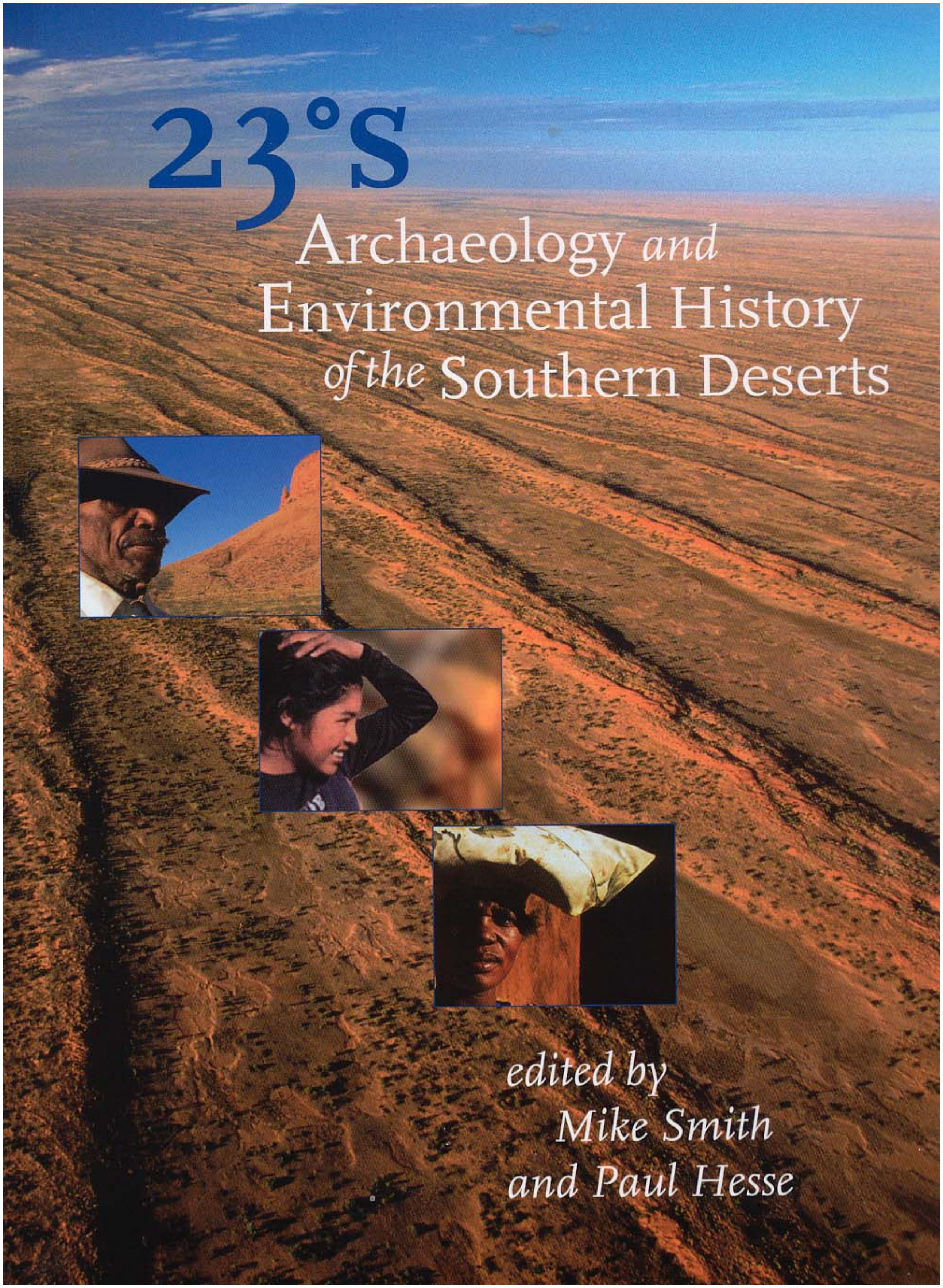

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CHAPTER 6

Claudio Latorre, Julio L Betancourt, Jason A Rech, Jay Quade, Camille Holmgren, Christa Placzek, Antonio JC Maldonado, Mathias Vuille and Kate Rylander

Late Quaternary history of the Atacama Desert

Of the major subtropical deserts found in the Southern Hemisphere, the Atacama Desert is the driest. Throughout the Quaternary, the most pervasive climatic influence on the desert has been millennial-scale changes in the frequency and seasonality of the scant rainfall, and associated shifts in plant and animal distributions with elevation along the eastern margin of the desert. Over the past six years, we have mapped modern vegetation gradients and developed a number of palaeoenvironmental records, including vegetation histories from fossil rodent middens, groundwater levels from wetland (spring) deposits, and lake levels from shoreline evidence, along a 1200-kilometre transect (16–26°S) in the Atacama Desert. A strength of this palaeoclimate transect has been the ability to apply the same methodologies across broad elevational, latitudinal, climatic, vegetation and hydrological gradients. We are using this transect to reconstruct the histories of key components of the South American tropical (summer) and extratropical (winter) rainfall belts, precisely at those elevations where average annual rainfall wanes to zero. The focus has been on the transition from sparse, shrubby vegetation (known as the *prepuna*) into *absolute desert*, an expansive hyperarid terrain that extends from just above the coastal fog zone (approximately 800 metres) to more than 3500 metres in the most arid sectors in the southern Atacama.

