Clim. Past, 11, 27–44, 2015
www.clim-past.net/11/27/2015/
doi:10.5194/cp-11-27-2015

Climate of the Past
Open Access

Holocene environmental changes in the highlands of the southern Peruvian Andes (14° S) and their impact on pre-Columbian cultures

K. Schittek[1], M. Forbriger[2], B. Mächtle[3], F. Schäbitz[1], V. Wennrich[4], M. Reindel[5], and B. Eitel[3]

[1]Seminar of Geography and Geographical Education, University of Cologne, Germany
[2]Institute of Geography, University of Cologne, Germany
[3]Geographical Institute, University of Heidelberg, Germany
[4]Institute of Geology and Mineralogy, University of Cologne, Germany
[5]German Archaeological Institute, Commission for Archaeology of Non-European Cultures (KAAK), Bonn, Germany

Correspondence to: K. Schittek (schittek@uni-koeln.de)

Received: 28 February 2014 – Published in Clim. Past Discuss.: 11 April 2014
Revised: 31 October 2014 – Accepted: 20 November 2014 – Published: 7 January 2015

Abstract. High-altitude peatlands of the Andes still remain relatively unexploited although they offer an excellent opportunity for well-dated palaeoenvironmental records.

To improve knowledge about climatic and environmental changes in the western Andes of southern Peru, we present a high-resolution record of the Cerro Llamoca peatland for the last 8600 years. The 10.5 m long core consists of peat and intercalated sediment layers and was examined for all kinds of microfossils. We chose homogeneous peat sections for pollen analysis at decadal to centennial resolution. The inorganic geochemistry was analysed in 2 mm resolution (corresponding >2 years) using an ITRAX X-ray fluorescence core scanner.

We interpret phases of relatively high abundances of Poaceae pollen in our record as an expansion of Andean grasslands during humid phases. Drier conditions are indicated by a significant decrease of Poaceae pollen and higher abundances of Asteraceae pollen. The results are substantiated by changes in arsenic contents and manganese/iron ratios, which turned out to be applicable proxies for in situ palaeoredox conditions.

The mid-Holocene period of 8.6–5.6 ka is characterised by a series of episodic dry spells alternating with spells that are more humid. After a pronounced dry period at 4.6–4.2 ka, conditions generally shifted towards a more humid climate. We stress a humid/relatively stable interval between 1.8 and 1.2 ka, which coincides with the florescence of the Nasca culture in the Andean foothills. An abrupt turn to a sustained dry period occurs at 1.2 ka, which is contemporaneous with the demise of the Nasca/Wari society in the Palpa lowlands. Markedly drier conditions prevail until 0.75 ka, providing evidence of the presence of a Medieval Climate Anomaly. Moister but hydrologically highly variable conditions prevailed again after 0.75 ka, which allowed re-expansion of tussock grasses in the highlands, increased discharge into the Andean foreland and resettling of the lowlands during this so-called late Intermediate Period (LIP).

On a supraregional scale, our findings can ideally be linked to and proved by the archaeological chronology of the Nasca–Palpa region as well as other high-resolution marine and terrestrial palaeoenvironmental records. Our findings show that hydrological fluctuations, triggered by the changing intensity of the monsoonal tropical summer rains emerging from the Amazon Basin in the north-east, have controlled the climate in the study area.

1 Introduction

There is clear evidence that marked, global-scale climatic changes during the Holocene induced significant and complex environmental responses in the central Andes, which repeatedly led to abrupt changes in temperature, precipitation and the periodicity of circulation regimes (Jansen et al., 2007; Bird et al., 2011a). This region is characterised by distinct gradients of several climatic parameters over short distances and hence is particularly sensitive to the effects of environmental change. It hosts a multitude of

Published by Copernicus Publications on behalf of the European Geosciences Union.

microenvironments that have varied with climatic changes, resulting in significant responses of vegetation zonation, geomorphodynamics and other variations in biotic and abiotic systems (Grosjean et al., 2001; Garreaud et al. 2003; Grosjean and Veit, 2005).

During the last decade, several studies improved understanding of South American climate, related mechanisms and teleconnections substantially (Baker et al., 2005; Ekdahl et al., 2008; Garreaud et al., 2008; Bird et al., 2011a, b; Vuille et al., 2012). Although considerable efforts have been made to decipher the palaeoenvironmental history of the central Andes, many aspects of the timing, magnitude and origin of past climate changes remain poorly defined (Grosjean et al., 2001; Latorre et al., 2003; Gayo et al., 2012).

Particularly the distorting effects of high-amplitude precipitation changes, such as complex series of humid/dry spells that repeatedly appeared throughout the Holocene, often affect the continuity and resolution of palaeoenvironmental records. Especially in the central Andes, detailed knowledge of the distribution and amplitude of abrupt climatic changes is still sparse and it remains unclear how these climatic oscillations align with the Southern Hemisphere circulation regimes (Baker et al., 2005; Moreno et al., 2007).

Considering the possible relationship between environmental and cultural changes, the emergence, persistence and subsequent collapse of pre-Columbian civilisations offer important insights into human–environment interactions (Binford et al., 1997). The success of pre-Columbian civilisations was closely coupled to areas of geo-ecological favourability, which were directly controlled by distinct regional impacts of large-scale atmospheric circulation mechanisms (Eitel et al., 2005; Mächtle and Eitel, 2013).

A large number of archaeological sites in the northern part of the Río Grande de Nasca drainage were documented by the German Archaeological Institute between 1997 and 2010 (Reindel, 2009; Sossna, 2012; Reindel and Isla, 2013). Based on more than 150 ^{14}C samples, Unkel et al. (2012) presented a numerical chronology for the cultural development of this area that covers the time from the Archaic Period to the late Intermediate Period (LIP) (5.7–0.5 ka/$\sim$ 3760 cal BC–AD 1450 cal). This archaeological data source represents a unique prerequisite to facilitate linkages with palaeoenvironmental records obtained from continuous geoarchives in the nearby Andean highlands.

To supplement and specify the current knowledge about climatic and environmental changes in the western Andes of southern Peru, we present a new record from the Cerro Llamoca peatland (CLP) for the last 8.6 ka. The peat and sediment-bearing core was drilled within a Juncaceous cushion peatland in the headwater area of Río Viscas, a tributary to Río Grande, at an altitude of 4200 m a.s.l. The CLP record represents an ideal site for the reconstruction of precipitation changes over long periods that had an influence on desert margin shifts at the Andean footzone. If the record implies distinct dry conditions in the high mountain areas of CLP, we can assume extreme dryness for the lower parts and a significant reduction of river runoff affecting water availability in the lowlands.

In the Palpa–Nasca region, the rise and fade of pre-Columbian cultures can be an example of the significant impact of environmental changes on cultural development and human settlement strategies (Eitel and Mächtle, 2009; Reindel, 2009).

2 The study area

2.1 Geographical setting, regional climate and vegetation

The investigated CLP is located in the western cordillera of the Peruvian Andes (Fig. 1). The name-giving peak, Cerro Llamoca (14°10′ S, 74°44′ W; 4450 m a.s.l.), is the highest point of the Río Viscas catchment area. As part of the continental divide, water courses on the western flank drain towards the Pacific Ocean.

Geologically, the CLP is situated within an area dominated by Tertiary rocks. The Castrovirreyna formation, formed during the upper Oligocene to early Miocene, consists of andesitic conglomerates intercalated with rhyolitic, dacitic vitric tuffs and thin sandstone layers, followed by andesitic breccias with intermediate andesitic and dacitic tuffs overlain by sandstones and andesitic breccias. Cerro Llamoca itself is a volcanic dyke and part of the early-Pliocene Caudalosa formation. It consists of heavily weathered andesites, andesitic ash tuffs and volcanic conglomerates (Castillo et al., 1993).

Situated in the transition zone between dry and humid Puna (Troll, 1968), an annual rainfall amount based on the data from the Tropical Rainfall Measuring Mission (TRMM) (Bookhagen and Stecker, 2008) of about 200–400 mm a^{-1} is estimated for the Cerro Llamoca area (Schittek et al., 2012).

Precipitation in the study area originates from Atlantic Ocean moist air masses that are transported to the Western Cordillera by upper-level tropical easterly flow. The strength of the easterly flow is controlled by the El Niño–Southern Oscillation (ENSO) system, with increased flow during La Niña episodes (Garreaud et al., 2009). About 90 % of total rainfall is concentrated during the austral summer months between November and March (Garreaud, 2000). This seasonal rainfall variability is connected to the position of the Intertropical Convergence Zone (ITCZ) as well as to the strength of the South American summer monsoon (SASM) (Zhou and Lau, 1998; Maslin and Burns, 2000; Maslin et al., 2011; Vuille et al., 2012). Seasonal water excess in the highlands supports the river oases downstream in the desert, where irrigation agriculture is practised since pre-Columbian times (Mächtle, 2007; Reindel, 2009). Movement of moist air from the Pacific onto the Altiplano is prevented by a strong and persistent temperature inversion maintained by

