Chapter 23

An 1800-year Ice Core History of Climate and Environment in the Andes of Southern Peru and its Relationship with Highland/Lowland Cultural Oscillations

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Introduction

Climate is a fundamental and independent variable for human existence, as well as a factor in shaping the physical landscape within which human societies dwell. The record of human activities in South America before the arrival of the Spanish in 1532 is rich in archaeological remains but the process of reconstructing it is hampered by the lack of deciphered written languages. Through excavations of sites of precolonial civilisations in tropical South America, archaeologists have been able to unearth information about the chronology and activities of cultures in these regions. Climate variability may have played a significant role in the rise and fall of these civilisations, given that both coastal and highland populations were largely agrarian and located in climatically sensitive zones. The coastal cultures were heavily dependent on reliable water supplies, while the highland cultures, located near the upper limits of agriculture, were sensitive to variations in both precipitation and temperature (Paulsen 1976; Kolata 1986). This paper provides a climatic and environmental context of the Inca landscape that serves as a backdrop for the study of the Andean concept of '*ushnu*' (Zuidema, this volume).

In addition to rich cultural histories, tropical South America contains many types of archives of past climate and environmental change. Some of this evidence can be extracted from the ice fields of the Andes region, which contains over 70% of the world's tropical glaciers. Because they have the capacity to record so many climatic and environmental indicators, glaciers serve as one of our best archives of climate change. Here we present 1800-year temperature and precipitation proxy records extracted from an ice core drilled through the Quelccaya ice cap located on the southern Peruvian *altiplano*. These histories help reveal the potential relationships between climate and the rise and fall of coastal and highland cultures in precolonial times, with emphasis on the period leading up to and during the Inca Empire. We present evidence for both decadal- and century-length 'El Niño-like' oscillations and the role they may have played in the rise and fall of highland and coastal cultures in Peru as was argued in Thompson *et al*. 1994 and re-examined using new high-resolution ice core records recovered in 2003. It is serendipitous that these records were recovered from a location within the boundaries of the former Inca Empire, located less than ~100 km from the Inca capital of Cusco.

The Quelccaya ice core programme

One of the largest tropical ice fields on Earth, the Quelccaya ice cap is located close to Lake Titicaca on the easternmost rise of the Andes before a sharp descent into the Amazon basin (Fig. 23.1). Each summer from 1976 to 1984, field programmes were conducted on Quelccaya (13°56′ S; 70°50′ W; 5670 m above sea level) with the ultimate goal of establishing a climate record from an ice core for at least the last 1000 years. In 1983 the objective was achieved with the successful recovery of two cores, one to bedrock and containing 1500 years (Core 1, 163.6 m) and a second, containing 1350 years (Summit core, 154.8 m).

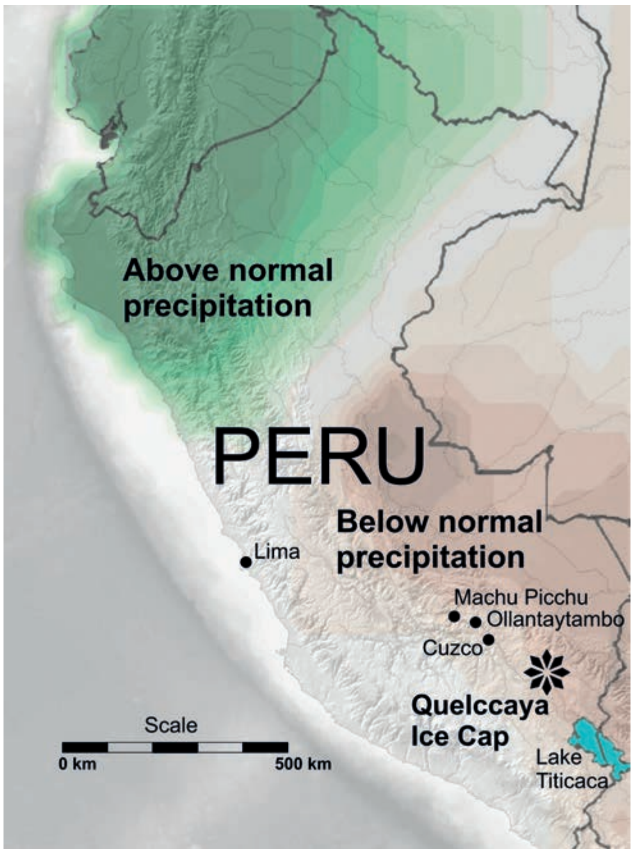

Figure 23.1 Map of Peru showing the location of the Quelccaya ice cap in relation to other features mentioned in the text. The green shading shows areas that experienced higher precipitation during the 1997/1998 El Niño, while brown depicts areas that experienced greater aridity. Accumulated rainfall departures are from November 1997 to April 1998 (adapted from Bell *et al*. 1999 and from www.cpc.ncep.noaa.gov/products/assessments/assess_98/enso.html#warm, fig. 22).