Our study focuses on rodent middens (cf. Betancourt et al. 1990). These are amalgamations of plant remains (including seeds, flowers, leaves and wood), bones, insects, feathers and rodent faeces, glued together within a crystallised matrix of rodent urine. In arid climates, they can survive for thousands of years underneath rock slabs and within crevices and caves. Midden plant remains are from within the rodent's foraging range (usually 200 metres or less) and include plants collected for consumption, nest building and protection. In the Atacama, middens are produced by at least four different rodent families: Abrocomidae (*Abrocoma cinerea*, 'chinchilla rats'); Chinchillidae (*Lagidium viscacia* and *Lagidium peruanum*, 'viscachas'); Muridae (*Phyllotis* spp. 'leaf-eared mice') and Octodontidae (*Octodontomys gliroides*, 'brush-tailed rat'). Modern studies of *Phyllotis*, *Lagidium* and *Abrocoma* indicate that they are dietary generalists and probably not selective enough to introduce large biases into the midden record (Pearson 1948; Pizzimenti and DeSalle 1980; Cortés et al. 2003).

Climatic controls

The Atacama extends along the Pacific Andean slope from the southern border of Peru (18°S) to Copiapó, Chile (27°S). The region's hyperaridity is due to a combination of the extreme rain shadow of the high Andes, which blocks the advection of tropical/subtropical moisture from the east; the blocking influence of the semipermanent South Pacific Anticyclone, which limits the influence of winter storm tracks from the south; and the generation of a temperature inversion at approximately 1000 metres by the cold, north-flowing Humboldt Current, which constrains inland (upslope) penetration of Pacific moisture.

The South Pacific Anticyclone has been anchored against the westward bend in the South American continent throughout the late Tertiary. Uplift of the Central Andes to their current elevation may have occurred as early as 15 million years ago (Ma) (Alpers and Brimhall 1988; Vandervoot et al. 1995), although palaeobotanical evidence suggests that the Central Andes were only at half their modern elevation at 10 Ma (Gregory-Wodzicki 2000). The Humboldt Current is thought to have been active since the early Tertiary (Keller et al. 1997), but may have reached its present intensity during the major expansion of the Antarctic ice sheet between 15 and 2.5 Ma (Flower and Kennett 1993), or after the Central American Seaway closed between 3.5 and 3.0 Ma (Ibaraki 1997).

Seasonal and annual precipitation totals in the region are determined by the number of precipitation days, and associated circulation anomalies during those days. Precipitation variability in both summer and winter is modulated primarily by Pacific sea surface temperature (SST) gradients and associated upper-air circulation anomalies (Vuille et al. 2000; Garreaud et al. 2003). These anomalies promote either greater spillover of summer moisture from the Amazon to the north-east or the Gran Chaco to the south-east or, conversely, greater penetration of winter storm tracks from the south-west.

The recent flurry of palaeoclimate research in the wider Central Andes region stems from interest about leads and lags between low and high latitudes, and the role of the tropics in global change at millennial to Glacial–Interglacial scales. Are variations in summer rainfall over the region just a function of minor seasonal variations in regional insolation, and their impact on the Bolivian High, or is the intensity of the South American summer monsoon forced instead by changes in Pacific SST gradients with both tropical and extratropical teleconnections? A diverse array of records of continental climate change is now available to test these ideas. Notable among these are lake and salt cores from Lake Titicaca and Salar de Uyuni, chronostratigraphic work on shoreline deposits throughout the Altiplano, ice cores from Nevado Sajama and Illimani, salt cores from Salar de Atacama and Hombre Muerto and a lake core from Laguna Miscanti.

The northern Atacama Desert (16–21°S)

The northern portion of the Atacama Desert runs from Arequipa, in southern Peru (approximately 16°S), to the northern rim of the Río Loa catchment in northern Chile (approximately 21°S). Characterised by abrupt relief, the northern Atacama is defined by a narrow and steep-sloping stretch between the Andes and the Pacific Ocean, with extensive wall canyons over a kilometre in depth. Less than 100 kilometres separate the Pacific Coast from the six-kilometre-high Andean peaks.

The rodent midden record described here comes from the vicinity of Arequipa, the second largest city in Peru, nestled in the foothills of the western cordillera. Here, absolute desert grades into desert *matorral* (shrubland) at about 2400 metres of elevation, characterised by columnar cacti and xerophytic shrubs as well as small herbs and annual grasses. Plant cover increases dramatically above 2600 metres but greater diversity occurs starting at 2800 metres, with a mixture of *matorral* and *pajonal* (grassland) species.

The Arequipa record, described in Holmgren et al. (2001), incorporates middens found between 2350 and 2850 metres of elevation. The majority were made by leaf-eared mice and chinchilla rats although a few were also made by mountain viscachas. Overall, the Arequipa midden record is remarkably stable over the last 9500 years (all ages are quoted as cal. BP, calibrated radiocarbon ages) (Figs 6.1a and 6.1b). At lower elevations, middens between 9500 and 7400 years ago have remarkably low numbers of annuals, grasses and perennials as well as a low total number of taxa (10 and under). These taxa experience a threefold increase at 6700 years cal. BP, with annuals increasing from three to nine taxa, and the total number of taxa rising to 26. Other mid-Holocene middens are also characterised by a rich assemblage of annuals until 3800 years cal. BP. Middens from the late Holocene date between 1300 cal. BP and the present, and are slightly poorer in annuals and perennials when compared to mid-Holocene ones. The numbers of cacti remain surprisingly constant throughout the record, diminishing only slightly in the early Holocene.