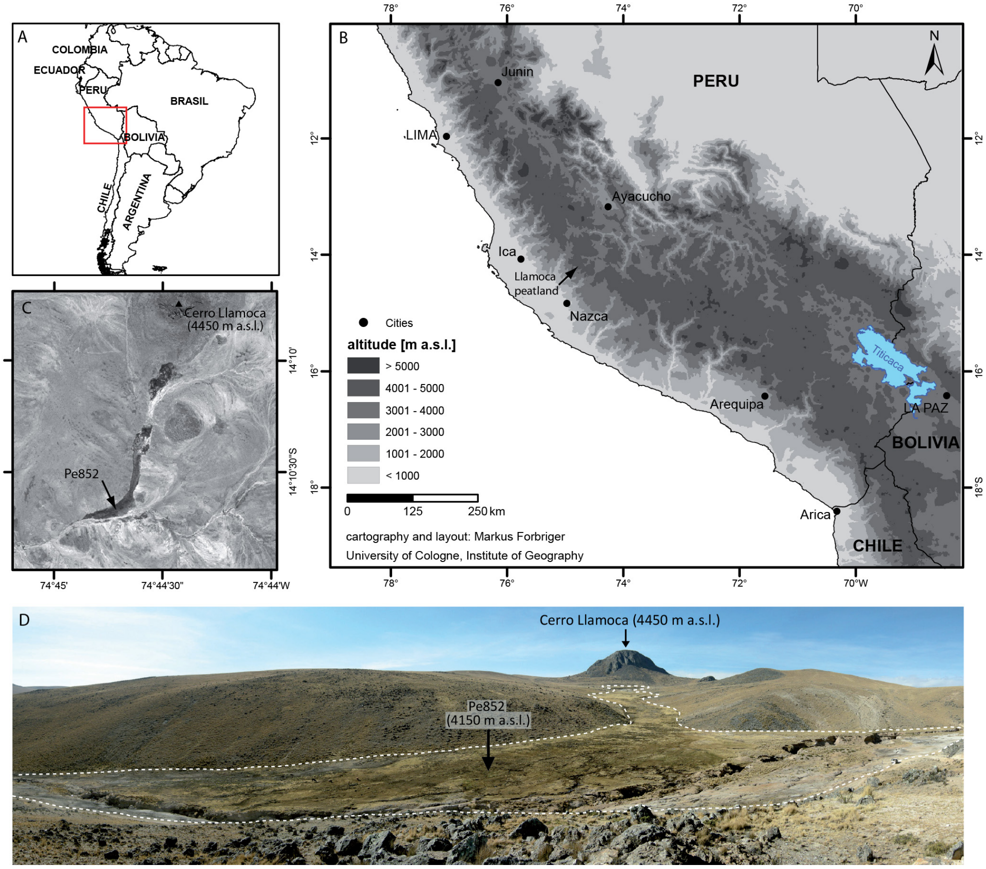

Figure 1. **(a)** Map of Peru and adjacent countries (data source: GLCF World Data). **(b)** The location of Cerro Llamoca peatland (CLP) in the western Andes of southern Peru (data source: DGM-GTOPO 30). **(c)** Aerial photograph of CLP with Cerro Llamoca in the north and location of the coring site of core Pe852 (Servicio Aerofotográfico Nacional – SAN, Lima). **(d)** Panorama of CLP with the name-giving peak and the location of the coring site. Dashed lines indicate the extension of the peat- and sediment-accumulating area. The southern part of the peatland is separated from water supply by a deeply incised gully.

cool waters offshore and large-scale subsidence over the southeastern Pacific (Vuille, 1999).

Several springs in the uppermost headwater zone feed the valley-bottom-type minerotrophic peatland on the southwestern slope of Cerro Llamoca. The peat-accumulating area occupies the upper valley up to its confluence with an incised, tributary stream channel. During heavy rainfall events it carries sediment to the peatland area (Schittek et al., 2012; Höfle et al., 2013). The slopes within the peatland's catchment area, depending on prevailing stable or unstable environmental conditions, represent a source area for allochthonous input to the peat-dominated valley bottom, resulting in a complex intercalation of organic and inorganic sediment layers.

High-altitude cushion peatlands occur along the Andean range with gradually changing floristic composition (Ruthsatz, 2000; Squeo et al., 2006). At CLP, the Juncaceae *Distichia muscoides* and *Oxychloe andina* are the dominant peat-forming cushion plants. They often grow so densely that they can form extensive, stable mats ranging in shape from almost flat to hemispherical. The shoots continue to grow at their tops but die off from the bottom (Rauh, 1988). A more detailed description of the vegetation and present condition of CLP is presented in Schittek et al. (2012).

The natural vegetation of the slopes, mostly dominated by the tussock grasses *Festuca dolichophylla*, *Stipa brachyphylla* and *Stipa ichu*, has been changed significantly by grazing. Today's regional vegetation is dominated by scattered, often grouped stands of xerophilic dwarf shrubs. The overall vegetation cover usually does not exceed 30 %. Especially slopes exposed to the north are scarcely vegetated, which is responsible for an increased erodibility. In areas protected by rocks and where there is less grazing, as well as on slopes exposed to the south-east, tussock grasses still prevail.

2.2 Human settlement history

Pre-Columbian settlement history in the south Peruvian coastal desert dates back to more than 5 ka (Fig. 5). Although there is some evidence of hunting and gathering in the study area since at least the early Holocene, earliest numerically dated human remains in the Palpa–Nasca region reach back to the Archaic Period (5.7–5.0 ka/3760–3060 cal BC) at a site called Pernil Alto, situated in the lower Rio Grande valley (Unkel et al., 2012; Gorbahn, 2013). Here, after a 1600-year hiatus, signs of reoccupation are evidenced during the Initial Period from 3.41 to 2.79 ka/1460 to 840 cal BC. Agriculture is now the primary subsistence strategy. Still, there are no signs of occupation of the higher-elevated Andean area within the Rio Grande catchment. The Initial Period can be considered the basis from which the Paracas culture later emerged (Reindel, 2009).

The early Horizon (2.79–2.21 ka/840–260 cal BC) is subdivided into early, middle and late Paracas. From approximately the late fifth century BC, immigration of people from regions with comparable environmental conditions, experienced with highland farming and camelid herding, led to an intensifying of human activity in the upper slope region of the western cordillera of the Andes called *cabezadas* (Sossna, 2014). Highlights of their cultural activities are petroglyphs and the first geoglyphs on the slopes of the Palpa valley.

The initial Nasca phase (2.21–1.87 ka/260 cal BC–AD 80 cal) was a very dynamic epoch regarding settlement patterns, ceramic technology and textile craft. Between 2.25 and 2.05 ka/300 and 100 cal BC the *cabezadas* were abandoned, whereas downstream along the river oases a strong increase in population occurred during the transition from Paracas to Nasca culture (Reindel, 2009; Sossna, 2014).

Followed by the early Intermediate Period (1.87–1.31 ka/80–AD 640 cal) that is subdivided into early, middle and late Nasca, the early Nasca period (1.87–1.65 ka/80–AD 300 cal) was a time of high cultural development. Settlement density grew, political structures developed and ceramic as well as textile production was intensified and professionalised. Systematic agriculture, partly with irrigation systems, and especially the creation of huge geoglyphs resulted in enormous landscape changes. In contrast to the Initial Period, settlements evolved in the large floodplains at that time, close to the valley border with implications for clear hierarchic features. The cultural evolution climaxed around AD 200, with Cahuachi as a great temple city that was abandoned 100 years later. The highest density of settlements occurred during the middle Nasca (1.65–1.51 ka/300–AD 440 cal). Towards the end of the middle Nasca phase, the settlements tended to shift to the middle valleys and the population underwent a general decline (Reindel, 2009; Sossna, 2014).

This trend continued during the late Nasca phase (1.51–1.31 ka/440–AD 640 cal). The middle Horizon (1.31–1.16 ka/640–AD 790 cal) is documented by only a few findings in the region (Unkel et al., 2012). The lack of archaeological material during the next ca. 400 years indicates a second hiatus in the settlement chronology. During that period the area was influenced by the Wari empire from further east.

From the ninth century AD on, the area was more or less depopulated. At the beginning of LIP (0.77–0.5 ka/1180–AD 1450 cal), human activity rose again markedly along the river oases (Reindel, 2009; Unkel et al., 2012) and at the *cabezadas*. Large groups of immigrants from the highlands recolonised the area (Fehren-Schmitz et al., 2014). The population peaked during the 14th/15th century AD, incident to a massive expansion of agricultural terraces (Sossna, 2014).

3 Methods

The coring field work was carried out in August 2009. For the selection of a suitable coring site within the peatland we applied electrical resistivity tomography (Schittek et al., 2012). Several transects were measured to receive an insight into the peatland's internal structure and depth to bedrock. Multiple cores were drilled at several sites within the whole peatland range by using percussion hammer coring equipment. The retrieved sediment was sealed in liner tubes with a diameter of 5 cm.

This study focuses on the deepest core (Pe852), which reached a depth of 10.5 m. The core was divided into two core halves, photographed and sedimentologically described at the Palaeoecology Laboratory of the Department of Geography and Geographical Education (University of Cologne). One core half was sub-sampled at 5–10 cm intervals (depending on the stratigraphy) from the peat sections for micro- and macrofossil analyses.

The inorganic geochemistry of the other core half was analysed in 2 mm resolution using an ITRAX X-ray fluorescence (XRF) core scanner (Cox Analytical Systems) at the Institute of Geology and Mineralogy (University of Cologne). XRF scanning was performed with a Mo tube at 30 kV and 30 mA, using an exposure time of 20 s per measurement.

