et al.* 2017: Table 3).

Apart from the large range of estimated elevations of lake-level minima and maxima, two characteristics of this lake-level reconstruction limit its utility for comparison with the archeological record. First, the lake-level reconstruction is aliased, as it only identifies intervals of lake-level change sufficiently large to produce unconformities. This is in contrast to the higher frequency intra-annual to quasi-decadal lake-level variations that we know from the instrumental measurements (Figure 1C), which do not drop lake level enough to create an erosional surface at the sediment/water interface. Second, erosion of sediment and associated material during lake-level lowstands may have removed portions of the stratigraphic record. In most cases, Abbott *et al*. (1997) estimated approximately 200 years of missing section, thus missing history, at each site based on calculated sedimentation rates. For these reasons, Abbott *et al.* (1997: Fig. 4) illustrated these intervals with broad shaded bands indicating the error ranges and question marks where lake elevation is uncertain.

Diatoms and lake levels

To increase the temporal resolution of the lake-level history during the late Holocene, we analyzed a new core (CHUA3) from the 42-meter deep Chua sub-basin of Lake Wiñaymarka. The Chua basin never dried up during the last ~4,000 years, thus providing a continuous lacustrine sedimentary record. We compared and correlated this core with another core (3A) obtained as part of the earlier Lake Titicaca Drilling Project (Fritz *et al.* 2007), which spans at least the past 100,000 years but did not recover the sediment-water interface containing the last ~1,000 years of history. Using the analysis of diatom assemblages as a proxy for lake level, data from these two cores allowed us to reconstruct a complete history of relative lake level spanning the past 4,000 years (Weide *et al.* 2017).

Diatoms are single-celled algae that can live in most near-surface aquatic environments that have sufficient light. Their siliceous cell wall preserves well in many lake and ocean sediments and can be used to reconstruct paleoenvironments at the time of diatom deposition, because individual species are characteristic of specific habitats (Smol & Stoermer 2010).

In the Chua Basin sediment core, diatoms were grouped into the following ecological categories based on their salinity and habitat characteristics (Figure 2): (1) freshwater planktic, those that live in the open waters of the lake and occur in freshwater (salinity less than 2 g l^{-1}) (*Cyclostephanos andinus*, *Discostella stelligera*, and *Fragilaria crotonensis*); (2) saline-indifferent planktic, species that can grow in water of fresh to moderate salinity (*Cyclotella meneghiniana*); (3) benthic, which includes all species that grow attached to substrates in shallow water (among benthic taxa, *Nitzschia denticulata* and *Epithemia* species were especially abundant); (4) epiphytic, taxa that grow attached to aquatic plants (*Cocconeis* spp.); and (5) saline species that only grow in saline conditions (>2 g l^{-1}, *Chaetoceros* sp., *Fragilaria zelleri*).

These broad ecological groups were used to infer past changes in water depth and salinity of Lake Wiñaymarka (Figure 2). In very shallow water, light reaches rooted aquatic plants and the sediment surface, favoring the proliferation of epiphytic and benthic species. If the basin is closed, in other words if there is no outflow, salinity gradually builds up over time, which