The drilling of the Summit core was aborted above the bedrock because a stratigraphic disruption was encountered at 153.7 m. After logging the visible stratigraphy of the cores during the drilling operation, they were cut into samples that were melted by passive solar heating, bottled and shipped to the ice core laboratory at The Ohio State University (OSU). Unfortunately, the logistics needed to bring the ice cores back frozen from this tropical location did not exist in 1983, which limited both the types of analyses and the ability to recheck visual observations made on the cores in the field. The *in situ* sampling of the cores led to increasing age uncertainties at greater depths and limited the ice accumulation reconstructions, or An (proxy for precipitation) from the layer thicknesses that were measured in the field using a simple straight-edge ruler (Thompson *et al.* 1985). At OSU the bottled samples (over 6000 in total for both cores) were analysed for micro particle (dust) concentration and size distribution using TAII Coulter Counters (Thompson *et al*. 1986). Determinations of oxygen isotopic ratios (δ^{18}O) of samples from Core 1 were performed at the University of Washington and analyses of the Summit core at the University of Copenhagen. Stable isotopic ratios such as those of oxygen have been used as proxies for temperature at both the moisture source region and of air temperature over the Andes, but this interpretation is complicated by other processes such as moisture transport over the Amazon basin (Grootes *et al*. 1989), upper level atmospheric circulation (Henderson *et al*. 1999), and precipitation variability (Hoffman *et al*. 2003).

The record of decadal-scale precipitation from these cores is presented in Thompson *et al*. 1985, while a climatic record of the last 1000 years, including the period incorporating the Little Ice Age (LIA) from the mid-fifteenth to the mid-nineteenth century, is reviewed in Thompson *et al*. 1986. After the retrieval of the cores in 1983, research programmes were continued on Quelccaya from 1984 to 2011 as the potential of this ice cap to provide high-resolution records of climate and the environment in the tropics was quite clear. In 2003 two more cores were drilled, one at the summit (Summit Dome core) and one at the north dome (North Dome core). Unlike the cores drilled in 1983, the new cores were returned frozen to the cold storage facility at OSU and dust concentrations and δ^{18}O were measured. The high annual snowfall on the ice cap and the distinct wet (austral summer; November to March) and dry (austral winter; centred on June, July and August) seasons in the *altiplano* result in visible annual dust bands separated by thick ice layers, as seen on the margin (Fig. 23.2a). The seasonal variations in dust and δ^{18}O can be seen graphically in Figure 23.2 (b and c) for the period 1800–1850 and 1400–1532, respectively. Analysis of this ice, which was more extensive than that performed on bottled samples 20 years earlier, revealed that the Summit Dome core (169.6 m long) preserves an annual time series of tropical climate and environmental history back to AD 226. The shorter North Dome core (128.5 m) contains a record that extends back to AD 789.

Because very fine sampling of these new cores could be performed under laboratory conditions at OSU rather than at the field site, ice accumulation (An) was calculated using methods described in Thompson *et al.* 1985 from the seasonal variations in dust concentration and δ^{18}O rather than from the measurement of visible dust layers by a ruler. Whereas both cores drilled in 1983 contained a total of 6000 samples, the number of samples cut from the 2003 Summit Dome core alone was 6800. We used the distinct annual dust layers to partition the individual years so that the reconstruction represents the period from July to June for each annual layer thickness. These layers progressively thin with depth due to snow to ice densification and the viscous nature of ice, and thus have to be corrected for thinning with depth using a basic flow model that was used on the 1983 cores and discussed in Thompson *et al.* 1985. Ice flow models have been used to date the older sections of ice cores since the first drilling programme in Greenland in 1966 (Johnsen *et al.*1992). The physics of ice flow is well established (Paterson 2000) and has been successfully applied to glaciers around the world, including mountaintop glaciers, often with independent time checks on the model results. Quelccaya was the first high altitude tropical ice cap dated to the base via a modelling approach (Thompson *et al.* 1982) before the first drilling in 1983.