For pollen sample preparation we applied an extended protocol. After KOH treatment for deflocculation, the samples were sieved in three additional sections (2 mm, 250 µm, 125 µm). These three size fractions were separated for the study of macrofossils. After spiking with *Lycopodium* markers to allow for concentration calculation, the further pollen preparation followed standard techniques described in Faegri and Iversen (1993). Microfossil samples were mounted in glycerine and pollen was identified under ×400 and ×1000 magnification. A minimum of 300 terrestrial pollen grains was analysed in each sample. Identifications were based on our own reference collection and on published atlases and keys (Heusser, 1971; Markgraf and D'Antoni, 1978; Graf, 1979; Hooghiemstra, 1984; Sandoval et al., 2010; Torres et al., 2012). Pollen and non-pollen palynomorphs data were subjected to numerical zonation using binary

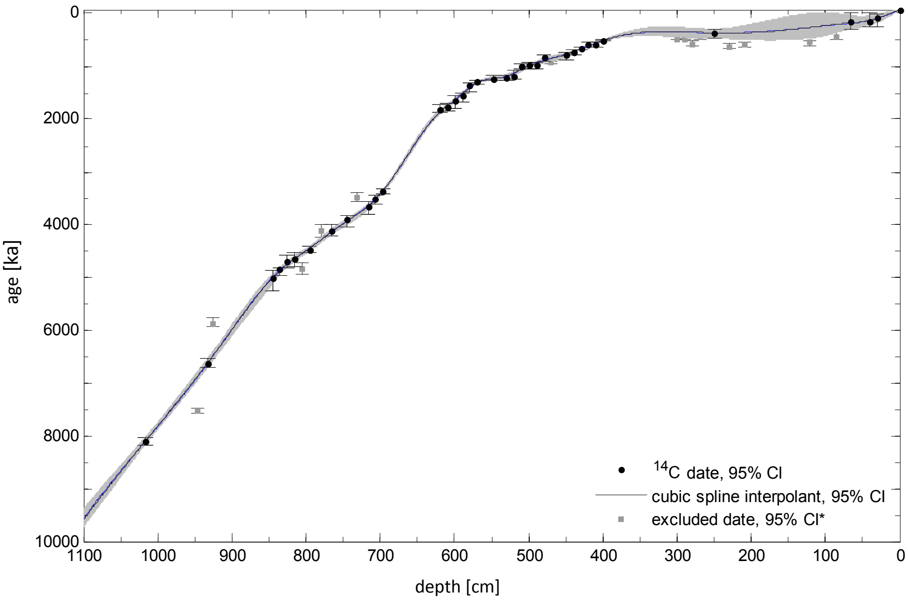

Figure 2. Age-versus-depth model for core Pe852 retrieved from Cerro Llamoca peatland based on 35 ^{14}C dates. The grey band represents the modelled range of dates and the black line the 50th percentile of all runs.

splitting techniques (Hammer et al., 2001), which highlighted five main zones.

Radiocarbon dating was performed from the same samples used for pollen analyses, concerning the 10 cm interval from the peat sections. A total of 50 samples were dated by Dr. Bernd Kromer and Susanne Lindauer (Klaus Tschira Centre for Archaeometry and Heidelberg Academy of Sciences) (Table 1). All radiocarbon dates were calibrated using CALIB 6.0.1 and the IntCal09 data set for Northern Hemisphere calibration (Reimer et al., 2009). Southern Hemisphere calibration is recommended for regions south of the thermal equator (McCormac et al., 2004). As the seasonal shift of the ITCZ brings atmospheric CO_2 from the Northern Hemisphere to the Andes during spring and summer seasons, it is primarily taken up by the vegetation. The age–depth model is based on a Monte Carlo approach to generate confidence intervals that incorporate the probabilistic nature of calibrated radiocarbon dates by using the MCAgeDepth software (Higuera, 2008). The program generates a cubic smoothing spline through all the dates. A total of 800 Monte Carlo simulations were used to generate confidence intervals. The final probability age–depth model is based on the median of all the simulations.

4 Results

4.1 Stratigraphy and chronology

The sedimentary deposits of CLP consist of an interlayered bedding of peat layers and layers of silt, clay and sand in varying compositions and with different contents of plant remains. These are repeatedly interrupted by layers of inorganic debris, which comprise either fine and middle sands or coarse sand and gravel.

The most frequent substrate types are peat and coarse sand. The peat and sediment matrices show variable contents of embedded silt and clay. A rapid change of coarse sediment and layers of silt/clay with variable contents of organic matter characterise the lowermost section (1050–850 cm). The middle section (850–400 cm) shows homogenous peat layers, less frequently interrupted by coarse sediment. The upper 400 cm section contains the highest variability of substrate types and comprises repeated deposition of coarse sediment. This type of peat-debris deposit is typical for high-altitude peatlands in the more arid central and western Altiplano, characterised by an interplay of fan aggradation and peat growth (Schittek et al., 2012).

The age–depth model is based on 50 radiocarbon dates of mostly bulk sediment samples (Fig. 2). Due to redeposition effects, 15 dates were omitted from the model. This is especially the case between 100 and 400 cm, where rapid deposition of allochthonous debris within a short time frame might have eroded and redeposited peat and soil material to the coring site. Ages therefore remain within the same time range.

Nonetheless, the peat sections in particular reveal a continuous chronology, allowing a high-resolution palaeoclimate reconstruction. Sample resolution varies between about 10 and 30 yr cm^{-1} and is highest during periods of peat formation. Pollen analysis allows a palaeoenvironmental reconstruction at decadal to centennial resolution. The inorganic

Table 1. Radiocarbon ages of core Pe852. The calibrated age ranges were calculated using CALIB 6.0.1 and the IntCal09 data set (Reimer et al., 2009). The modelled ages are the result of a probabilistic age–depth model using MCAgeDepth (Higuera, 2008). The range represents the 2σ values, and the median ages are in parentheses.

Lab #	Depth (cm)	Measured ^{14}C	Measured error (±)	2σ calibrated age age (cal yr BP)	MCAgeDepth modelled age (cal yr BP)
MAMS-13291	30.5	96	21	26-(107)-257	28-(108)-188
MAMS-13292	40.5	150	20	8-(177)-276	53-(148)-235
MAMS-11767	65.5	220	28	1-(181)-304	43-(198)-307
MAMS-11768*	84.5	394	30	331-(466)-506	10-(225)-371
MAMS-13293*	120.5	558	23	529-(558)-633	6-(276)-483
MAMS-13294*	147.5	292	31	293-(383)-456	57-(313)-510
MAMS-13295*	209.5	633	26	557-(597)-660	235-(373)-510
MAMS-13296*	229.5	699	31	568-(662)-687	282-(382)-496
MAMS-13297	249.5	334	21	316-(384)-472	311-(383)-489
MAMS-11769*	269.5	392	26	333-(469)-504	295-(377)-477
MAMS-11770*	279.5	574	19	539-(605)-636	286-(372)-473
Hd-29328*	289.5	433	21	471-(502)-518	278-(368)-471
MAMS-10840*	299.5	421	23	346-(496)-514	266-(364)-462
Hd-29296	399.5	428	19	506-(519)-536	506-(520)-539
MAMS-10842	409.5	636	24	559-(595)-660	549-(569)-594
MAMS-10843	419.5	610	25	550-(602)-653	597-(619)-648
MAMS-10844	429.5	729	24	659-(675)-711	662-(675)-708
MAMS-10845	439.5	837	24	694-(742)-789	712-(733)-772
Hd-29297	449.5	893	18	744-(808)-900	750-(783)-842
Hd-29298*	469.5	1016	18	920-(937)-961	813-(854)-917
MAMS-10859	479.5	958	25	799-(854)-926	859-(893)-948
MAMS-10864	489.5	1094	30	940-(1000)-1060	914-(945)-994
MAMS-10857	499.5	1080	25	937-(983)-1053	971-(997)-1038
MAMS-10862	509.5	1115	25	965-(1013)-1068	1030-(1061)-1110
MAMS-10863	519.5	1244	24	1085-(1204)-1262	1100-(1141)-1190
Hd-29340	529.5	1285	19	1181-(1234)-1278	1153-(1203)-1235
MAMS-10861	547.5	1299	24	1182-(1244)-1286	1199-(1246)-1266
Hd-29299	569.5	1398	19	1290-(1304)-1340	1300-(1317)-1347
MAMS-10866	579.5	1499	30	1320-(1378)-1498	1376-(1404)-1446
MAMS-10867	589.5	1673	31	1518-(1577)-1686	1483-(1519)-1570
MAMS-10868	599.5	1764	32	1578-(1669)-1798	1596-(1636)-1687
MAMS-10869	609.5	1845	31	1712-(1779)-1863	1711-(1748)-1800
Hd-29312	619.5	1875	19	1737-(1828)-1872	1816-(1869)-1911
Hd-29313	696.5	3146	22	3335-(3374)-3436	3326-(3358)-3394
MAMS-10905	706.5	3307	33	3458-(3529)-3626	3487-(3515)-3560
MAMS-10906	716.5	3413	34	3579-(3663)-3810	3604-(3647)-3713
MAMS-10907*	730.5	3268	34	3409-(3496)-3574	3757-(3795)-3883
MAMS-10908	744.5	3606	33	3840-(3914)-4051	3879-(3924)-4010
MAMS-10912	766.5	3764	33	4002-(4127)-4233	4085-(4140)-4202
MAMS-10913*	779.5	3764	34	4001-(4127)-4235	4235-(4281)-4338
MAMS-10914	795.5	3997	33	4416-(4476)-4544	4410-(4451)-4510
MAMS-10915*	805.5	4280	34	4739-(4849)-4947	4493-(4546)-4601
Hd-29300	815.5	4123	21	4544-(4650)-4806	4583-(4638)-4704
MAMS-10909	825.5	4171	34	4584-(4713)-4826	4697-(4738)-4808
MAMS-10910	835.5	4299	35	4832-(4859)-4961	4817-(4858)-4943
MAMS-10911	845.5	4429	34	4885-(5017)-5264	4943-(4999)-5129
MAMS-10917*	925.5	5127	28	5761-(5892)-5930	6386-(6483)-6571
MAMS-10958	932.5	5820	29	6527-(6634)-6716	6517-(6619)-6701
MAMS-10959*	946.5	6666	30	7484-(7536)-7584	6768-(6883)-6951
Hd-28899	1016.5	7281	27	8022-(8094)-8167	8010-(8093)-8153

* Ages not used for the age–depth model.