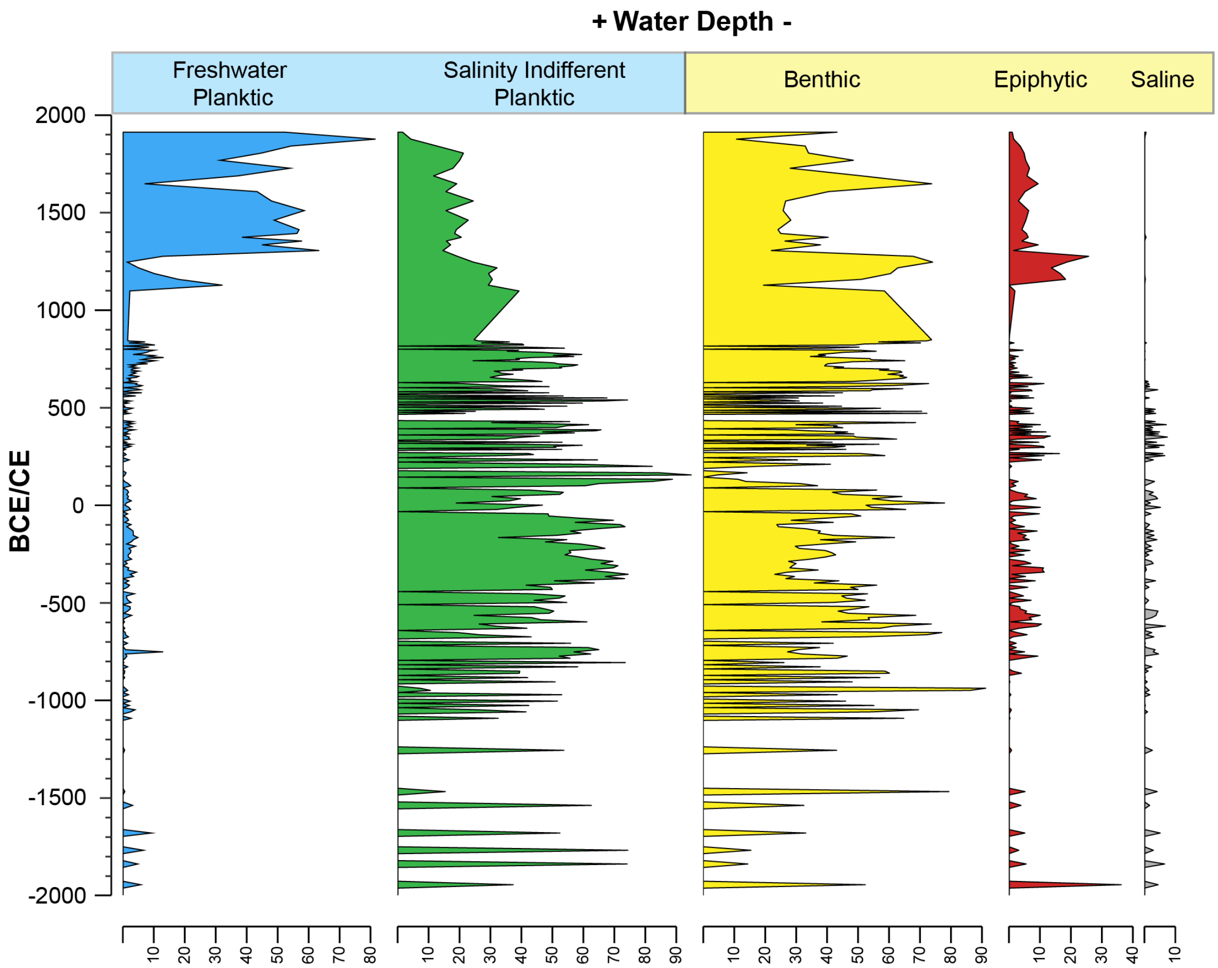

Figure 2. A summary of major diatom ecological groups during the last 4,000 years in Lake Wiñaymarka sediments (modified from Weide *et al.* 2017).

eventually enables saline taxa to proliferate. The "salinity indifferent" planktic taxon can grow in the open waters of shallow systems, both fresh and saline, but they increase in abundance relative to the benthic and epiphytic species as water level increases. Finally, as lake depth rises above the outlet threshold, the lake becomes both fresher and deeper, thus less light reaches the lake floor. Together such changes favor the abundance of freshwater planktic species. Although diatom relative abundance data do not permit quantitative environmental reconstructions, they do permit a nearly continuous reconstruction of relative changes of water salinity and depth.

An integrated lake-level history

The radiocarbon ages that bracket the low-stand intervals identified by Abbott and colleagues (1997) were recalibrated by Weide *et al*. (2017) using the same calibration curve as used for the diatom data in order to compare the two. The recalibration of the radiocarbon dates produces changes in the timing, and, in some cases, the duration of low-stand intervals identified previously (see Weide *et al.* 2017 for additional detail). A comparison of the two data sets reveals some coherence (Figure 3), with peaks in the relative abundance of diatoms characteristic of shallow water habitats (benthic taxa) during portions of each of the Abbott low- stand intervals. Yet, the diatom data show significant variation on multi-decadal and centennial time scales. The evidence for more frequent lake-level variation in the diatom data in comparison with the sedimentological data likely occurs, because 1) samples for diatom analysis were collected at closely spaced intervals and record a more continuous history, in contrast to the episodic unconformities in the sedimentological data; and 2) the deep Chua sub-basin has a high and continuous sedimentation rate for the past ~4,000 years, with no evidence for erosion at the sediment surface. Thus, it records the time intervals that were lost due to erosion at the shallower sites studied by Abbott and colleagues.