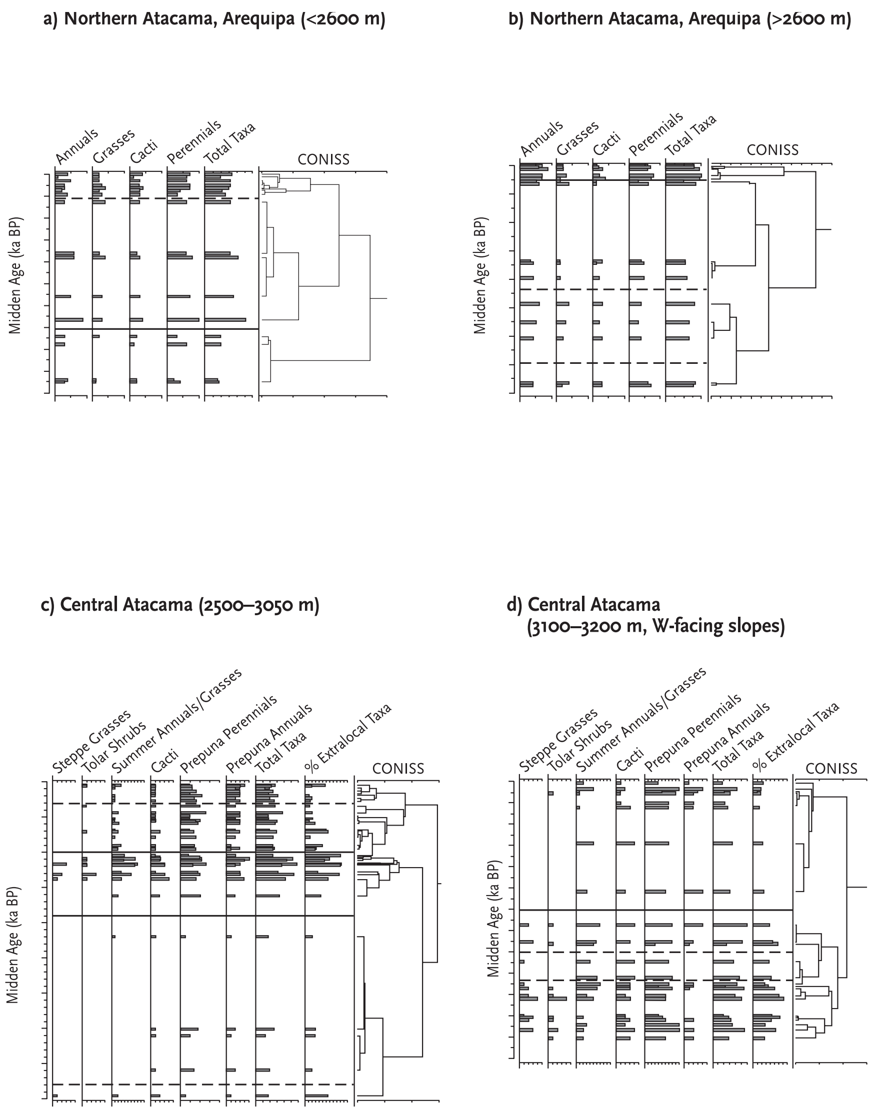
Middens above 2600 metres show somewhat greater vegetation stability. Most of the middens have between 15 and 20 taxa. Those dated between 4000 and 3400 years ago, however, have fewer grasses and only 10 to 11 taxa. Middens younger than 700 cal. BP have the largest numbers of annuals and perennials. Cacti again remain remarkably constant. Of note in this series is the presence of *Stipa ichu* (a steppe grass) and *Opuntia ignescens* (a cushion cactus), between 5000 to 4500 years ago. Both species now occur 450 and 750 metres higher than the midden sites.

Other late Quaternary records from the northern Atacama include Holocene lake level changes at Lago Aricota in southern Peru (17°22'S) and groundwater fluctuations recorded in terraced spring deposits throughout northernmost Chile. Radiocarbon dates of shoreline deposits at Lago Aricota indicate a maximum highstand (more than eight metres above the pre-dam 1955 lake level) between more than 7100 to 2800 years ago, with a minor highstand dated to 1700 to 1300 years ago (Placzek et al. 2001). Fossil spring and wetland deposits, which are located around modern springs and wetlands, are common surficial deposits in the Atacama Desert. These deposits generally consist of alluvial silt and sand, diatomite, organic mats and tufa. Wetland deposits from four separate hydrologic settings were studied to reconstruct fluctuations in the height of local water tables: Zapahuira Springs (18.3°S, 3500 metres), a small point-source spring; Quebrada la Higuera (18.6°S, 3500 metres), a high-elevation drainage with isolated wetlands; Quebrada Tana (19.5°S, 1200 metres), a low-elevation drainage that flows into the Pacific, and Quebrada Guataguata (20.1°S, 2050 metres), a low-elevation drainage with isolated wetlands (Rech et al. 2001). We identified the following time-stratigraphic units of palaeowetland deposits indicating periods of elevated groundwater tables: Unit B (more than 13,800 to 10,200 cal. BP) represents the highest episode of local water tables, Unit C (more than 5900 to 4800 cal. BP and a second episode dating from 4800 to 2800 cal. BP) and Unit D, composed of several episodes of deposits that are over 3000 years old. The units are separated by episodes of fluvial downcutting, which occurs when the water table drops, causing desiccation of these fine-grained sediments and subsequent erosion.