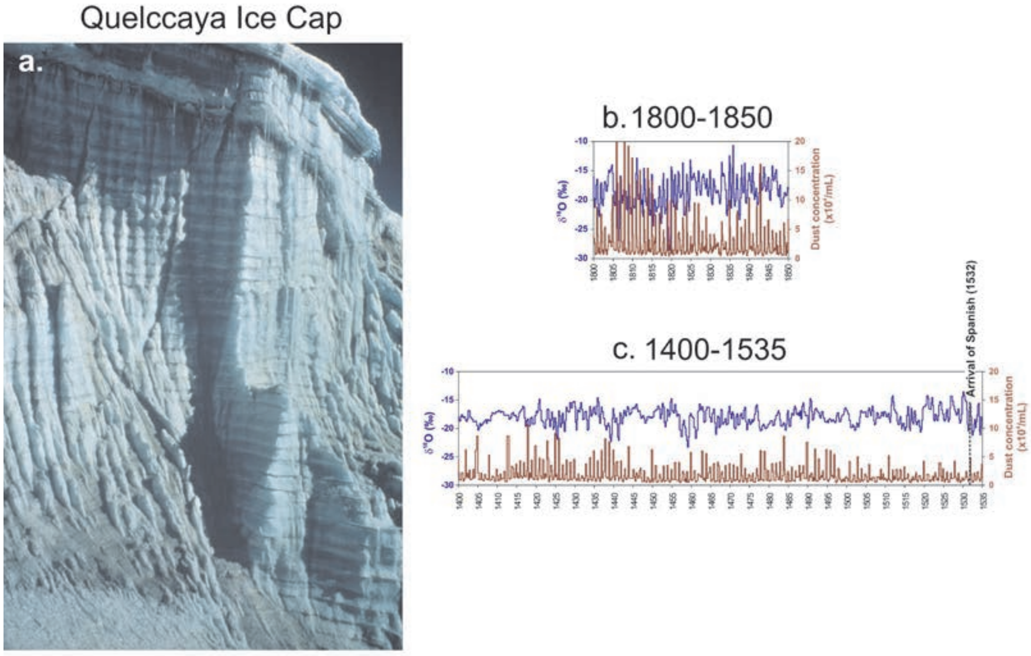

Figure 23.2 (a) The annual layers on the margin of the ice cap are shown in this 1978 photograph. These layers are also evident as annual variations in (b) the concentrations of dust (brown line) and the oxygen isotopic ratios (blue line) from 1800 to 1850 and (c) from 1400 to 1535 through the period of the Inca Empire.

The Quelccaya record of *altiplano* climate variation since the early third century AD

Figure 23.3a shows the 1800-year Quelccaya record from the Summit Dome core as decadal averages of $\delta^{18}O$ and accumulation in metres of ice equivalent, which serve as proxies for temperature and precipitation, respectively. These records from an ice cap located ~100 km southeast of the heartland of the Inca Empire provide a history of climate in the southern Peruvian highlands. Based on temperature and precipitation trends through the past 1800 years, four major climate regimes are discernible in the *altiplano* of southern Peru (Fig. 23.3a). As discussed in the next section and shown in Figure 23.3 (a–e) the migration of population centres between the coastal regions and the highlands appears to be linked to the prevailing environmental and climatic conditions. On the *altiplano* before AD 500 conditions were generally warmer (less negative $\delta^{18}O$) and drier (lower An). From ~AD 500 to 1000 the average precipitation increased in the highlands, although the amounts were variable on decadal time scales. Temperatures gradually decreased, but like precipitation remained variable. The medieval climatic anomaly (MCA) from ~1000 to 1400 was marked by slightly rising temperatures but with a distinct trend towards aridity, with precipitation showing persistently low levels from 1180 to 1450. The MCA was followed by the LIA, which is clearly marked in the ice core record by depletion in oxygen-18, or ^{18}O (lower $\delta^{18}O$ values) from ~1450 to 1880, reaching record low values in the early nineteenth century. Precipitation abruptly increased from ~1450 to ~1700 followed by a decrease from ~1700 to ~1880. As noted above, $\delta^{18}O$, the ratio of ^{18}O to oxygen-16 (^{16}O), provides a proxy for temperature such that a lower or more negative value implies less ^{18}O relative to ^{16}O in the precipitation or snowfall and indicates cooler temperatures. Conversely a higher or less negative value implies more ^{18}O relative to ^{16}O and indicates warmer temperatures (Thompson *et al*. 2000a).

In the region where Quelccaya is located, the effect of the El Niño-Southern Oscillation (ENSO) often results in arid conditions and low accumulation on the ice cap, and is recorded in the stratigraphy of the ice (Thompson *et al*. 1984, 2000b). Therefore the Quelccaya precipitation history can also be used as a proxy record of ENSO frequency. The ice core record is compared with a lake core record (Fig. 23.3a) from the Andes of southwestern Ecuador (Moy *et al.* 2002). The intensity of red colour in the sediments is used to generate a record of ENSO variability. For example, during ENSO events, convective precipitation generated by warm sea surface temperatures (SSTs) off the coast of Ecuador and northern Peru is augmented by orographic uplift of moist air masses along the western flank of the Andes. This leads to an increase in stream discharge and the erosion of andesite and ignimbrite bedrock so that the sediment load into Laguna Pallcacocha produces light-coloured laminae. A red-colour intensity scale was generated by measuring the reflectance of digital scans of the core surface. In the resulting lake record, the higher intensity of red colour signifies more frequent ENSO events. Comparison with the Quelccaya ice accumulation shows that prolonged periods of low/high ENSO frequency generally correspond to wet/dry intervals in the southern Peruvian highlands. This is especially notable before ~AD 600 and from ~AD 1000 to ~1700. This suggests that the decadal-to-centennial-scale variations in precipitation on the *altiplano* may have been linked to El Niño frequency.