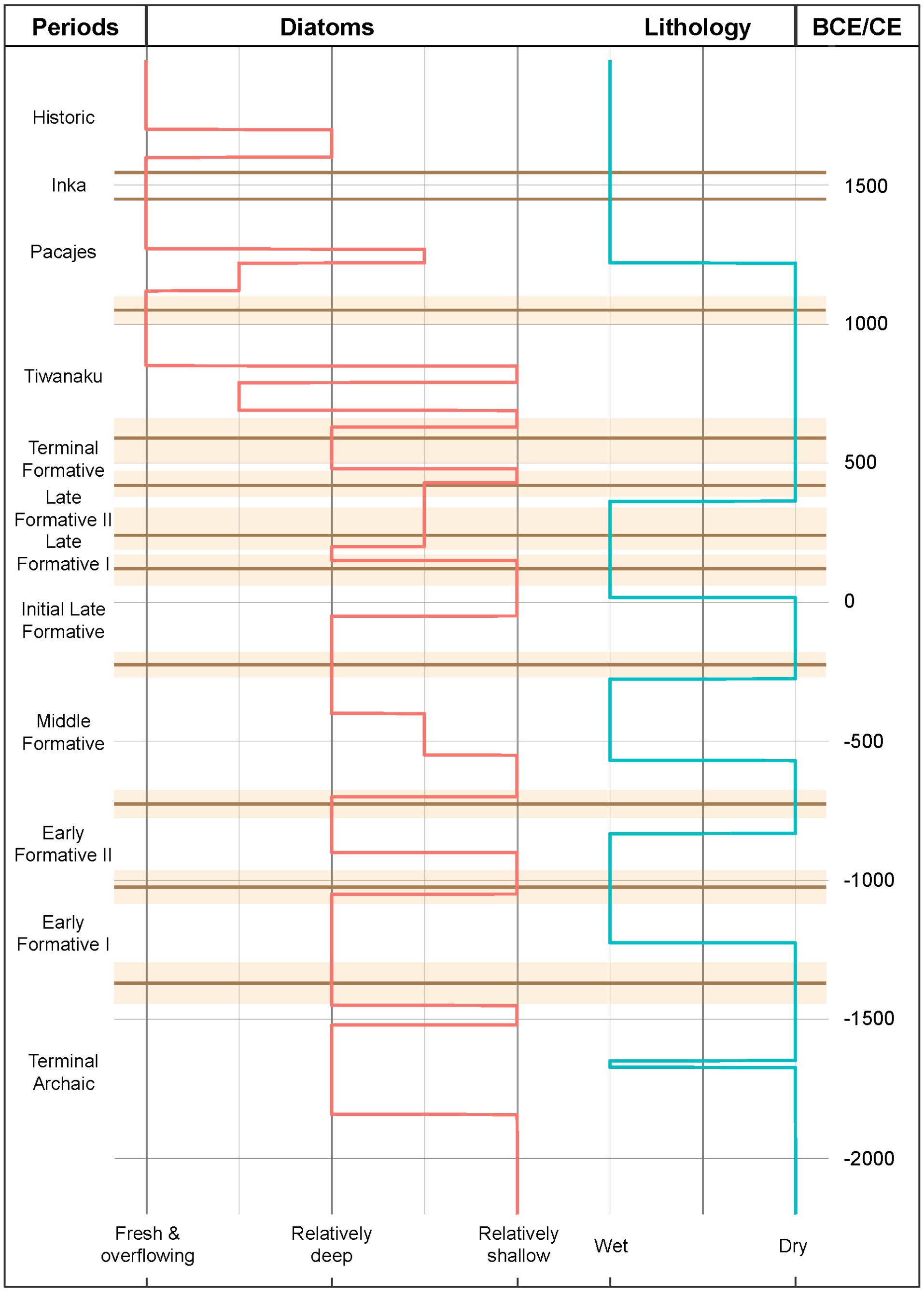

Figure 3. Lake-level reconstructions of Lake Wiñaymarka based on a qualitative summary of the diatom ecological categories shown in Figure 2 (red) and the recalibrated lithology (cyan) (both modified from Weide *et al.* 2017), with the archaeological periods and dates indicated on the y-axis, including the uncertainties associated with their boundaries as derived from Bayesian models (beige).