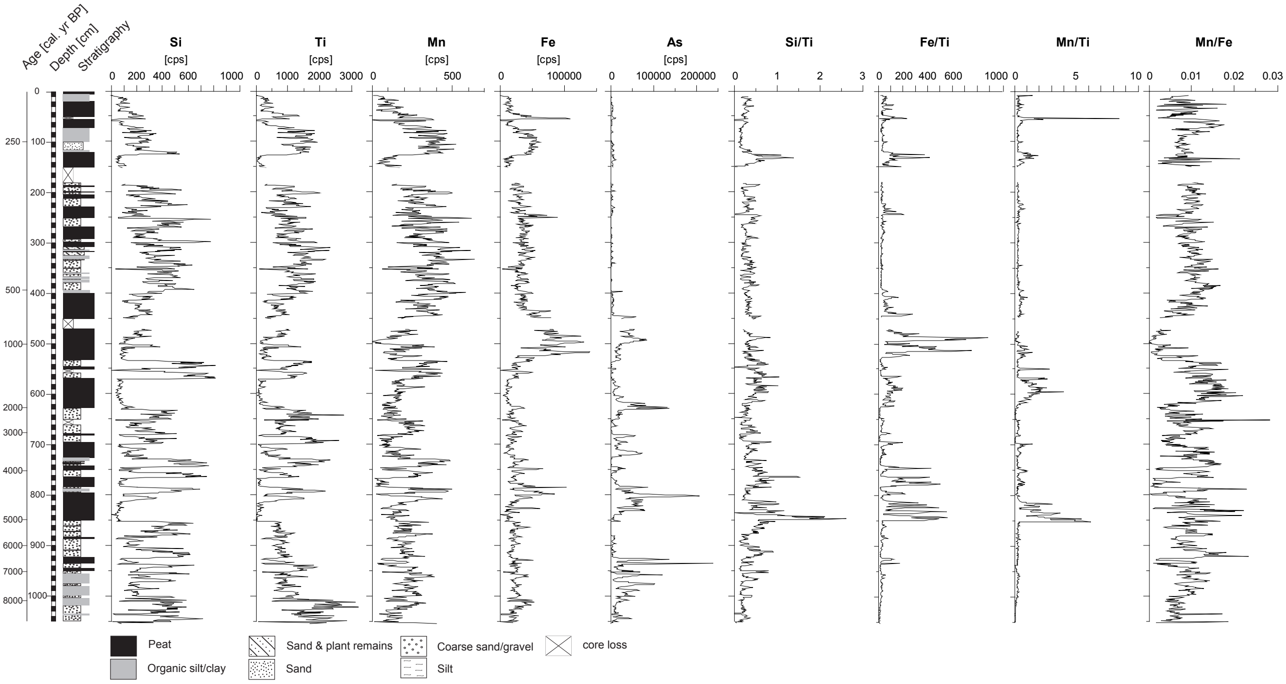

Figure 3. Stratigraphy and selection of elements and elemental ratios measured by the XRF core scanner for core Pe852 of the Cerro Llamoca peatland.

geochemistry (XRF data) was analysed in 2 mm steps, which allows a sub-decadal resolution for the peat sections.

4.2 Geochemical variability of the record

The peatland record is characterised by an interplay of peat accumulation and repeated deposition of inorganic sediments. Several distinct changes can be observed in the XRF signals of the measured elements reflecting the heterogeneous stratigraphy (Fig. 3). Silicon (Si) and titanium (Ti) originate from allochthonous lithogenic material and therefore show highest values in layers dominated by inorganic components. Si is further added by biogenic silica. Cyperaceae and Poaceae are highly abundant components of the peatland vegetation. These Si-accumulating plants deposit significant amounts of amorphous hydrated silica in their tissues as opal phytoliths (Street-Perrot and Barker, 2008). Diatoms represent another source of biosilicification (Servant-Vildary et al., 2001). Hence the Si / Ti ratio is used to discern the biogenic silica amount but might also reflect changes in grain sizes in the clastic sediment. Manganese (Mn) and iron (Fe) are also of lithogenic origin, but contents further depend on environmental factors that control post-depositional processes. By contrast, Ti is considered to be immobile in peat (Muller et al., 2006, 2008). Therefore, the Mn and Fe data were normalised to Ti to better reflect the variations in autochthonous in-peatland dynamics of the record. The Mn / Fe ratio is mainly linked to autochthonous precipitation of iron oxides and can be used as an indicator of redox conditions (Lopez et al., 2006).

Due to the weathering of volcanic rocks, spring waters in the upper headwater area of CLP (as at many other sites of the area) are enriched with arsenic (As). Recently wetlands, and in particular peatlands, were identified as a trap for As under anoxic redox conditions (Eh) (Langner et al., 2012; Hoffmann et al., 2012). We therefore use As as an indicator for hydrological changes in CLP.

The data show the most marked changes at 1050–930 cm (8.6–6.3 ka) with a high variability of values ranging between 10000 and > 100000 cps (Fig. 3). The following section at 930–840 cm (6.3–4.8 ka) is characterised by very low As values. Significantly higher As values are observed at 840–770 cm (4.8–4.3 ka), peaking at about 810–800 cm (4.5–4.4 ka). Further As peaks, which span shorter periods, are recorded at about 730 cm (3.7 ka), 680 cm (3.0 ka), 620–630 cm (1.9–1.8 ka) and 500–470 cm (1.0–0.9 ka).

Comparable to the As record, Si / Ti ratios are highly variable at 1050–930 cm (8.6–6.3 ka). At about 850–840 cm (5.0–4.9 ka), the Si / Ti ratio reaches its maximum value, corresponding to the Mn / Ti and Fe / Ti ratios. Afterwards, until about 630 cm (2.0 ka), the Si / Ti ratio tends to decrease. Only between 590 and 530 cm (1.9–1.3 ka) does it rise to higher values again, before decreasing towards the present.

Highest Fe / Ti and Mn / Ti ratios are observed during peat-accumulating periods. The Fe / Ti ratio is characterised by a high variability between 850 and 740 cm (5.0–3.9 ka). The

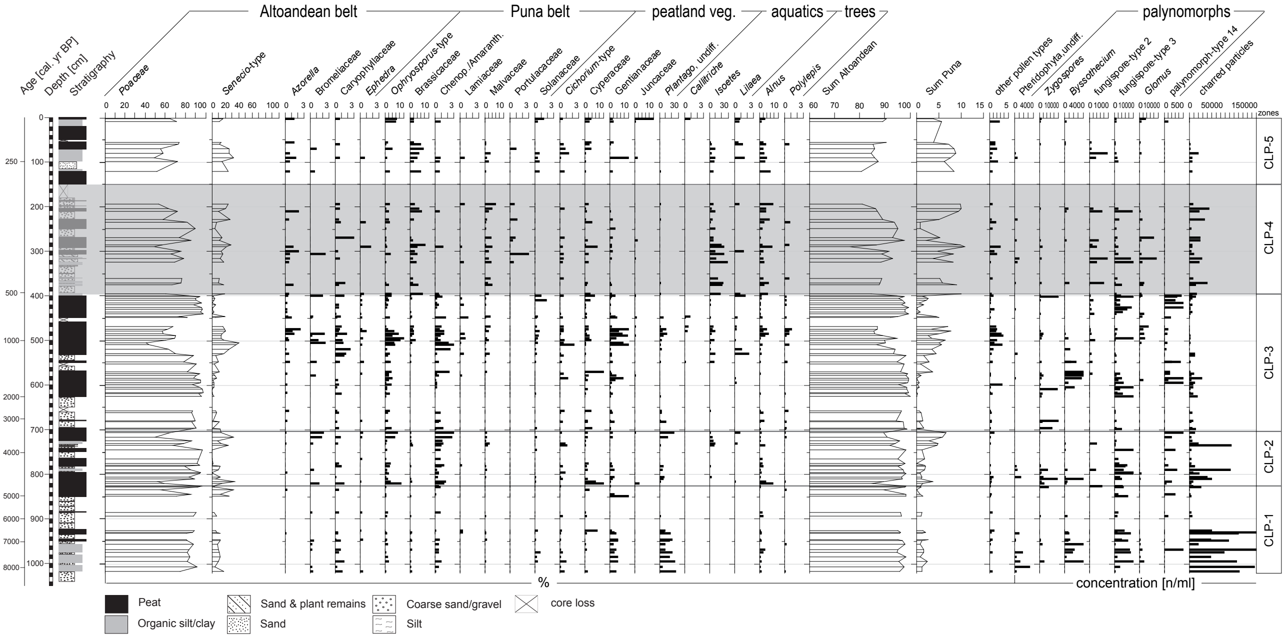

Figure 4. Pollen, palynomorphs and charred particles diagram for the Cerro Llamoca peatland, plotted against depth. Peatland vegetation and aquatic types were excluded from the pollen sum. The shaded zone is mainly composed of redeposited, erosional material.

highest peaks of the record occur at 480 cm (0.9 ka) and 520 cm (1.1 ka). After peaking at 850–840 cm (5.0–4.9 ka), Mn / Ti reaches higher values only between 630 and 570 cm (2.0–1.6 ka). The Mn / Fe ratio is highly variable throughout the record. Periods of low values tend to correspond to periods of higher As concentrations.

4.3 Pollen analysis

The results of the microfossil counts are plotted in Fig. 4. Usually only peat and organic silt/clay layers yielded sufficient pollen for counting. The pollen types are grouped together according to their main regional or local distribution range. As the peatland site is situated in the lower Altoandean altitudinal belt (Ruthsatz, 1977), the overall pollen spectrum is clearly dominated by Poaceae, which make up 40–95 % of the regional pollen assemblage. The other main regional taxa are all typical components of the Altoandean and Puna belts (Reese and Liu, 2005; Kuentz et al., 2007). Apart from *Senecio*-type Asteraceae (5–40 %), only *Ophryosporus*-type Asteraceae, Brassicaceae, Malvaceae and *Alnus* reach percentages > 3 %. Cyperaceae, Gentianaceae and *Plantago* represent local peatland and aquatic vegetation. *Isoetes* spores were included to the pollen counts. All local types are excluded from the pollen sum. Extra-regional pollen types are few throughout the sequence, mainly represented by *Alnus* and *Polylepis*. Other types comprise Ericaceae, Polemoniaceae, Bignoniaceae, Malpighiaceae, *Juglans* and *Podocarpus*, which appeared in very low abundances.