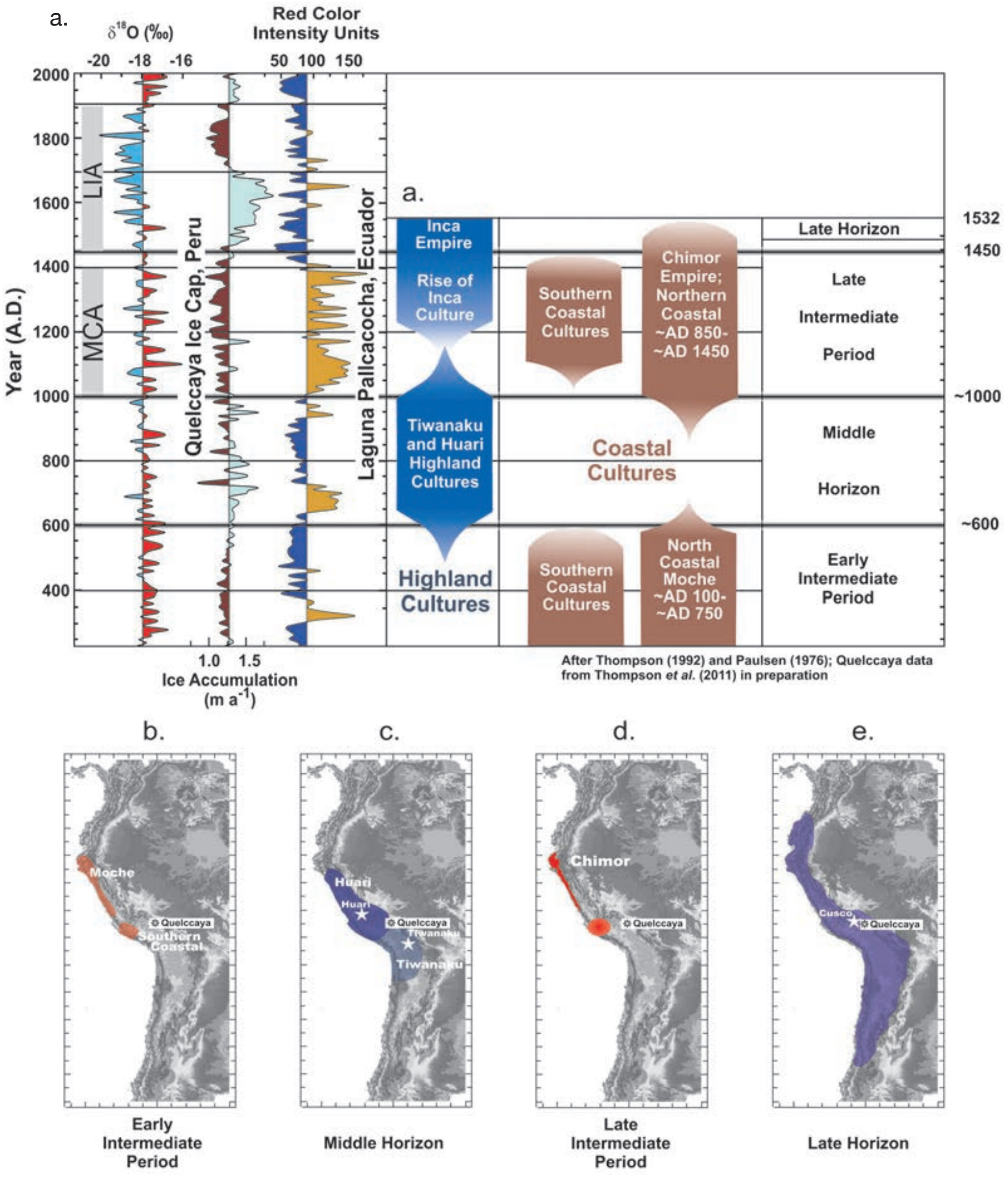

Figure 23.3 (a) Decadally averaged records of δ18O (proxy for temperature) and ice accumulation (proxy for precipitation) from the Quelccaya Summit Dome ice core, drilled in 2003, are shown alongside the red colour intensity record (proxy for El Niño frequency) from the Laguna Pallcacocha sediment core from southeastern Ecuador (Moy *et al.* 2002). The medieval climate anomaly (MCA) and the Little Ice Age (LIA) are marked. The chronology of the rise and fall of the coastal and highland cultures over the four major precolonial epochs shows broad patterns relative to the ice core-derived proxy records of temperature and precipitation. The locations of the major population centres are shown for the coastal cultures during the Early Intermediate (b) and Late Intermediate (d) Periods and for the highland cultures during the Middle Horizon (c) and Late Horizon (e).

Climate and the precolonial cultural history of Peru

Allison Paulsen (1976) examined the social and environmental relationships in southwestern coastal Ecuador on the Santa Elena Peninsula and the precolonial history of the southern coast of Peru from 500 BC to AD 1532. Today these areas are affected on a seasonal basis both by El Niño and the moderate advances and withdrawal of the Peru Current. The peninsula has undergone longer-term changes with the gradual northward advance of the Peru Current from its original Pleistocene position off the north coast of Peru to its present position north of the peninsula.

Paulsen argued that the pluvial episodes on the peninsula are best understood as exaggerated versions of the yearly cycle of advances and retreats of the Peru Current. The contraction and expansion of cultures on the Santa Elena Peninsula were largely synchronous with those along the south coast of Peru between BC 500 and AD 1532. During the Early Intermediate Period (500 BC–AD 600) coastal cultures flourished (Fig. 23.3 a and b). Pottery remains from the Middle Horizon (AD 600–AD 1000) provide evidence that the dominant cultures were highland Wari and Tiwanaku, while the Santa Elena Peninsula was largely deserted, especially from AD 800 to 1000 (Fig. 23.3 a and c). During the Late Intermediate Period (1000–1476) there were a number of centres of regional culture on the Peruvian coast and the Libertad people reoccupied old sites and wells and built new ones on the peninsula (Fig. 23.3 a and d). In the Late Horizon from 1476 to 1532, while the coastal climate deteriorated, the Inca Empire, which originated in the highlands, also dominated the Peruvian coast and the deterioration of climate on the peninsula was contemporaneous with its abandonment (Fig. 23.3 a and e). Paulsen speculated that the Andean interpluvial that began ~AD 600 was a factor in the rise of the Wari-Tiwanaku empires of the Middle Horizon and that another such Andean interpluvial beginning ~1400 was of similar importance for the establishment of the Inca Empire of the Late Horizon.