The diatom data suggest that the lake fluctuated regularly from relatively shallow to moderately deep until ~700 CE (Figures 2 and 3). About that time, saline diatoms declined in abundance, and freshwater planktic species increased. This indicates that lake level reached the outlet level, flushing salts from Lake Wiñaymarka for the first time since the mid-Holocene low stand (Cross *et al.* 2001). Thus, the lake reached the deep freshwater conditions that characterize it today. The initial increase in freshwater planktic diatoms was truncated ~1120 CE, suggesting moderate lake-level lowering, followed by a subsequent increase ~1270 CE. Values generally remained high for the remainder of the record, suggesting persistent wet conditions, with modest variability in lake level, such as is seen today (Figure 1C). Overall the lacustrine record indicates that present-day conditions did not exist until the middle Tiwanaku period and that lake-levels lower than today characterized most of the human occupation of the basin, until just before the Pacajes period.

Zooarchaeological and archaeobotanical indicators of local response to climate change

To examine local responses to these documented changes in climate change and lake level, we compared six categories of animal and plant remains that are sensitive to environmental change and are also direct indicators of human utilization of these resources (Figure 4). The remains derive from flotation samples from four excavated sites in the Taraco Peninsula (Table 2). We use the measure of ubiquity, or percent presence, to track the presence of species through time.

Animal resources

Large mammal bones identified from Taraco sites include a few deer specimens but were dominated by domesticated camelid remains (Moore 2011; Moore *et al*. 1999). These are abundant throughout the sequence, occurring in over 95% of samples across all periods. Camelid herding is a flexible subsistence activity, because herds can be moved in times of shortages of food or water. An inverse relationship of fish (discussed below) and large mammals is apparent, suggesting that camelids may have taken on greater importance when fish were difficult to obtain.

Size patterns of domesticated camelids reflect specific animal husbandry strategies in response to environmental change. Based on modern data on body size, larger camelids, likely llamas, are predicted to thrive under drier conditions, whereas smaller camelids, likely alpacas, thrive under wetter conditions. Moore (2011) examined the size of camelids through time using osteometry and found that the mean size range of camelids was smaller in the EF and Tiwanaku periods, implying potentially wetter conditions, whereas across both MF and LF camelids tended to be larger, suggesting drier conditions. Yet, lake level fluctuated throughout these cultural periods, without a clear correlation between inferred body size and environmental conditions. While shifting the herd composition of camelids may have offered a strategy to manage shifts in local conditions, camelid herding remained consistent through time.

Fish are the most likely taxa to vary with lake-level, because populations vary in relation to lake size, water depth, salinity, and nutrient loading, all of which are directly controlled by water balance (precipitation plus inflow minus evaporation plus outflow). Despite known periods of low lake level within each period, fish are abundant throughout the sequence, with over 95% ubiquity across all periods. Capriles and colleagues (Capriles *et al.* 2008; Capriles *et al.* 2014) showed that although fish ubiquities declined during low-stand periods, they were still present in significant quantities, suggesting that people continued to consume fish through diverse climate conditions and despite variable distance of the lake from settlement locations.

The use and importance of birds seem unrelated to environmental variables and may be associated with other desires/demands for this resource. Overall, bird bones were less represented than fish or camelids, with ubiquities ranging between 80% and 50%. Although the proportion of birds and particularly aquatic birds, which dominate the archaeofaunal assemblages (Kent et al. 1999; Moore et al. 1999; Steadman & Hastorf 2015), might be expected to vary in relation to changing environmental conditions, this does not appear to be the case. In fact, they are quite sparse during the MF period when lake level was high, yet elevated during the low lake levels between the ILF/LFI and LFII/TF transition. Over time, the slight correlation observed between birds and sedges (Cyperaceae) suggests an association of habitats, such as totora beds, as nesting sites for coots and teals, the two most abundant bird taxa. Possibly, the procurement of wild resources, including both aquatic and terrestrial birds, also became increasingly important during periods of decreased lake level, perhaps as fallback foods or part of opportunistic hunting during movements from residential settlements to fields increasingly farther away. More research is required to further understand the dynamics of bird procurement in the peninsula.

Table 2. Number of flotation samples from the Taraco Peninsula sorted for the identification of animal and plant remains and used to derive the ubiquity percentages presented in Figure 4.