Zone CLP-1 (1050–830 cm; 8.6–4.8 ka) is characterised by a steady presence of Poaceae and *Senecio*-type Asteraceae pollen, both at medium percentage values. Caryophyllaceae are also steadily present with medium percentages. *Plantago* and Gentianaceae pollen are highly abundant. Fern and charred particle concentrations reach the highest values of the whole record within this zone. Due to higher contents of coarse sediment, the upper section of zone CLP-1 mostly lacked countable amounts of pollen.

Zone CLP-2 (830–710 cm; 4.8–3.6 ka) is marked by a high variation of Poaceae and *Senecio*-type Asteraceae pollen percentages. Interestingly, types typical of the Puna belt gain higher abundances towards the upper part of the zone. Cyperaceae pollen peaks at the beginning of zone two.

Zone CLP-3 (710–400 cm; 4.8–0.5 ka) at its initial section is scarce in palaeobotanical evidence due to the characteristics of the sediment. Between 630 and 540 cm (2.0–1.2 ka) high percentages of Poaceae are recorded, dominating the pollen spectrum. At 540–470 cm (1.2–0.8 ka), pollen values of *Senecio*-type Asteraceae and Puna belt types gain higher abundances. Poaceae reach their lowest values of the entire record here. Peatland pollen types show increases of Gentianaceae, Cyperaceae and *Plantago* values. The latter nearly disappears from the record afterwards, whereas *Azorella*, Brassicaceae, Malvaceae and *Isoetes* start to appear more frequently and in higher abundances from this point on. Poaceae are represented in high abundances again at 450–400 cm (0.8–0.5 ka).

Zone CLP-4 (400–150 cm; 0.5–0.3 ka) is mainly composed of re-deposited, erosional material. It therefore remains questionable if this zone can be used for interpretation. Age control reveals that this part of the core was deposited within a short time frame.

Zone CLP-5 (150–0 cm; 0.3 ka to today) represents the youngest section of the CLP record and, at least at its bottom, might be affected by redeposition. The sediment did not always contain sufficient pollen, due to increased decomposition of the peat. Overall, the Altoandean belt types remain at a relatively low level, whereas Puna belt types show high abundances.

5 Discussion

5.1 As, Mn and Fe retention and release under fluctuating water table conditions

Arsenic (As) and its compounds are mobile in the environment (Alonso, 1992; Kumar and Suzuki, 2002; Rothwell et al., 2009; Cumbal et al., 2010). In spring-water samples of the 2009 and 2010 campaigns we measured As contents of 140–270 $\mu g\,L^{-1}$ at the head of the peatland; however, the small stream leaving the peatland's main branch further down only contained 4–6 $\mu g\,L^{-1}$ (Schittek; unpublished data), which clearly shows that CLP is a sink for As. An analogous remediation of As-bearing waters by peat is reported for a minerotrophic peatland in Switzerland (González et al., 2006).

Langner et al. (2012) report that natural organic matter (NOM) can represent a major sorbent for As in sulfur-rich anoxic environments. They postulate that covalent binding of trivalent As^{3+} to NOM via organic sulfur species is the primary mechanism of As–NOM interactions under sulfate-reducing conditions. Therefore, As mobilisation is suppressed by sorption of As to NOM by the formation of stable inner-sphere complexes.

However, the CLP record shows several significant peaks in As (Figs. 4 and 5). Concerning the last 4000 years, the modelled periods of these events with high As contents strongly correlate with dry events, identified for the central Andes by several authors (Thompson et al., 1995; Rein et al., 2004; Chepstow-Lusty et al., 2009; Bird et al., 2011b). This presumably implies an enhanced As mobility under a climate regime with sustained dry periods, which may be attributed to the fixation of dissolved NOM (Langner et al., 2012) concurrent with a higher humification degree. The increasing sorption capacity to trace elements with increasing decomposition of peat was also found by Klavins et al. (2009) in peatlands in Latvia. The formation of humic acids leads to an increase of functional groups and therefore to an increasing sorption capacity.

Cloy et al. (2009), Rothwell et al. (2009) and Rothwell et al. (2010) report similar As dynamics in Scottish ombrotrophic peatlands. Here, stream water As concentrations are elevated during late summer stormflow periods, when there has been rewetting of peat after significant water table draw-down. Blodau et al. (2008) demonstrate that rewetting of previously dry minerotrophic peat leads to the rapid release of As and Fe into pore waters coupled with Fe reduction in the peat. Langner et al. (2012) highlight that, under oxic conditions, NOM promotes the release of As from metal (hydr-)oxides, thereby enhancing the mobility of As. Unfortunately, basic information on As biogeochemistry and As dynamics in naturally enriched peat ecosystems is still lacking. The results of this study underline that NOM might play an important role in As dynamics. Further research is needed to identify the exact As retention and release mechanisms. This would not only be of interest to (palaeo-)environmental research, but also be of significance for the protection of ecosystems and water resources.

Changes in Fe and Mn require careful consideration. The behaviour of Fe and Mn strongly depends on pH and water saturation. The portion of Mn^{2+} increases under anoxic conditions and forms soluble complexes with Mn^{2+} humic substances (Graham et al., 2002; Blume et al., 2010). Graham et al. (2002) identified that Mn contents were lowest and in a non-easily reducible form where the extent of humification was greatest. High Fe / Ti ratios indicate an upward movement of Fe^{2+} from the anoxic peat to the upper aerated layers, followed by precipitation as Fe^{3+}-oxide. This process leads to an enrichment of Fe in the zone of water table fluctuations (Damman et al., 1992; Margalef et al., 2013). As the peatland environment is naturally highly enriched with Fe, it strongly precipitates under oxic conditions and thus lowers the Mn / Fe ratio. Low values, indicating prevailing water table fluctuations and a more frequent occurrence of oxic conditions, correlate with As peaks. At about 1.8–1.2 ka, an outstanding period of high Mn / Fe ratios prevails, which indicates a period of steady saturation of the peat deposits at this site.

5.2 Mid-Holocene and late Holocene palaeoenvironmental changes

Selected proxies from the CLP record were plotted on the temporal scale and compared with published records from the Cariaco Basin (Haug et al., 2001) and Huascarán ice core (Thompson et al., 1995) (Fig. 5). The dominant driver of long-term climatic variations in the tropical Andes during the Holocene is the ITCZ (Haug et al., 2001; Ledru et al., 2009; Bird et al., 2011a, b; Vuille et al., 2012). Similarities in the $\delta^{18}O$ isotopic signatures from speleothems (van Breukelen et al., 2008; Cruz et al., 2009; Reuter et al., 2009), lake records (Ekdahl et al., 2008; Bird et al., 2011a, b; Placzek et al., 2011) and glacier ice cores (Thompson et al., 1998) in the South American tropics and subtropics indicate that water had a common main origin. The methodological advances in the application of multi-proxy approaches and the increasing number of palaeoclimatic studies in the tropical/subtropical Andes underline the hypothesis of Haug et al. (2001) that

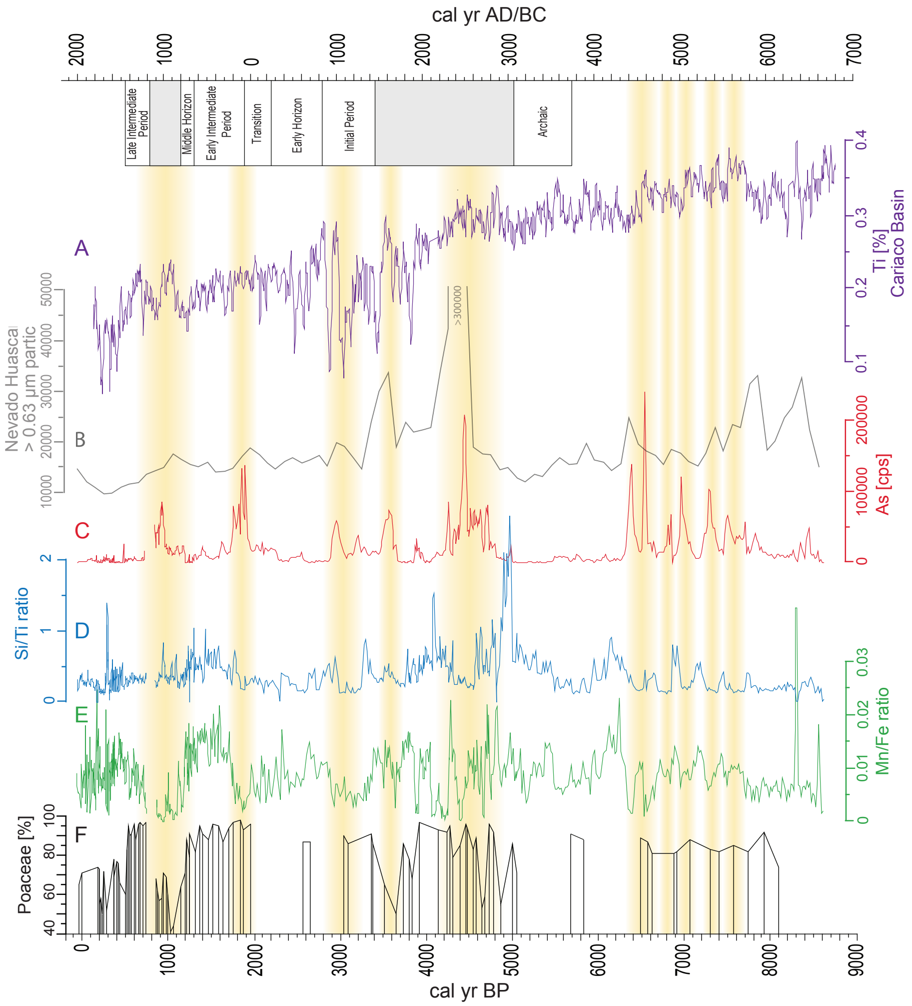

Figure 5. The archaeological chronology of the pre-Columbian cultures in the Palpa valleys (Unkel et al., 2012) compared with the bulk Ti content of Cariaco Basin sediments (**a**; Haug et al., 2001) and dust particle concentrations of Huascarán ice core (**b**; Thompson et al., 1995). **(c)**, **(d)**, **(e)** In situ geochemical parameters and the Poaceae pollen record **(f)** of the Cerro Llamoca peatland.

changes in precipitation relate to shifts in the mean latitude of the ITCZ. A more southerly position of the ITCZ triggers moisture flux into the tropical lowlands, which enhances convective activity in the Amazon Basin.