Paulsen's hypothesis – that climate had a deterministic influence in the rise and fall of Peruvian civilisations – has detractors. Peter Stahl (1984) argued that conclusions made about the apparent abandonment of the Santa Elena Peninsula might have resulted more from a lack of evidence of coastal cultures from this period. Michael Calaway (2005) also challenges the importance of long-term climate variation and the distribution of Pre-Columbian Peruvian civilisations. The rapid expansion of the Inca from the Cusco area of highland Peru (~1400–1532) produced the largest empire in the New World. Calaway hypothesises that the rapid growth of the empire most likely occurred as the result of a nexus of events, which may have included more favourable climatic conditions on the *altiplano* of southern Peru. Other chronologies have been proposed for the Titicaca basin (Arkush 2008: 347 table 1), such as Formative/Late phase (200 BC–AD 400); Middle Horizon (AD 400–1000); Late Intermediate Period Phase I (1000–1300) and Phase II (1300–1450); and Late Horizon (1450–1532). Clearly, time is required for the geographic transition of population centres and it was only the Inca Empire that experienced an abrupt termination with the arrival of the Spanish in 1532. In other words, these cultures rose and fell slowly (Paulsen 1976). More detailed references for geographical variations and the timing of the rise and fall of cultures can be reviewed in Kolata *et al.* 2000 and Shimada *et al.* 1991.

The production of the multi-proxy, high-resolution 1800-year ice core record from the Quelccaya ice cap presents an opportunity to evaluate Paulsen's hypothesis. The Quelccaya record is often quoted in literature today for documenting the climatic and environmental changes in the region and has been used frequently in the archaeological literature (such as Ortloff and Kolata 1993; Binford *et al.* 1997; Manzanilla 1997; Kolata *et al.* 2000; Magilligan and Goldstein 2001; Janusek 2004; Owen 2005; Sterken *et al.* 2006; Kemp *et al.* 2006; Branch *et al.* 2007; Arkush 2008; Chepstow-Lusty *et al.* 2009). Others, such as Calaway (2005) question the use of climatic records from ice cores and lake sediments to argue for civilisation collapse and more specifically the use of the net balance reconstructions to draw conclusions about the role of precipitation in the collapse of the highland cultures in the twelfth century AD. Thus, it is important to re-examine this relationship in light of the new climate records from the higher resolution and longer ice cores drilled on Quelccaya in 2003.

The Early Intermediate Period and Middle Horizon: ~AD 230–1000

The beginning of the Quelccaya ice core record in ~AD 230 implies a period of sustained warmth and aridity on the *altiplano* until ~AD 500 followed by more pluvial conditions that continued for several centuries (Fig. 23.3). This falls within the Early Intermediate Period (Fig. 23.3b), when cultures such as the Moche were confined mainly to the northern coastal region of Peru (Shimada *et al.*1991) and the Nazca culture (Rink and Bartoll 2005) populated the south coast. The Moche established large, sophisticated urban centres on the coast that were abruptly abandoned ~AD 600, apparently because of the increasingly arid climate and the migration of the population to highland valleys where water was more readily available. The Nazca in the south, by contrast, appeared to have been a less integrated society than the Moche, instead being composed of several alliances of 'chiefdoms' (Schreiber 1998). Although the Nazca settled in the arid Ica region, they seemed to have been able to sustain themselves sufficiently (Drusini *et al.* 2001). However, it is thought that severe ENSO-triggered floods toward the end of the Early Intermediate Period, exacerbated by the decimation of the huarango forests, may have been instrumental in their demise (Beresford-Jones *et al.* 2009). The Laguna Pallcacocha record (Fig. 23.3a) shows a period of high ENSO frequency centred ~AD 700, although the accumulation on Quelccaya is more variable and less conclusive through this period.

As the Early Intermediate Period ended, populations expanded toward the highlands as the coastal cultures declined (Fig. 23.3c). The Wari settled in the north where they practised terraced field agriculture and established a capital close to the later site of the city of Ayacucho. The Tiwanaku culture was established close to the shore of Lake Titicaca, where the farmers utilised raised field agriculture (Kolata 1993). The collapse of the Tiwanaku civilisation has been blamed on deteriorating climate (aridity) from ~1100 to 1400 (Kolata 1993; Ortloff and Kolata 1993; Binford *et al.* 1997), which led to field abandonment. Others dispute this, claiming that those who rely on geological, biological and cryological evidence to date the collapse of Tiwanaku are misreading the data or relying on circular reasoning (Erickson 1999; Calaway 2005). According to the Quelccaya climate record, the precipitation and temperature from AD 500 to 1000 experienced short-term variations, but were relatively stable over the long term. Around AD 1000, the Laguna Pallcacocha record shows the onset of a four-century period of high frequency ENSO, which is broadly synchronous with decreasing accumulation on Quelccaya. Precipitation peaked around AD 950 (as shown in Fig. 23.3a), and began a steady decline until ~1200. Whether climate was responsible for the decline of the Huari and Tiwanaku civilisations, or the causes were anthropogenic, or, as hypothesised for the collapse of the Nazca, one factor aggravated the other, the deterioration of Middle Horizon cultures was nevertheless contemporaneous with a period of increasing aridity.