Period	Fauna	Flora
Early Formative I (EF I)	50	94
Early Formative II (EF II)	32	94
Middle Formative (MF)	141	379
Initial Late Formative (ILF) and Late Formative I (LF I)	93	128
Late Formative II (LF II) and Terminal Formative (TF)	9	20
Tiwanaku	42	42
Total	367	757

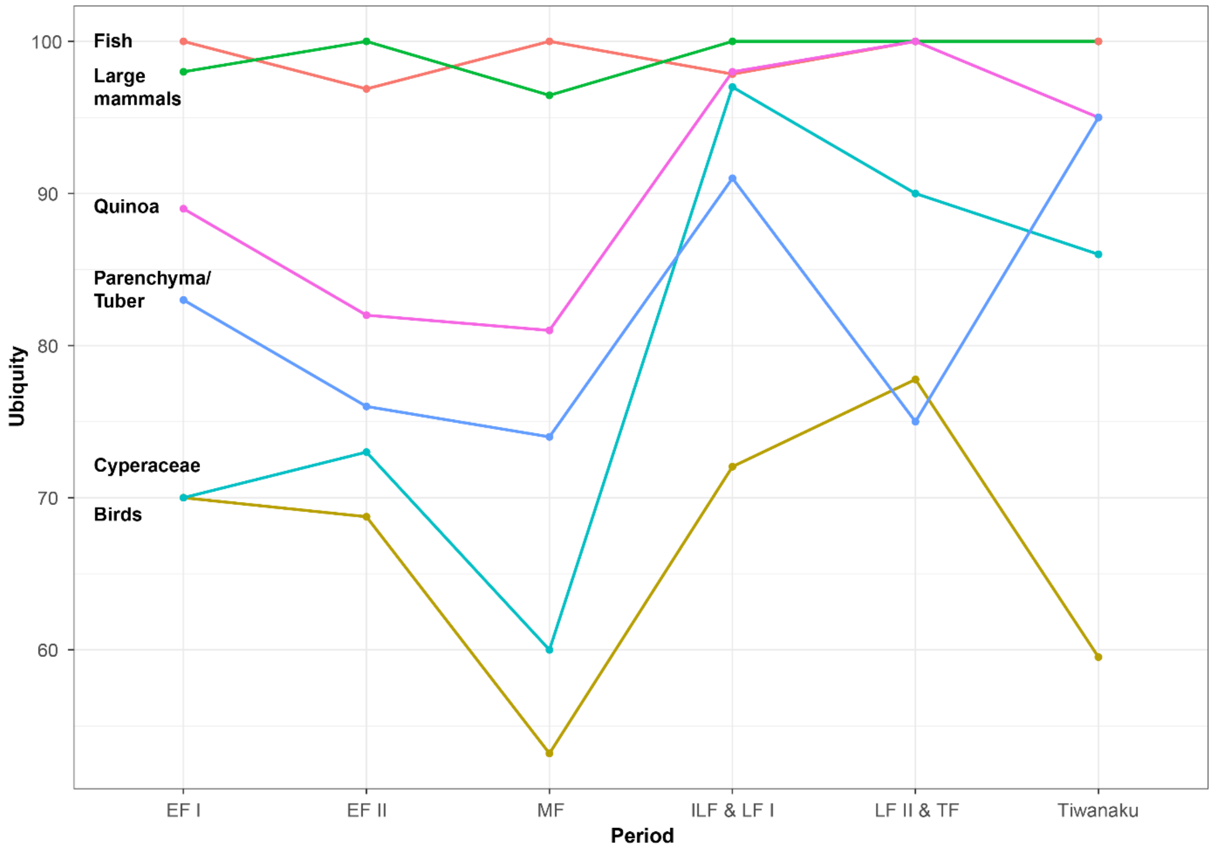

Figure 4. Ubiquity (percent presence) of plant and animal species from TAP excavations at Chiripa, Kala Uyuni, Sonaji, and Kumi Kipa. See Table 2 for sample sizes and abbreviations.