Data on mid-Holocene palaeoclimate in the central Andes remain discontinuous and still only provide snapshots of information. Moreno et al. (2007) identified the interval between 8.6 and 6.4 ka as the driest episode of the Chungará lake record in the northern Chilean Altiplano. They point out that dry conditions were not constant but rather characterised by a series of short and rapid dry spells. This finding coincides very well with the CLP record for nearly the same period. Here dry spells, indicated by marked As peaks, alternate with humid spells, indicated by a higher degree of anoxic conditions (Mn / Fe ratio) and higher amounts of biogenic silica (Si / Ti ratio). Grass pollen percentages remain at medium values.

That the generally dry conditions were repeatedly interrupted by short-lived, abrupt moisture changes was also found in other central Andean lake and sediment archives (Grosjean et al., 2001). Nonetheless, records of mid-Holocene climate conditions are not synchronous in the central Andes (Betancourt et al., 2000; Holmgren et al., 2001; Abbott et al., 2003; Latorre et al., 2003; Kuentz et al., 2011). Discrepancies in the exact timing of climatic changes and the interpretation of their causes are common as proxy records are obtained from different archives and geographically heterogeneous localities. A major constraint of most palaeoclimate records of the central Andes is that they do not show a significant variability on multi-centennial to millennial scales (Lamy et al., 2001), which is needed to compare them with other continent-scale, high-resolution records.

Based on oxygen isotope ratios, Bird et al. (2011a) suggest weak SASM precipitation at Lake Pumaqucha from 7.0 to 5.0 ka, which corresponds to a low stand of Lake Titicaca from 7.5 to 5.0 ka inferred from seismic profiling and sediment δ^{13}C (Seltzer et al., 1998; Rowe et al., 2003). Following the concept of Haug et al. (2001), the ITCZ had remained at a relatively stable northern position throughout the middle Holocene. Thus, monsoon intensity might have been predominantly weak. However, minor intensifications in the southward migration of the ITCZ might have temporarily increased moisture availability at CLP during the middle Holocene, as visible by the episodically higher levels of Si / Ti and Mn / Fe ratios (Fig. 5).

The CLP record does not offer clear palaeoenvironmental evidence for the period of 6.4 to 5.1 ka due to the dominance of coarse sediment in the record and a lack of pollen. Higher Mn / Fe and Si / Ti ratios suggest moister conditions at around 6.3–6.0 ka and again starting from 5.5 ka. At 5.0–4.9 ka a significant transition to wetter conditions is evidenced in the CLP record by a pronounced Si / Ti peak. This abrupt climate change has been recognised in several records from the tropical Andes (Abbott et al., 2003; Thompson et al., 2006; Ekdahl et al., 2008; Buffen et al., 2009). The onset of this cool and wet period led to an expansion of the Quelccaya ice cap (Thompson et al., 2006) and an increase of the Lake Titicaca lake level (Baker et al., 2001). A climatic transition ~ 5000 years ago is also notable, e.g. in eastern equatorial Africa and the eastern Mediterranean region (Thompson et al., 2006). The colder conditions promoted an increased peat growth at CLP but remained highly variable and unstable as evidenced by the high fluctuations of the pollen and Mn / Fe ratio in the sediment record. The humid period between 5.4 and 4.9 ka probably culminated in the formation of a palaeosoil within a loess sequence in the desert margin area of southern Peru. This indicates stable conditions with weathering processes and a dense vegetation cover in an area now characterised by extremely arid conditions (Mächtle and Eitel, 2013).

The cool and wet period is followed by a marked dry period at about 4.6–4.2 ka, as indicated by the extremely high As contents in the CLP record. Peaking at 4.5–4.4 ka, the As record coincides with a peak of insoluble dust concentrations evidenced in the Huascarán ice core (Thompson et al., 1995). The further As peaks in the CLP record strongly correlate to dry events identified at the lake site of Marcacocha (Chepstow-Lusty et al., 2003, 2009), which started to accumulate lake sediments after 4.2 ka. Based on inorganic contents and Cyperaceae pollen concentrations, drier episodes, coinciding with the CLP record, occurred around 3.6–3.5, 3.1–2.9, 2.0–1.8 and 1.2–0.8 ka. The highly variable Mn / Fe and Si / Ti ratios prior to 4.5 ka suggest unstable climatic conditions until 1.8 ka. The pollen record in this section is rather fragmentary due to the dominance of coarse sediments in the retrieved cores.

After about 2.0 ka, Mn / Fe ratios declined at CLP and remained low until about 1.8 ka (Fig. 6). Elevated As contents point to a pronounced dry period. Vinther et al. (2009) recorded higher temperatures in Greenland at exactly the same time span. The timing and extent of this dry period can be well correlated to the Roman Warm Period (RWP) (Zolitschka et al., 2003; Ljungqvist, 2010). Warmer and drier conditions in South America during that period have been found by Jenny et al. (2002), based on geochemical, sedimentology and diatom assemblage data derived from sediment cores extracted from Laguna Aculeo (central Chile). Similar observations have also been made by Chepstow-Lusty et al. (2003), who evidenced the RWP as a period of 100 to 200 years of relative warmth and dryness in comparison to the periods before and after.

The occurrence of a sustained cold period in South America after about 1.8 ka is evidenced by concomitant glacier expansions in the Peruvian (Wright, 1984; Seltzer and Hastorf, 1990; Thompson et al., 1995) and Bolivian Andes (Abbott et al., 1997). Chepstow-Lusty et al. (2003) noted a suppression of agriculture at Lake Marcacocha, which is suggested to be a direct reflection of a period of colder climate conditions leading to significantly reduced human population in that area. Poaceae pollen percentages and Mn / Fe ratios remain at elevated and stable levels in the CLP record from 1.8 to 1.2 ka.

A harsh return to drier conditions at CLP at around 1.2–1.15 ka can be inferred from a sudden reduction in Poaceae pollen percentages and Mn / Fe ratios, which must have severely affected the peatland water regime and the vegetation cover of the surrounding high-Andean grasslands. Grass percentages dropped down to the lowest value of the record at 1.05 ka. The period of extreme drought lasts until about 0.75–0.7 ka, when grass pollen become highly abundant again. Rein et al. (2004), who presented a high-resolution marine record from the Peruvian shelf west of Lima, also discussed this sustained dry period contemporary to the Medieval Climate Anomaly (MCA) (Fig. 6). Based on lithic concentrations, they identified this period as characterised by a lack of strong flooding, because of reduced river runoff, from 1.15 to 0.7 ka. Bird et al. (2011a) suggested a considerable weakening of the SASM during 1.05 and 0.85 ka and linked this event with the Northern Hemisphere MCA and a northward position of the Atlantic ITCZ.

Starting shortly after 0.75 ka, grass pollen abundance at CLP was back to levels $> 90\,\%$ and remained being highly abundant until about 0.5 ka. Mn / Fe ratios indicate variable redox conditions in the peatland.

After 0.5 ka the proxy signals of CLP underwent strong and repeated shifts. These changes are likely to be linked to the destabilisation of slopes within the CLP water catchment area (Schittek et al., 2012). More than 3 m of debris were deposited upon the peatland sediments between 0.5 and 0.25 ka. The cooling of the Little Ice Age (LIA) might have altered the resilience of the peatland and its water catchment area to erosion and triggered the fluvial input of alluvial sediment by very strong episodic rainfall events and by a reduction of vegetation cover on the slopes due to aridity and/or increased pasturing. Debris flows usually occurred during periods of slow vegetation growth on the slopes of the water catchment