The Late Intermediate Period: AD 1000–1400

Coastal cultures

While the frequent ENSO events may have brought drought to the highlands towards the end of the Middle Horizon, the coastal areas were experiencing heavier rains and flooding. Flood strata dated from the Late Intermediate Period occur in some coastal sites of northern Peru (Moseley 1987). These strata are linked with an intense ENSO event (Craig and Shimada 1986), the evidence for which is reinforced by legends in which the Naymlap dynasty, which ruled in the Lambayeque Valley, was brought down by strong rains and catastrophic floods. The population of this region was then absorbed around 1375 by the Chimú to the south. The Chimú, residents of the Chimor kingdom, ruled the northern coast of Peru from ~AD 850 to 1470. Their culture grew from the remnants of the Moche (Moseley 1990). Chimor was the largest kingdom in the Late Intermediate Period, covering over 1000 km of coastline (Fig. 23.3d) and ruled from the imperial city of Chan Chan. The Chimú also had to contend with coastal flooding resulting from the frequent occurrence of El Niño throughout this period; thus, they had to adapt their agricultural and fishing practices to this climate regime, such as developing raised fields and expanding irrigation systems into coastal valleys (Moore 1991). Marine food sources, which were the major source of protein for coastal Pre-Columbian civilisations, were adversely affected by flooding (Manzanilla 1997), although Jerry Moore (1991) cites a lack of evidence for a shift to terrestrial-based protein sources.

Highland cultures

The MCA beginning ~1000 was characterised in the southern Peruvian highlands by persistent drought conditions during which Titicaca lake levels dropped (Abbott *et al.* 1997) and raised fields were abandoned. The Quelccaya ice accumulation record also shows persistently low levels throughout the thirteenth and fourteenth centuries, while $\delta^{18}O$ (Fig. 23.3a) suggests that this period was warm on the *altiplano* (Thompson *et al.* 1988, 1994; Abbott *et al.*1997; Binford *et al.*1997). The proxy precipitation record matches well with the data from Laguna Pallcacocha in southern Ecuador, which show that the Late Intermediate Period was a time of almost persistent intense ENSO episodes that would have resulted in *altiplano* drought (Fig. 23.3a). In the central Andes, populations relocated to higher elevation settlements, perhaps in response to deteriorating climatic conditions around AD 1000 (Williams 2002, 2006) where they transitioned from raised-field and lower valley farming to more diversified agriculture (Stanish 2003; Arkush 2006, 2008). A limited arable-based economy existed in the valleys near Cusco (Chepstow-Lusty *et al.* 2009), but the intense aridity during this period may have forced the populations still living in the highlands to move to higher elevations to obtain water. In addition this may have led to the establishment of sacred sites on mountaintops possibly reflecting a need to encourage favourable weather conditions, secure adequate water provisions and maintain close communication with the mountain deities (*wamaní* or *apu*) (Meddens *et al*. 2010). Elizabeth Arkush (2008) argued that during the Late Intermediate Period people on the *altiplano* moved away from rich agricultural lands to settle in defensive sites high on hills and ridges. Building of hilltop forts (*pukaras*) was extensive, indicating a concern for warfare not seen at any other time in the archaeological record. Radiocarbon dates suggest that the building of hill forts in the northern Titicaca basin did not become common until after ~1300.

The streams originating along the southern margins of the Quelccaya ice cap flow into Lake Titicaca ~200 km to the southeast. The maximum sustained drought of the Late Intermediate Period, which occurred in the fourteenth century according to the ice core record, may have led to decreasing water supplies near Lake Titicaca. This might have compelled the local population to migrate to higher terrain closer to the water sources, and in easier positions to defend against outsiders. Arkush (2008) indicated that it was highly probable that drought and attendant resource stress played a significant part in the escalation of war in the Late Intermediate Period. Such local trends reflect more widespread movements recorded across the Andean highlands at this time.

The discovery of Killke pottery around Cusco, dated to as early as AD 1000, suggests the presence of an Inca-related culture in this region several hundred years before the Late Horizon (Rowe 1944; Bauer 2004). After ~1100 evidence appears of early Inca agro-forestry as expressed by the spread of aliso (*Alnus acuminata*) in the Patacancha Valley region near Ollantaytambo (Fig. 23.1) (Chepstow-Lusty and Winfield 2000). These early Incas may have planted these trees to inhibit erosion because of their ability to grow fast and straight in degraded soils. They may have benefited from the warmer, dry climate during the MCA to take advantage of glacier melt to irrigate their crops at higher altitude (Chepstow-Lusty *et al.* 2009)**.**

The Late Horizon: AD 1400–1540

Although the Inca were present in the Cusco Valley during the Late Intermediate Period when the coastal cultures flourished, it was only after ~1400 that their empire expanded rapidly to cover the coastal and highland regions from central Chile to northern Ecuador (Fig. 23.3e) and major imperial institutions had been established in the nearby town of Ollantaytambo (Fig. 23.1) (Bauer 2004). Efficient agricultural production at higher elevations alleviated the stress on food production, thus allowing the Inca to concentrate more energy and resources on expanding their geographic influence over other populations under a centralised government at Cusco. A sediment core record from Lake Marcacocha in the Patacancha Valley, which is