Plant resources

Analysis of macrobotanical plant remains from Taraco Peninsula sites reveals that quinoa and tubers formed the basis of local farming systems for centuries (Bruno 2008; Whitehead 2007). While quinoa tends to be more ubiquitous than tubers (likely due to differences in preservation), they trend in similar ways, with consistent ubiquities across the EF and MF periods, increasing into the LF and Tiwanaku periods.[2] This increase in crop ubiquity along with increased diversity of weed assemblages and stone agricultural implements suggests that farmers were intensifying agricultural production in the LF, possibly with increased tilling and

[2] The decline in parenchyma ubiquity during the LFII&TF period may be the result of a smaller sample size and the fact that several samples were from contexts with very low overall densities of plant remains. When considering the LF periods as a whole (see Bruno 2014) the trend seems to be towards increased tuber presence.

shortening fallow periods (Bruno 2014b), despite indications of a period of drier conditions and lower lake levels.

Bruno (2008) considered changes in the ubiquity of water-loving sedges (Cyperaceae), which could be indicative of drier versus wetter periods. Interestingly, their ubiquities generally increase through time independent of lake level. These species are consumed by animals and provide raw materials for buildings and basketry. Thus, possibly like birds and fish, their presence is more reflective of human interest to obtain them than immediate availability on the landscape.

Overall, these changing patterns of fishing, herding, hunting, farming, and wild plant collection on the Taraco Peninsula point to the importance of a mixed economy that began with the EF and persisted at least through the Tiwanaku period. We have not excavated any Pacajes Period sites on the Taraco Peninsula. Although settlement patterns and cultural practices across the basin changed dramatically during this time, archaeobotanical studies from the ridge top site of Ayawiri, Peru demonstrate that these communities, historically known for camelid pastoralism, were also involved in varied agriculture, including tubers and chenopods, on hillside terraces (Langlie 2018). Overall, the Taraco Peninsula animal and plant remains illustrate that the relative importance of individual subsistence strategies likely varied as both the environmental and socio-political climate changed, but without any strong relationship with rainfall and lake level (Bruno 2011; Capriles *et al.* 2014; Moore 2011). In the long-term view, subsistence activities of the Taraco residents persisted with relatively little change in the face of relatively consistent episodes of environmental variability.

Environmental and human history in the Wiñaymarka basin

Our synthesis of paleoenvironmental and climatic data suggest that recurrent changes in rainfall and lake level were relatively common and unexceptional in the lives of people residing in this region. A comparison of lake-level trends with the archaeologically distinctive social and political changes across the Formative and Tiwanaku periods suggests no simple relationship between lake-level and broader societal change (Figure 3). Each archaeological period included extended periods, sometimes over a century, of drier *and* wetter conditions. For example, conditions were drier, with lower lake levels, during the start of the MF, then became wetter. This contrasts with the early steady onset of new ceremonial construction in the MF at Chiripa, which suggests that dry conditions did not limit food production, social or political elaboration.

Variable lake-levels characterized the long Tiwanaku period. The original Abbott *et al.* (1997) low-stand reconstruction depicted lake-levels as somewhat uncertain across much of this period but identified a major low-stand at its termination. The diatom data suggest that the lake varied between century-long intervals of low versus moderately high levels throughout this period. The inference is that the Tiwanaku state successfully persisted during long intervals of drier climate (moderate drought), lending credence to arguments that political and social factors, not only climate factors, played a substantive role in the polity's ultimate demise (Janusek 2003). Both the diatom data and the recalibrated ages of the last hiatus in the Abbott *et al*. study support the presence of major prolonged drought beginning around 1200 CE, which may have contributed to social disruption, instability, and warfare within the Pacajes polities, after Tiwanaku had lost its religious and political potency. This was followed by a wetter interval, as has been documented in the north basin (Arkush 2008). From the Inka period onward, both the diatom and sedimentological data suggest no major periods of lake-level decline relative to those of prior millennia, although certainly substantial droughts and floods are registered in historical times.

Ethnographic information from the Taraco Peninsula reveals how contemporary indigenous residents in the Wiñaymarka basin integrate seasonal changes in rainfall and lake level into their land-use and resource management strategies (Bruno 2008, 2011). Today, Aymara speaking communities on the north and western end of the Peninsula still obtain most of their food through a combination of subsistence farming, cattle and sheep herding, and fishing[3]. Additionally, the entire agricultural cycle is timed and planned around seasonal changes in rainfall and lake level (Bruno 2008, 2011). Accordingly, all agricultural activities are closely connected to local knowledge of environmental variables, such as soil type, precipitation, and changes in the lake. In the dry season, the lakeshore recedes as much as 100 m horizontally, exposing moist soil that can be planted earlier at the start of the growing seasons. This moist swath of land is referred to as *milli*, which translates as "first potato". These fields mature and are ready to harvest when the lake level begins to encroach upon plants, as the rainy season refills the lake. Rains then permit planting further up the pampa and hillside.