In summary, these records indicate episodes of increased effective moisture throughout the northern Atacama. Wet conditions were prominent during the late Glacial period (14,000 to 10,000 years ago) as implied by the palaeowetland record. Slightly more arid conditions occurred during the early Holocene, followed by a wetter episode during the mid-Holocene (especially between about 7000 and 4500 years ago), and a slightly drier late Holocene, punctuated by minor precipitation increases between 1000 and 2000 cal. BP. These results, however, are largely at odds with other published records from high Andean lake records in the Peru/Bolivian Altiplano.

The central Atacama Desert (21–24°S)

Among the salient features of the central Atacama are two pronounced embayments in the Andes cordillera, the Calama and Salar de Atacama basins, and the only perennial river to actually reach the Pacific Ocean, the Río Loa. Inland extension of the absolute desert is here much greater than in the northern Atacama, reaching elevations of 2900–3100 metres and up to 300 kilometres from the coast. An older mountain range, the Cordillera Domeyko, has its origins in this sector and runs parallel along the western Andean front into the southern Atacama. Here, plant diversity and distribution is tightly


a) Northern Atacama, Arequipa (<2600 m)
Annuals
Grasses
Cacti
Perennials
Total Taxa
CONISS
Midden Age (ka BP)
b) Northern Atacama, Arequipa (>2600 m)
Annuals
Grasses
Cacti
Perennials
Total Taxa
CONISS
Midden Age (ka BP)
c) Central Atacama (2500–3050 m)
Steppe Grasses
Tolar Shrubs
Summer Annuals/Grasses
Cacti
Prepuna Perennials
Prepuna Annuals
Total Taxa
% Extralocal Taxa
CONISS
Midden Age (ka BP)
d) Central Atacama
(3100–3200 m, W-facing slopes)
Steppe Grasses
Tolar Shrubs
Summer Annuals/Grasses
Cacti
Prepuna Perennials
Prepuna Annuals
Total Taxa
% Extralocal Taxa
CONISS
Midden Age (ka BP)

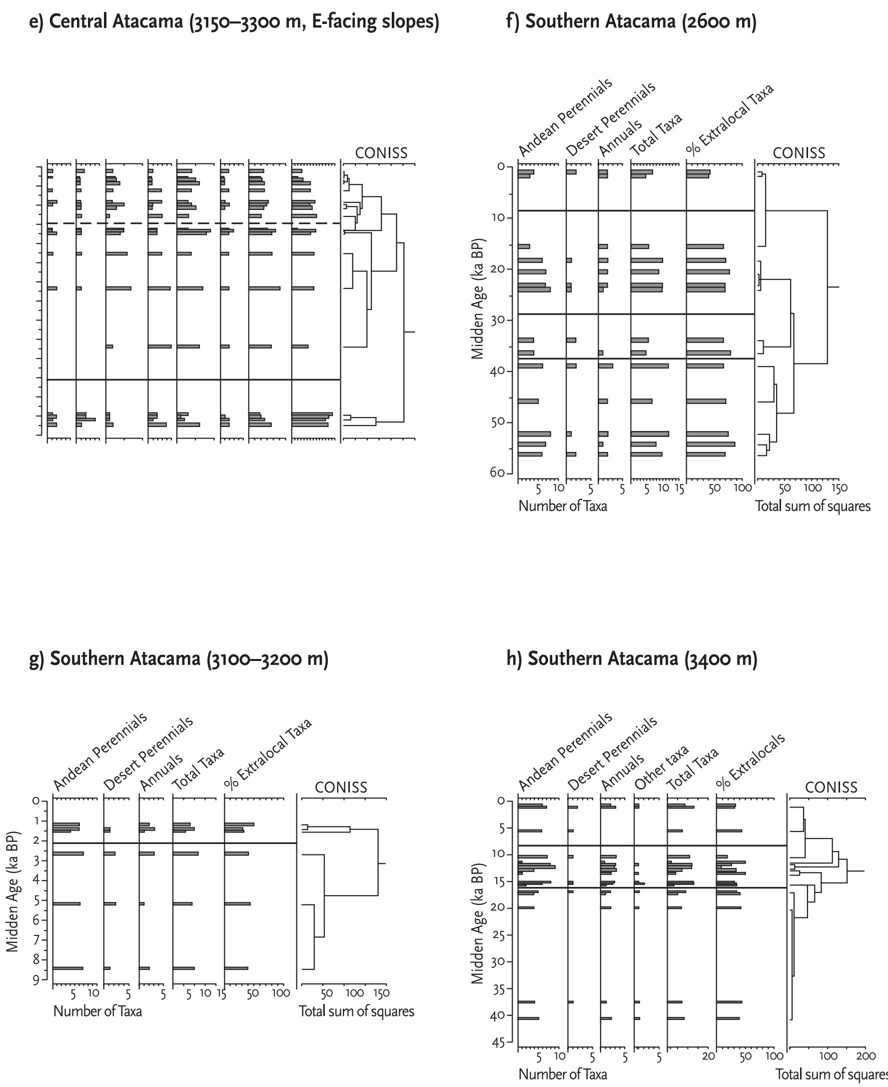


Figure 6.1

Rodent midden records from the Atacama Desert, summarised by plant life-form and phytogeographic affinity

Major vegetation breaks, in part established by a constrained sum of squares (CONISS) cluster analysis, are shown as solid black lines. Minor breaks are shown as dotted lines. Note changes in scale.

linked to mean annual precipitation, which increases from almost nothing at about 2400 metres to 200 millimetres per year at 4000 metres. Along the Andean slope, a sparse vegetation of shrubs and small herbs, known as the *prepuna*, appears at 2900 metres and gradually transitions into the *puna* (locally called *tolar*) vegetation belt. The *puna* belt, between 3100 and 3900 metres, is dominated by shrubs of the Asteraceae and Solanaceae with numerous summer annuals and columnar cacti. High Andean grassland dominated by tussock grasses such as *Stipa*, *Nassella* and *Festuca* is found above 3900 metres. A more heterogenous mix of vegetation occurs along the Cordillera Domeyko, with impoverished *Stipa* grassland found above 3400 metres and slightly wetter conditions on the east-facing slopes with *tolar* shrubs extending down to 3100 metres. These same shrubs occur above 3200 metres on the drier west-facing slopes.