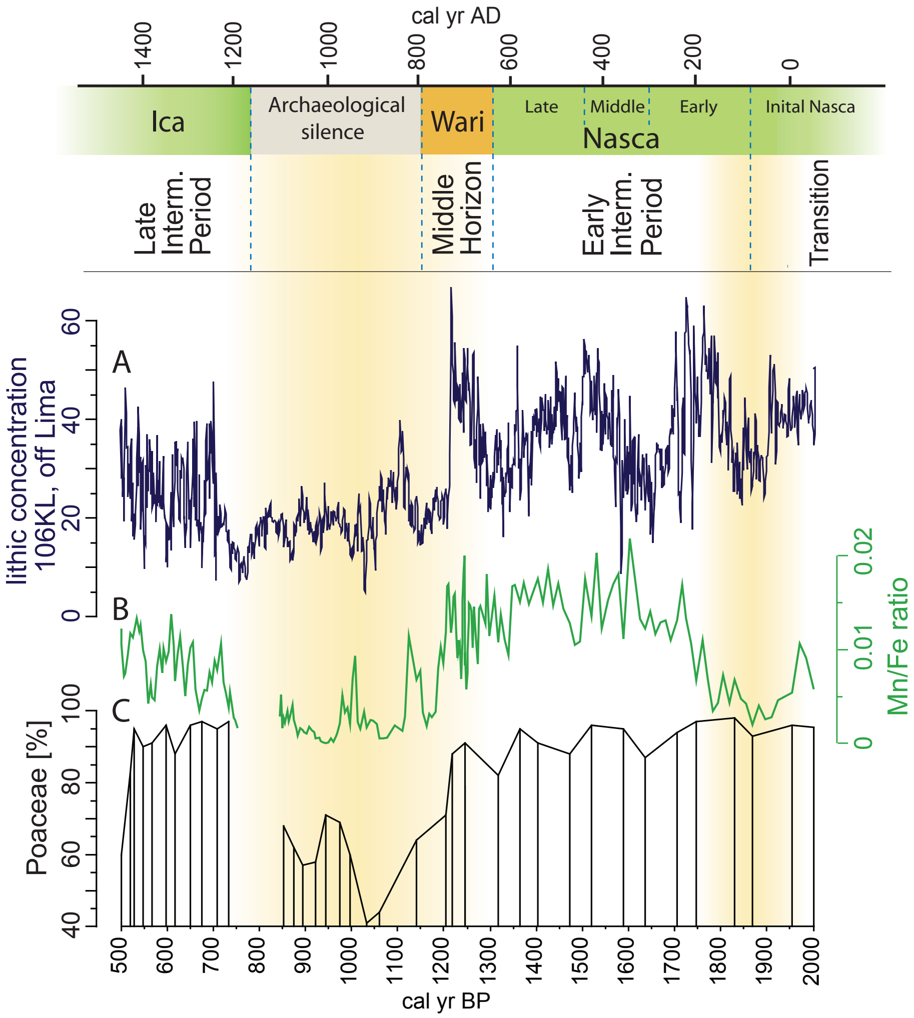

Figure 6. The archaeological chronology of the last 2000 years in the Palpa valleys (Unkel et al., 2012) in comparison to lithic concentration of a marine core from the Peruvian shelf west of Lima (**a**; Rein et al., 2004), Mn / Fe ratios **(b)** and Poaceae pollen percentages **(c)** from the Cerro Llamoca peatland.

area because of climatic changes and/or soil degradation by overgrazing (Schittek et al., 2012).

Bird et al. (2011b) noted a pronounced decrease in Pumaqucha δ^{18}O between 0.55 and 0.13 ka, which was likely in response to a southward displacement of the Atlantic ITCZ, associated with cooler temperatures and significantly increased precipitation. However, Morales et al. (2012) pointed out that the LIA was not a persistent period of wet/cool conditions. Moreover, several severe droughts occurred during that period.

The CLP sequence represents an exemplary record of long-term trajectories between periods of landscape stability and transitional phases of landscape destabilisation. Periods of relative landscape stability under a more humid and balanced climate regime with less pronounced droughts would promote soil accumulation and the establishment of a dense grassland vegetation cover on the surrounding mountain slopes, which significantly slows down overland water runoff.

The abundant presence of grass pollen reflects very well the predominance of grasses in the high-Andean vegetation belt. The density of the grass cover diminishes during drier periods and better-adapted high-mountainous vegetation components like Asteraceae (mostly *Senecio*-type), Brassicaceae, Caryophyllaceae and Chenopodiaceae/Amaranthaceae become more evident in the pollen spectrum. Gentianaceae and *Plantago* typically spread in oxidised sections of Andean peatlands where water table fluctuations prevail.

The dynamics of the SASM appears to be a conceivable driver for moisture fluctuations in the investigated area. Vuille et al. (2012) pointed out that the intensity of the SASM, and thus the amount of Andean rainfall, is sensitive to the position of the ITCZ, which depends on sea surface temperatures in the North Atlantic and the eastern tropical Pacific. Episodes of water table fluctuations at CLP, as reflected by low Mn / Fe ratios and high As contents, and, in some cases, a reduction of grass pollen abundances, tend to correlate with northward positions of the ITCZ and hence a reduced SASM intensity (Fig. 5). A reduced convection in the Amazonian lowlands might shorten the rainy season at CLP and result in an enforced seasonality with a concentration of rainfall in summer and a prolonged dry phase during the rest of the year. These conditions trigger erosion and, consequently, the deposition of debris upon the peatland after heavy episodic rainfall events. Although moisture transport is closely connected to ITCZ dynamics, SASM intensity is more or less determined by further modes of climatic variability like ENSO, the Pacific Decadal Oscillation and latitudinal shifts of the southern westerlies. The role of Pacific modes of variability as a control over precipitation in the tropical/subtropical Andes is still controversially discussed (Mann et al., 2009).

5.3 The impact of climate change on pre-Columbian cultures

Constructing comparable chronologies between past climate and cultural changes based on palaeoenvironmental and archaeological records should be exercised with utmost discernment. Only when both records are sufficiently continuous and reliable might they offer the opportunity for correlation (Seltzer and Hastorf, 1990).

The numerical archaeological chronology of the Palpa–Nasca valleys presented by Unkel et al. (2012) is one of the best-dated chronologies available in South America and serves as the backbone of our integrated approach in the climatically sensitive western margin of the Andes. The CLP palaeoenvironmental record evidences repeated climatic fluctuations, concurrent with changes in cultural florescence of local people. This is especially the case between the early and late Intermediate periods (Fig. 6) when the resolution of the CLP record is highest and most reliable.

When tracking climate and settlement patterns it is important to remember that the success of early cultures in areas close to desert margins mainly depended on the availability of water. Although civilisations were able to expand natural limits by inventing and adapting techniques of water harvesting and agriculture, they were not able to master long-lasting periods of severe drought. A typical settlement pattern in the Palpa–Nasca valleys is that the main settlement and agricultural production area repeatedly shifted between the Andean foothills/lower valleys and the highland section (*cabezadas*) (Reindel, 2009; Sossna, 2012, 2014).

At present, human activity and environmental changes cannot be linked during the early phase (∼ 5.25 ka), due to the low population of non-sedentary pre-Columbian people and very little archaeological evidence. The earliest well-dated occupation period in Pernil Alto (∼ 5.7–5.0 ka) coincides with a transition to wetter conditions, starting at around 5.5 ka. River runoff from the high Andes may have allowed for hunters and gatherers to temporarily settle in pit houses close to the floodplains and revisit that site over a long period of time (Reindel, 2009; Unkel et al., 2012; Gorbahn, 2013). At 4.6 ka, the onset of repeated dry periods could have been the trigger for a temporary abandonment of the settlement.

During the Initial Period (∼ 3.4–2.8 ka), a reoccupation of Pernil Alto is evidenced by the construction of buildings with depots, hearths and workshops out of adobe, which displays permanent sedentary lifestyle apparently based on agriculture (Reindel, 2009).

The CLP record suggests unstable conditions during the transition of the Initial Period and the early Horizon, manifested by a contemporaneous, high heterogeneity of the stratigraphic record, which limits the informative value of the pollen sequence. Monsoon intensity might have been temporarily strong, and conditions at the desert margin were anything but stable. Population density was low and settlements clustered in the upper Palpa valley (Sossna, 2014). This significantly changed in the middle Paracas phase, when settlement activity boomed and a large number of settlements were established in the formerly almost uninhabited *cabezadas*. This coincides with the onset of a period of less marked ITCZ shifts at around 2.5 ka. At CLP, stratigraphy and variable Mn / Fe ratios suggest unstable conditions, but climate was more humid than during the Initial Period, as evidenced by overall higher Mn / Fe ratio values after 2.5 ka (Fig. 5). The end of the late Paracas phase and the earlier Initial Nasca phase (around 2.25–2.05 ka) is characterised by the abandonment of many settlements in the *cabezadas* and a dramatic increase of population density at the foothills. This trend continued during the Initial Nasca phase (2.21–1.87 ka).

Due to the gradual character of cultural transitions and a limited number of ^{14}C dates, the emergence of the Initial Nasca phase and its transition into the early Nasca phase is still inaccurately dated. It therefore remains uncertain if the short dry episode, evidenced at about 2.0–1.75 ka at CLP, had any effect on the evolution of the Nasca culture. At least it very clearly marks the transition between the two phases.

General precipitation and increased river runoff can be assumed for 1.75–1.2 ka (see Sect. 5.2; Rein et al., 2004), which led to a concentration of settlements along the river oases (Eitel and Mächtle, 2009; Sossna, 2014). Widespread agricultural terraces fed a large population. These terraces were mainly irrigated by local rainfall reaching beyond today's desert margin.

The short decrease in Poaceae pollen percentages, as well as a decrease in lithic concentration (Rein et al., 2004), can be correlated with a short decrease in lowland population. During this dry episode, river runoff was reduced, which led to a re-occupation of the *cabezadas* (Sossna, 2014). In the lowlands, the most important centres were abandoned, and the focus of the settlements shifted to the middle and upper valleys. The processes again coincide with oscillations registered in the CLP pollen record and the marine core at the same time by Rein et al. (2014) (Fig. 6).

During the late Nasca phase, new centres of power were once again re-established in the lowlands. But population levels stayed relatively low and further decreased towards the end of the phase, which again might have been triggered by reduced precipitation as evidenced by reduced Mn / Fe ratios and pollen percentages at CLP around 1.3 ka (Rein et al., 2004).

This significant dry period, which was fully developed around 1.05 ka, again corresponds to the archaeological silence when the foothills may have been depopulated almost completely. This archaeological silence without any findings in the study area is recorded in the CLP record by a massive decrease of Poaceae pollen and is also corroborated within the results of Rein et al. (2004). A rapid shift to more humid conditions during the late Intermediate Period (Ica) triggered a massive migration from the highlands to lower valleys and the river oases (Fehren-Schmitz et al., 2014) where agricultural terraces expanded to the slopes (Sossna, 2014), which were also fed by water from local rainfall in an area where hyper-arid conditions now prevail (Mächtle, 2007). Still many people remained in the highlands and the upper valleys.