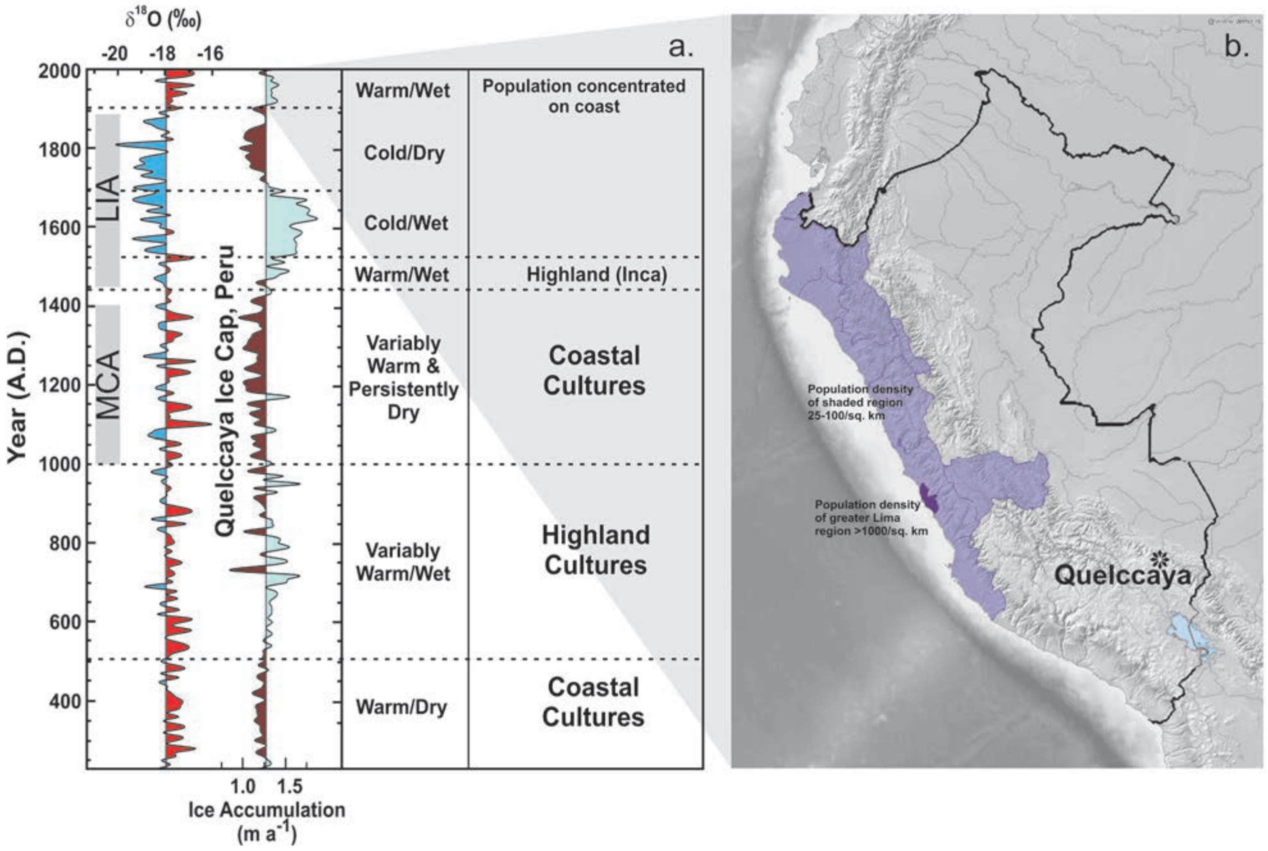

Figure 23.4 (a) Decadally averaged records of δ^{18}O (proxy for temperature) and ice accumulation (proxy for precipitation) from the Quelccaya Summit Dome ice core, drilled in 2003, are shown along with the major climate periods and centres of cultural activity. (b) The current population distribution map shows the highest density around the capital city of Lima. Modern climate conditions on the *altiplano* near Quelccaya are warm and wet, which would have been conducive to cultural development in the highlands rather than along the coast during precolonial times.

located close to an Inca caravan route 20 km to the north of Ollantaytambo, shows increased abundances of mites that are parasitic to llamas during the height of the Inca Empire (Chepstow-Lusty *et al.* 2007). From this evidence investigators deduced an increase in the population of these large herbivores and thus increased economic activity associated with caravans in the catchment near Cusco. They also noted that aliso pollen concentrations increased to record levels during the Late Horizon, indicative of more intense agro-forestry around the basin. This species was one of the most economic and symbolically important trees for the Incas (Chepstow-Lusty and Winfield 2000; Chepstow-Lusty *et al.* 2009).

It is also important to note the distribution of high altitude Late Horizon mountaintop shrines and *capac hucha* (child) sacrifices. Mountaintop shrines are also associated with *ushnu* platforms (Meddens *et al.* 2010). Their distribution may be linked to the area of increased rainfall so as to ensure continued plentiful rainfall in this area by feeding the *wamanis*, Sun god and thunder/rain deity. At the same time the increased precipitation resulted in declining snowlines to the north (equatorward). These changes, and the way they were perceived by the regional inhabitants, may have influenced the ultimate distribution of *capac hucha* sacrifices (Reinhard and Ceruti 2010).