We collected rodent middens from two major areas in the central Atacama. The first area is in the *prepuna* along the west-facing and east-facing slopes of the northern Cordillera Domeyko, between 3100 and 3300 metres of elevation. The other midden area is along an escarpment of volcanic rocks at the southern portion of the Salar de Atacama, known as Tilocalar (between 2400 and 3050 metres), an area now mostly devoid of all but the most drought-resistant plants (for more details see Betancourt et al. 2000; Latorre et al. 2002, 2003).

The Tilocalar series (44 middens) records vegetation invasions into what is now absolute desert over the last 45,000 years (summarised in Fig. 6.1c). Major wet phases, indicated by more than 30 per cent extralocal plants (species not found in the area today), presence of steppe (some grass species present are found approximately 900 metres above the localities today) and *tolar* (*puna*) shrubs as well as summer annuals and columnar cacti, occurred sometime before 44,000 years ago and between 16,200 and 10,000 cal. BP. Minor pulses of increased precipitation occurred between 7000 and 3000 cal. BP, mostly evinced by increases in the number of *prepuna* perennials as well as the occasional appearance of summer annuals and *tolar* taxa. The few middens dated to between 40,000 and 22,000 cal. BP possess very dry assemblages, along with those marking the abrupt onset of aridity after 10,000 cal. BP. The poor plant assemblages present in middens younger than 3000 years old also indicate dry climates, possibly the driest over the last 22,000 years. The youngest midden in the record, however, indicates the possibility of a more recent wet phase approximately 500 years ago.

Middens from further north and at slightly higher elevations in the Cordillera Domeyko are divided into two series, spanning the last 12,000 years (west-facing slopes, Fig. 6.1d) and 13,400 years (east-facing slopes, Fig. 6.1e). West-facing middens at the localities of Tuina and Cerros de Aiquina reflect wetter conditions between 12,000 and 9500 cal. BP and again between 7600 and 6700 cal. BP, as inferred from the high percentages of extralocal taxa (generally greater than 40 per cent), steppe grasses and *tolar* shrubs. Middens dated to between 9200 and 8400 cal. BP, and those 5100 years old and younger, all have much drier plant assemblages.

East-facing middens at the localities of El Hotel and Pampa Vizcachilla, dated to between 13,400 and 12,900 years ago, are rich in extralocal taxa, steppe grasses and *tolar* shrubs (including *Parastrephia quadrangularis*, a high *tolar* shrub found today between 3800 and 4000 metres in elevation), all indicating much wetter conditions. A single midden dated to 9400 cal. BP displays an array of plant species similar to the modern floras found there today. Total and extralocal taxa increased again in middens dated to between 6100 and 3200 years ago and then decrease in middens dated to between 2500 and 170 cal. BP.

Radiocarbon dating of terrestrial macrofossils on terraced palaeowetland and fossil spring deposits along the Río Salado (a tributary of the Río Loa), at Quebrada Puripica and at Tilomonte, indicates times of elevated groundwater tables and increased groundwater recharge (Rech et al. 2002, 2003). Four chronostratigraphic units are recognised: Unit A, dated to older than 44,000 cal. BP; Unit B, dated to between more than 15,400 and 9000 years ago; Unit C, dated between 8000 and 3000 years ago; and Unit D, which is less than 1000 years old. As in the northern Atacama, aggradation of these units culminated in abrupt incision and erosion of the deposits. In some cases (such as with Unit B at the Río Loa and Salado localities), these units may have been completely eroded away before further accumulation resumed.

In summary, the midden and palaeowetland records from the central Atacama are in close agreement, in particular for a major wet phase between more than 15,000 and 9000 years ago. Based on new evidence from our ongoing midden research at Río Salado in the Calama Basin, this wet phase may have begun as early as 17,400 cal. BP, coinciding closely with globally warmer temperatures and the onset of deglaciation at higher latitudes. Further research, however, in the central Atacama will seek to establish the full extent of the mid-Holocene wet phase, dated approximately 7000 to 3000 cal. BP. Our evidence is at odds with the notion of a *silencio archaeológico*, a conspicuous, temporal gap in the archeological record attributed to greater mid-Holocene aridity (Grosjean et al. 2001; Núñez et al. 2002).

The southern Atacama (24–27°S)

With very little rainfall either from tropical or extratropical sources, this sector is undisputedly the driest portion of the Atacama Desert. Inland penetration of absolute desert may reach 4000 metres in altitude along the western slopes of the Cordillera Domeyko, with peaks that here rise to over 5000 metres in altitude. Many closed basin *salars* (salt pans and playas) dot the high elevation intermontane basins found between the Domeyko and Andes cordilleras. Among the most prominent are Salar de Punta Negra, Salar de Pedernales and Salar de Maricunga. The sharp southern boundary of the Atacama is delimited by increased penetration of the westerlies during winter.