Certainly, many differences exist between past and present Taraco Peninsula farmers, including crops, technologies, and variation in the relative distribution of soils on the landscape. Yet relational analogies (Wylie 2002:147-148) can be used to hypothesize about how past farmers may have reacted to long-term shifts in rainfall and lake level based on modern-day use of the landscape for agriculture. For instance, Bruno (2011) postulated that past agropastoralists likely would have 1) scheduled planting and harvest with the predictable seasonal fluctuations, and 2) adapted to longer-term shifts, such as decadal-scale lake-level decline, by simply

[3] In addition, many community members regularly move to the city of La Paz and engage in wage labor as fishing has been greatly impacted by over-harvesting and pollution in recent decades.

following the shoreline migration, as has been recorded during historical droughts and subsequent wet periods. Recent underwater excavations near the northern shore of Lake Wiñaymarka suggest that people placed residential sites in previously exposed areas that eventually became abandoned and are now submerged as a consequence of increased lake levels (Delaere 2017). Both in the past as in the present, Wiñaymarka basin residents likely made decisions based on ongoing seasonal and inter-annual environmental variability, which contributed to shaping their socio-environmental systems. The persistence of Taraco peninsula communities on the landscape and the continuous records of agropastoral and lacustrine activities across these cultural time periods, with their associated climate changes, suggest that diverse subsistence strategies always accompanied flexible land use.

Conclusions

The Abbott *et al.* (1997) study was influential for archaeological researchers interested in understanding the variable landscapes and environmental context of ancient communities in the Wiñaymarka Basin of Lake Titicaca. From that record archaeologists correlated four identified low-stands with archaeological chronologies (Bandy 2001; Janusek 2008; Kolata 2003; Moore 2011). Yet more recent lake-level reconstructions (Weide *et al.* 2017) have added a new layer of complexity to our understanding of this highly dynamic environment in the Wiñaymarka basin, and, together with new archaeological data on resource use, have motivated a re-evaluation of the role of the lake and its climate vis a vis political changes observed in the material record by archeologists.

Long-term trends in fishing, herding, farming, and hunting uncovered from the archaeological record of the Taraco Peninsula, spanning the Formative through the Tiwanaku periods, reveal that climate and cultural shifts did not necessarily lead to the abandonment of any particular subsistence practice or settlement, but rather, motivated continued diversification of flexible food production practices. Ethnographic research supports the contention that indigenous communities of the Titicaca basin exercised a diversification strategy that involved developing several indigenous crop varieties suited for varied soil, moisture, temperature, and rainfall conditions (Browman 1987; Orlove 2002; van den Berg 1990). Similarly, multiple camelid varieties were developed during pre-Hispanic times, when some of the largest flocks in the Andes were in the Titicaca basin. Constant climatic change likely provided an incentive to maintain a diverse resource base, not just by maintaining a combination of fishing, herding, and farming but also by retaining species and varietal diversity within domesticated plant and animal populations. This could partially explain why the Lake Titicaca Basin is a center of crop diversity for quinoa and potatoes today (Ugarte & Iriarte 2009; Tapia 2014).

Unquestionably, this environment, including its rainfall, temperature, and high elevation created the parameters for people's livelihoods over the last 4,000 years. Yet, much like the Aymara communities inhabiting the region today, people in the past relied on flexible and resilient management traditions for fishing, herding, and farming. A next step would be for researchers to "zoom in" on particular time periods, at particular sites with refined dating and archaeological evidence, to develop more nuanced understandings of how people dealt with these shifts at specific moments in time. It is likely that within these broader socio-political periods, which appear to be quite stable in the long-view, multi-year drought or flooding events were disruptive to daily lives, as has been documented in historic times, but never enough to instigate abandonment. Although generations of Wiñaymarka basin communities clearly inherited the knowledge of how to be productive under a range of distinct climate conditions, the social and political configurations of households, villages, and large polities would have each contributed different stresses, shaping local responses to these changes. Continued multi-disciplinary collaboration at the individual site level, as well as the at the regional scale, will help us better understand, as Janusek and Kolata (2003:426) described, the "tenacious" ways the indigenous inhabitants of Wiñaymarka "responded creatively to changing environmental conditions" in the past and into the future.

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