The Quelccaya ice accumulation record shows an unambiguous increase in precipitation after 1450 (Fig. 23.3a). This is consistent with the decrease in red colour in the Laguna Pallcacocha data which indicates low ENSO frequency and thus wetter conditions in the *altiplano* (Fig. 23.3a). A diatom record from the Lake Marcacocha core does not show any marked transition between 1070 and 1650; however, the reason for this may not be climatological (Sterken *et al.* 2006). Although the rapid expansion of the Inca Empire after 1400 was synchronous with the pluvial conditions suggested by the Quelccaya ice accumulation, any causality has not been established.

Population and climate in the post-conquest and modern periods

Coincidently the Spanish conquest of the early 1530s occurred near the beginning of the LIA in the Peruvian Andes (Thompson *et al.* 1986), which persisted until the late nineteenth century (Fig. 23.3a). With the forceful arrival of the Europeans, the agricultural and pastoral practices of the indigenous people were abandoned as the newcomers confiscated the best land and introduced foreign plants, animals and diseases. Epidemics nearly wiped out whole populations (Glave and Remy 1983), and the deteriorating climate of the LIA further diminished living conditions. Although the Quelccaya record shows an intense pluvial period in the highlands from the early sixteenth century to ~1700, followed by a period of low precipitation comparable to the dry period between 1200 and 1400, the entire LIA period from the mid-1500s to the late 1800s was almost persistently colder. This pattern of precipitation through the LIA on the *altiplano* is confirmed by a pollen record from the Sajama ice cap in Bolivia (Liu *et al*. 2005). Between ~1700 and 1880 the usual pattern between high/low ice accumulation and low/high El Niño frequency reversed (Fig. 23.3a), which may have been driven in part by the southward migration of the Intertropical Convergence Zone (Haug *et al*. 2001) during the LIA.

Figure 23.4a summarises the climatic conditions on the *altiplano* as derived from the Quelccaya Summit Dome core, along with the four major epochs described above and the geographic locations of the cultural centres. In summary, arid climate conditions on the *altiplano* were synchronous with the dominance of coastal cultures, while populations tended to spread towards the highlands during high altitude pluvials. Interestingly, during the modern period (1880 to the present) the *altiplano* has experienced a relatively warm and wet climate. If population migration were consistent with the pre-1880 pattern of the rise and fall of cultures with climate, modern populations should be spreading into the higher elevations as they did during the Middle and Late Horizons (Figs 23.3a and 23.4a). However, since at least 1940 there has been a steady migration from the *altiplano* and highlands of Peru to the coastal desert cities as people seek opportunities for employment and a higher standard of living. The coastal city of Lima, which has grown from successive waves of rural migrants, now contains a population of 9 million, with a density of >1000 people per square kilometre (Fig. 23.4b). This city depends on the Rio Rimac, which rises from the glaciers of the Cordillera Central, for 75 per cent of its water supply (Leavell 2007). Since the 1980s, the Peruvian government has been promoting policies that encourage people to develop the coastal deserts, turning them into croplands. Peru is now the world's largest producer of asparagus, but this has required much water for irrigation during a time when all Peruvian glaciers are retreating (Thompson 2010). These recent developments of coastal expansion in a time of accelerating ice loss on glaciers throughout the Andes raises the question of whether these current trends are in fact sustainable.

Conclusion

The Quelccaya ice-core records provide a ~1800-year annual record of many environmental parameters including temperature and precipitation at a site less than 100 km from the capital of the Inca Empire. There remains controversy in the anthropology, archaeology and climatology communities over the extent of climate control on the rise and fall of pre-conquest cultures in Peru. On the one hand, there are those who claim that these people practised sustainable agricultural methods that harmonised with the natural climatic oscillations underpinned by phenomena such as ENSO. For example, the rise of the Inca is synchronous with increasingly wetter conditions on the Peruvian *altiplano*. When environmental conditions on which these agrarian societies depended deteriorated, the result was cultural decline (e.g. Shimada *et al*.1991; Binford *et al*.1997). This is disputed by those who assert that although climatic variability may have played a minor role, the more important factors in the viability of these civilisations were anthropogenic, for example warfare, societal decay, and bad economic and agricultural practices (see Beresford-Jones *et al*. 2009). Under this scenario, indigenous societies had the ability to adapt to changing climate, thus their agricultural infrastructure remained intact through the droughts and floods (see Erickson 1999). It is certain that modern society in Peru has the ability to adapt seemingly hostile landscapes to accommodate agriculture that under natural conditions would not be possible, and the economics of such land management has helped alter the apparent climate/population density relationship in an unprecedented way. Technology can buffer populations from the short-term effects of climate change, but long climate records such as that from Quelccaya show that centuries-long droughts and pluvials happened in the past and will certainly happen in the future. The effects on Peruvian society, both coastal and highland, will be aggravated by the intensified anthropogenic warming trend that is already melting glaciers and threatening water supplies.

Acknowledgements

We thank all the participants of the 2003 Quelccaya ice cap field programme during which the new Quelccaya ice cap cores were collected. This research was supported by NSF award ATM-0318430. This is Byrd Polar Research Center Contribution Number 1419.