Quebrada Chaco is a steep, walled canyon occupied by a dry streambed. The stream course begins at approximately 4000 metres in the Cordillera Domeyko, starts to form a defined canyon at 3700 metres, crosses an active spring just downstream of a 30-metre nickpoint and dry waterfall at 3400 metres, and eventually shallows into a wide floodplain at 1500 metres. Aside from local vegetation around a few springs, there are only a few shrubs and annual herbs below 3500 metres, mostly along dry washes. Some of the low elevation plants share a close affinity with those found along the coast in the specialised *lomas* fog communities, endemic relicts that probably formed during the Tertiary (for example *Malesherbia* and *Nolana*). These constitute the desert perennials in figures 6.1f–h. Other species are of Andean affinities (the 'Andean' perennials), which become more abundant above 3500 metres, although mostly confined to the canyon itself. Starting at 3900 metres, extensive low cover grassland appears dominated almost exclusively by a single species of steppe grass, *Stipa frigida*.

We have collected and ^{14}C-dated 42 middens from three different elevations at Quebrada Chaco. The middens were analysed for both the presence of plant macrofossils (Betancourt et al. 2001) and for pollen contained within the midden matrix (excluding faecal pellets). The lowermost series (Fig. 6.1f), collected within absolute desert along a small outcrop of ancient travertines at 2600 metres, includes 15 middens that span ages from more than 52,200 years ago to 590 cal. BP. Middens older than 15,000 cal. BP generally have very rich plant assemblages (especially Andean perennials) and high percentages of extralocals compared to those that date to the last 1500 years, which are more impoverished. A cluster of high species richness occurs in middens dated to between 23,800 to 18,100 years ago, although a few older middens with greater richness appear 38,900 years ago and more than 52,200 years ago. Pollen analyses of the midden matrix (excluding faecal pellets) reveals abundant Fabaceae and Brassicaceae pollen between 52,000 to 33,000 years ago. Diverse pollen assemblages, which include Brassicaceae, Fabaceae, Asteraceae (Tubiliflora) and Chenopodiaceae pollen, characterise middens dated to between 25,000 and 15,000 years ago. Desert taxa pollen (*Cistanthe* and Caryophyllaceae) dominate late Holocene middens younger than 1500 cal. BP.

Only six middens spanning the last 8400 years were collected from intermediate elevations (3100–3200 metres) within the canyon. Macrofossil content reveals a stable and arid Holocene (Fig. 6.1g). Despite a slight increase in pollen diversity after 1500 cal. BP, older assemblages are dominated by plants found nearby at a modern spring.

Closer to the lower vegetation limit, at 3450–3500 metres, we collected a series of 20 middens spanning the last 40,500 years along several volcanic outcrops (Fig. 6.1h). The two middens older than 35,000 years have impoverished floras dominated by Andean perennials. Middens dated between 19,600 and 10,100 cal. BP, however, exhibit higher numbers of taxa, with middens particularly rich in annuals as well as Andean perennials dated between 15,000 and 10,000 years ago. Only four middens are dated younger than 10,000 cal. BP, all of which display plant assemblages very similar to modern assemblages. The pollen assemblage from the oldest midden is dominated by Asteraceae (Tubuliflora) and Poaceae. Pollen from middens dated between 20,000 and 10,000 years ago is considerably more diverse, with Poaceae, Asteraceae (Tubuliflora), Chenopodiaceae and *Chaetanthera*-type all present. The genus *Chaetanthera* is found today only in the high Andes close to the upper vegetation limit (about 4500 metres), and is strong evidence for colder temperatures as well as increased precipitation between 20,000 and 15,000 years ago. Middens between 14,000 and 10,000 cal. BP show an increase in Brassicaceae and Asteraceae (Tubuliflora) with a concomitant decrease in grass pollen. Younger middens are dominated by Chenopodiaceae and Nolanaceae, implying much more arid conditions throughout the Holocene, save the last 1000 years, when an increase in Brassicaceae and Fabaceae pollen occurs.

Channel deposits in Quebrada Chaco are 3–5 metres thick and contain alluvial sediments (silt, sand, gravel) and wetland facies (diatomite, tufa, organic mats). We studied the age, sedimentology and stratigraphy of channel deposits along a 20-kilometre reach of Quebrada Chaco and along four of its main tributaries between 2700 metres and 3300 metres. The sedimentology of channel deposits ranges from mostly diatomite and organic mats to predominately alluvial sediments with a few beds of organic mats. Thirty accelerator mass spectrometer (AMS) ^{14}C ages, mostly on carbonised wood, provide good age control for these deposits. The oldest channel deposits are undated and lie beneath a clear unconformity. Younger channel deposits date between 20,800 and 10,200 cal. BP with the majority of deposits dating between 15,400 and 10,200 years BP. Sequences of diatomite and organic mats are interpreted as marshes/wetlands that were supported by much higher levels of ground water than are currently in the drainage (for recent discussion of wetland deposits in the Atacama, see Rech et al. 2003 and Grosjean et al., this volume).

The majority of wetland deposits in Quebrada Chaco and its tributaries, as well as midden records from upper and lower elevations dating between 15,400 and 10,200 years ago, are in good agreement with late Glacial/early Holocene wet phases indicated in the higher middens (greater than 3450 metres) at Quebrada Chaco and in the central Atacama. Aggradation beginning at approximately 20,800 cal. BP, however, agrees with low elevation midden evidence that there was an earlier pluvial period between 23,800 and 18,100 years ago. One source for this earlier pluvial could be the enhancement or northward migration of westerly storm tracks during the last glacial maximum (LGM). In the Holocene, absence of wetland deposits along with impoverished midden floras implies widespread aridity, with a slight increase in moisture over the last 1500 years. This pattern is clearly different from that found further north, and implies that increases in summer precipitation during the mid-Holocene were of insufficient magnitude to have reached Quebrada Chaco. Ongoing work in the southern Atacama, at localities directly north and south of Quebrada Chaco, will enable us to place both a maximum northward limit to the westerly excursion during the LGM as well as establishing the southern limit of increased summer moisture during the late Glacial and mid-Holocene.

Towards a regional synthesis

Figure 6.2 compares effective moisture interpretations from the diverse array of records of continental climate change now available. Large discrepancies in palaeoclimate interpretation are readily apparent.

- Lake cores from the Altiplano, including Lake Titicaca (Baker et al. 2001b) and Salar de Uyuni (Baker et al. 2001a), seem to indicate a wet LGM (over 20,000 years ago) — a pattern not seen along the Pacific slope of the Andes except in the Salar de Atacama salt core (Bobst et al. 2001) and in the southern Atacama. There are disagreements between core and shoreline evidence for palaeolakes on the Bolivian Altiplano. Twice in the last 110,000 years, overflow from Lake Titicaca inundated and, when lake levels rose above 3700 metres, integrated drier basins to the south (Poopó, Coipasa and Uyuni). The radiocarbon chronology for the oldest shoreline (Palaeolake Minchin) above 3700 metres is questionable, and in the process of being resolved through U-series dating. The younger and higher shoreline above 3700 metres (Palaeolake Tauca) is also being redated, but previous dates range

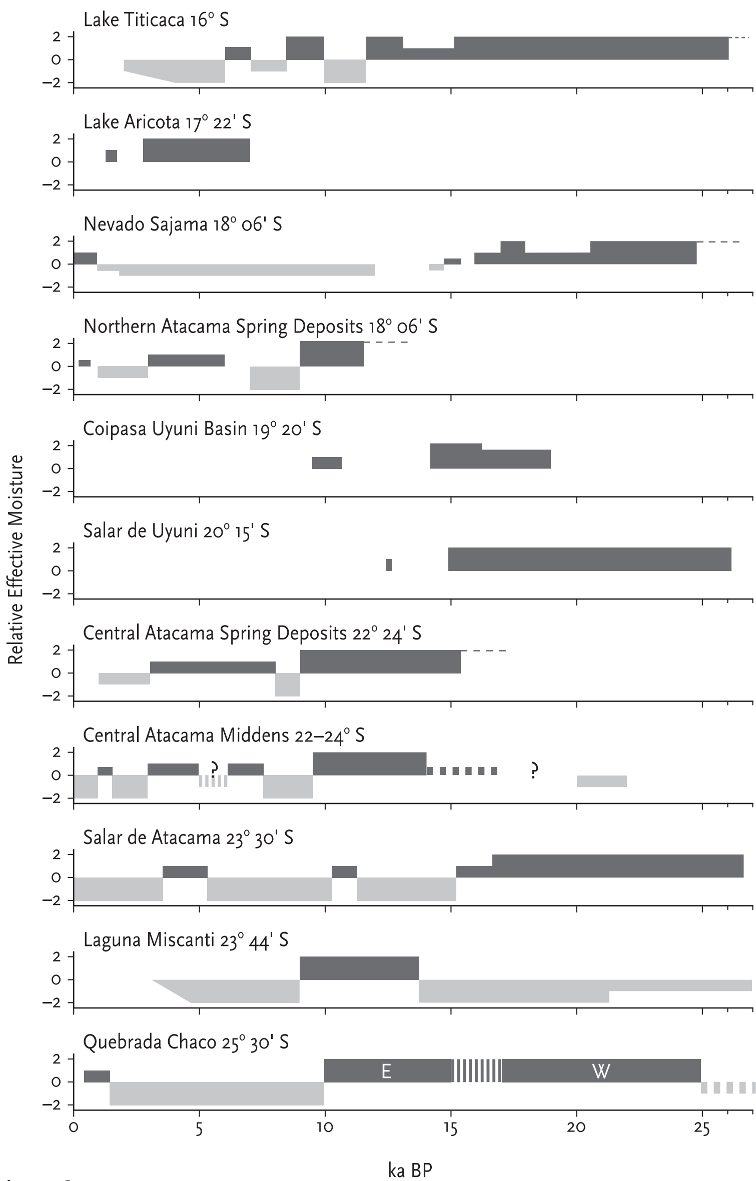


Figure 6.2

A regional comparison of paleoclimate records along a north–south transect across the Central Andes and Atacama Desert

Dry phases are indicated in light grey whereas dark grey denotes wet phases. For the southern Atacama record, the E and W indicate easterly and westerly sources of moisture, respectively.

between 18,900 and 14,000 years ago (Sylvestre et al. 1999). On the flanks of Cerro Tunupa in Salar de Uyuni, Tauca shoreline deposits are intercalated with well-dated glacial deposits at approximately 15,000 cal. BP (Clayton and Clapperton 1997). In the Uyuni and Coipasa basins there are other minor shorelines (representing smaller lakes that never rose above 3700 metres), the most recent one tentatively dated at 10,800 to 9,500 years ago (Sylvestre et al. 1999).

- A prominent late Glacial wet phase (15,000–10,000 years ago) is seen in all the Atacama records including high Andean lakes such as Lake Miscanti (Grosjean et al. 2001) and Lake Lejía (Geyh et al. 1999). Despite a clear easterly moisture signal evident in rodent midden assemblages, this wet phase may have had only minor impact at Salar de Uyuni and Salar de Atacama.
- A slightly wetter mid-Holocene is indicated by midden and palaeowetland records throughout the northern and central Atacama but not in the southern Atacama. The minor increases in easterly rainfall evinced from our records further north may not have been extensive enough to reach Quebrada del Chaco at 25°30'S. In stark contrast, however, are the high Andean lake records which indicate intense drought during the mid-Holocene.

At least some of the discrepancies in the palaeoclimate records may be explained by substantial geographic variation in the sources and mechanisms of precipitation over the Central Andes. Summertime precipitation variability in the Central Andes is by and large determined by the upper-air zonal wind component aloft, with an easterly flow favouring wet conditions. The influence of these upper-air circulation anomalies on precipitation becomes more dominant when a longer moisture transport is involved and hence is more prominent along the western slope of the Altiplano (Vuille et al. 2000).

For example, Lake Titicaca, which lies at the north-eastern margin of the Altiplano, still receives a considerable amount of rainfall under unfavourable atmospheric conditions for the rest of the region (i.e. westerly flow), while this is hardly ever the case for the more remote Salar de Atacama region. On interannual timescales the upper-air circulation over the northern Altiplano (north of about 22°S) is influenced by SST anomalies (SSTA) in the central equatorial Pacific, with warm SSTA causing enhanced westerly flow, due to changes in meridional baroclinicity between tropical and subtropical latitudes. This mechanism explains the apparent relationship between El Niño Southern Oscillation (ENSO) and Altiplano rainfall (Garreaud and Aceituno 2001). General Circulation Model (GCM) simulations, with changed orbital and glacial forcing, indicate that this mechanism observed today may even hold on Glacial–Interglacial timescales (Garreaud et al. 2003). This might explain why parts of the eastern Altiplano appear wet, and other regions appear dry, such as during the LGM.

Other explanations must be invoked to explain the reverse situation. In particular, how could moisture occur on the Pacific slope while leaving the Altiplano dry? This seems to be the case for the mid-Holocene wet phase of the northern and central Atacama. One possibility is that it could have been caused by an increase in extratropical moisture. The lack of a mid-Holocene wet phase in the southern Atacama seems to preclude this, however. One of the strengths of our transect rests on the fact that downslope migration of plants into absolute desert is almost exclusively controlled by precipitation. At such low precipitation amounts, any moisture increases far surpass any increases/decreases in heatload.

High Andean lake records, however, have also been interpreted exclusively in terms of changes in precipitation. For example, Lake Titicaca experienced about 4000 years of drought during the mid-Holocene from 8000 to 4000 cal. BP. Lake levels fell approximately 100 metres during this well-dated lowstand. Despite what appears to be a clear drought signal, a recent 20,000-year pollen record from Lake Titicaca indicates an extremely diverse pollen assemblage between 8000 and 3100 years ago, dominated by Andean cloud forest elements such as Podocarpaceae, Moraceae and other taxa such as *Polylepis* (Paduano et al. 2003). The Andean cloud forest occurs today some 600 metres *below* the modern lake level, implying a direct temperature increase of 2–3°C. The increased temperature, added to the additional evapotranspiration caused by what appears to be the most productive ecosystem present in the Titicaca watershed during the entire record, might have been enough to draw down lake levels despite any minor increases in precipitation. The same situation may have applied to another high Andean lake, Laguna Miscanti. Here, pollen concentrations seem to have varied very little during the Holocene, despite sedimentary evidence for a strong drop in the lake level between 8000 and 3000 cal. BP (Grosjean et al. 2001).

Finally there is one more argument which provides support for the notion that discrepancies in the palaeorecord might reflect different moisture sources and mechanisms of precipitation. A recent study based on satellite data indicates that precipitation variability in the Central Andes shows much less spatial coherence than previously thought, with many years displaying antiphasing of wet/dry conditions between the northern and southern Altiplano (Vuille and Keimig 2004, in press). South of about 22°S the main moisture source is no longer the Amazon basin but appears to lie to the south-east over north-western Argentina. Upper-air circulation anomalies, with easterly winds favouring wet and westerly winds producing dry conditions, still play a crucial role over the southern Altiplano, as they do further north. However, the zonal flow appears to respond to extratropical Rossby wave dispersion and modulation of the positioning and intensity of the Bolivian High. In addition, increased precipitation in the southern Altiplano is restricted to periods of higher water vapour content in the moisture source region to the east of the Andes, a mechanism which is of no relevance over the northern Altiplano region.

One of the major strengths of the Atacama record is the ability to discriminate between temperature and precipitation effects. Our records suggest that the upper-air circulation, responding to changes in tropical Pacific SST-gradients and related changes in the moisture source region to the east, are more important than local insolation to explain the late Quaternary changes in the Atacama Desert. Increases in westerly moisture, clearly seen in the southern portion of the Atacama, may not have been extensive enough to have impacted areas further north. Likewise, minor increases in precipitation that occurred during the mid-Holocene were of insufficient magnitude to impact areas south of 25°S. Ongoing research in the southern Atacama will help clarify the northward extent of the westerlies during the LGM and late Glacial period.

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Valle de la Luna, Atacama Desert

photograph by Jaime Plaza van Roon