A significant low stand of the Mn / Fe ratio around 0.66 ka, indicating a temporary decrease in precipitation, correlates with the construction of water harvesting systems in the Palpa lowlands (Mächtle et al., 2013). The unstable conditions during the LIP might favour the establishment of manifold storages, even above the household level (Reindel, 2009; Sossna, 2014).

6 Conclusions

This investigation supports the assumptions made by Bird et al. (2011a, b) and Vuille et al. (2012), who suggest that a more southerly position of the ITCZ triggers moisture flux into the tropical Amazonian lowlands, which leads to an intensification of the SASM and thus a stronger easterly moisture transport towards the western range of the Andes. Since the mid-Holocene, increased moisture flux has repeatedly reached the headwaters of some rivers that drain to the Pacific and bring water to the lowland river oases. Here, with a strong dependence on the moisture derived from across the Andes, pre-Columbian cultures developed or declined.

The sediment deposits of CLP in the high-Andean headwater of Río Viscas represent a high-resolution archive for the reconstruction of the palaeoenvironmental history in the western Peruvian Andes and their adjacent lowlands. The heterogeneity of the deposits reflects the sensitivity of high-Andean ecosystems towards environmental changes. Especially in the subarid western Andes of southern Peru, climatic changes have a strong influence on the surface geomorphic features, which led to repeated fan aggradation upon the peat-accumulating area.

The content of As and Mn / Fe ratios turned out to be valuable new proxies for in situ palaeoredox conditions. Verified by pollen analysis, the archaeological chronology for the cultural development in the valleys of Palpa and several independent, continent-scale proxy archives, the CLP record evidences prominent mid- and late Holocene climate oscillations.

The mid-Holocene period of 8.6–5.6 ka was identified as being characterised by highly variable moisture conditions with a series of episodic dry spells alternating with spells that were more humid. After a pronounced cool and humid spell at 5.0–4.9 ka, conditions generally remained unstable, being frequently interrupted by pronounced dry periods that enhanced erosional processes. Periods of cultural bloom in the Palpa–Nasca lowlands coincide with stable, humid periods at 1.8–1.2 ka and 0.75–0.5 ka at CLP. Our findings therefore show that past fluctuations in SASM intensity had a significant influence on the cultures within the Río Grande de Nasca drainage.

Acknowledgements. The authors give their sincere thanks to Jonathan Hense (Palynological Laboratory, University of Cologne) for the preparation of the pollen slides and to Armine Shahnazarian (Institute of Geology and Mineralogy, University of Cologne) for support and help with the interpretation of the XRF results. We also thank Christian Mikutta (Institute of Biogeochemistry and Pollutant Dynamics, ETH Zürich) for helpful explanations concerning the cycling of arsenic in peat. We further acknowledge the great support of the "Comunidad Campesina de Laramate" during fieldwork in Peru. Funding by the German Federal Ministry for Education and Research within the project "Andean transect – Climate Sensitivity of pre-Columbian Man–Environment Systems" (BMBF-01UA0804B) is greatly appreciated.

The manuscript has greatly benefitted from comments by Martha Bell, Rolf Kilian, Marcelo Morales (reviewers) and Finn Viehberg (communicating editor).

Edited by: F. Viehberg

References

Abbott, M. B., Seltzer, G. O., Kelts, K. R., and Southon, J.: Holocene paleohydrology of the tropical Andes from lake records, Quaternary Res., 47, 70–80, 1997.

Abbott, M. B., Wolfe, B. B., Wolfe, A.P., Seltzer, G. O., Aravena, R., Mark, B. G., Polissar, P. J., Rodbell, D. T., Rowe, H. D., and Vuille, M.: Holocene paleohydrology and glacial history of the central Andes using multiproxy lake sediment studies, Palaeogeogr. Palaeocl., 194, 123–138, 2003.

Alonso, H.: Arsenic enrichment in superficial waters. II. Región Northern Chile, in: Proceedings of the International Seminar on Arsenic in the Environment and Its Incidence on Health, Santiago: Universidad de Chile, 101–108, 1992.

Baker, P. A., Seltzer, G. O., Fritz, S. C., Dunbar, R. B., Grove, M. J., Tapia, P. M., Cross, S. L., Rowe, H. D., and Broda, J. P.: The history of South American tropical precipitation for the past 25 000 years, Science, 291, 640–643, 2001.

Baker, P. A., Fritz, S. C., Garland, J., and Ekdahl, E.: Holocene hydrologic variation at Lake Titicaca, Bolivia/Peru, and its relationship to North Atlantic climate variation, J. Quaternary Sci., 20, 655–662, 2005.

Betancourt, J. L., Latorre, C., Rech, J. A., Quade, J., and Rylander, K. A.: A 22,000-year record of monsoonal precipitation from Northern Chile's Atacama Desert, Science, 289, 1542–1546, 2000.

Binford, M. W., Kolata, A. L., Brenner, M., Janusek, J. W., Seddon, M. T., Abbott, M., and Curtis, J. H.: Climate variation and the rise and fall of an Andean civilization, Quaternary Res., 47, 235–248, 1997.

Bird, B. W., Abbott, M. B., Vuille, M., Rodbell, D. T., Stansell, N. D., and Rosenmeier, M. F.: A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes, Proc. Natl. Acad. Sci. USA, 21, 8583–8588, 2011a.

Bird, B. W., Abbott, M. B., Rodbell, D. T., and Vuille, M.: Holocene tropical South American hydroclimate revealed from a decadally resolved lake sediment δ18O record, Earth Planet. Sci. Lett., 310, 192–202, 2011b.

Blodau, C., Fulda, B., Bauer, M., and Knorr, K.-H.: Arsenic speciation and turnover in intact organic soils during experimental drought and rewetting, Geochim. Cosmochim. Ac., 72, 3991–4007, 2008.

Blume, H.-P., Brümmer, G. W., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., and Wilke, B.-M.: Scheffer/Schachtschabel: Lehrbuch der Bodenkunde, Springer, Heidelberg, 570 pp., 2010.

Bookhagen, B. and Strecker, M. R.: Orographic barriers, high-resolution TRMM rainfall, and relief variations along the eastern Andes, Geophys. Res. Lett., 35, L06403, doi:10.1029/2007GL032011, 2008.

Buffen, A. M., Thompson, L. G., Mosley-Thompson, E., and Huh, K. I.: Recently exposed vegetation reveals Holocene changes in the extent of the Quelccaya Ice Cap, Peru, Quaternary Res., 72, 157–163, 2009.

Castillo, J., Barreda, A., and Vella, C.: Geología de los cuadrángulos de Laramate y Santa Ana, hojas 29-n; 29-ñ, Ingemmet Boletin No. 45, Seria A. Editoral Allamanda, Lima, p. 66 , 1993.

Chepstow-Lusty, A., Frogley, M. R., Bauer, B. S., Bush, M. B., and Herreras, A. T.: A late Holocene record of arid events from the Cuzco region, Peru, J. Quaternary Sci., 18, 491–502, 2003.

Chepstow-Lusty, A. J., Frogley, M. R., Bauer, B. S., Leng, M. J., Boessenkool, K. P., Carcaillet, C., Ali, A. A., and Gioda, A.: Putting the rise of the Inca Empire within a climatic and land management context, Clim. Past, 5, 375–388, doi:10.5194/cp-5-375-2009, 2009.

Cloy, J. M., Farmer, J. G., Graham, M. C., and MacKenzie, A. B.: Retention of As and Sb in Ombrotrophic Peat Bogs: Records of As, Sb, and Pb Deposition at Four Scottish Sites, Environ. Sci. Technol., 43, 1756–1762, 2009.

Cruz, F. W., Karmann, I., Viana, O., Burns, S. J., Ferrari, J. A., Vuille, M., Sial, A. N., and Moreira, M. Z.: Stable isotope study of cave percolation waters in subtropical Brazil: Implications for paleoclimate inferences from speleothems, Chem. Geol., 220, 245–262, 2005.

Cumbal, L., Vallejo, P., Rodriguez, B., and Lopez, D.: Arsenic in geothermal sources at the north-central Andean region of Ecuador: concentrations and mechanisms of mobility, Environ. Earth Sci., 61, 299–310, 2010.

Damman, A. W. H., Tolonen, K., and Sallantaus, T.: Element retention and removal in ombotrophic peat of Hadetkeidas, a boreal Finnish peat bog, Suo, 43, 137–145, 1992.

Eitel, B. and Mächtle, B.: Man and Environment in the Eastern Atacama Desert (Southern Peru): Holocene Climate Changes and Their Impact on Pre-Columbian Cultures, in: New Technologies for Archaeology, Natural Science in Archaeology, edited by: Reindel, M. and Wagner, G. A., Springer-Verlag Berlin Heidelberg, 17–23, 2009.

Eitel, B., Hecht, S., Mächtle, B., Schukraft, G., Kadereit, A., Wagner, G. A., Kromer, B., Unkel, I., and Reindel, M.: Geoarchaeological evidence from desert loess in the nazca-palpa region, southern Peru: Palaeoenvironmental changes and their impact on pre-Columbian cultures, Archaeometry, 47, 137–158, 2005.

Ekdahl, E. J., Fritz, S. C., Baker. P.A., Rigsby, C. A., and Coley, K.: Holocene multidecadal- to millennial-scale hydrologic variability on the South America Altiplano, Holocene, 18, 867–876, 2008.

Faegri, K. and Iversen, J.: Bestimmungsschlüssel für die nordwesteuropäische Pollenflora, Gustav Fischer Verlag, Jena, 1993.

Fehren-Schmitz, L., Haak, W., Mächtle, B., Masch, F., Llamas, B., Tomasto Cagigao, E., Sossna, V., Schittek, K., Isla Cuadrado, J., Eitel, B., and Reindel, M.: Climate change underlies global demographic, genetic, and cultural transitions in pre-Columbian southern Peru, Proc. Natl. Acad. Sci. USA, 111, 9443–9448, 2014.

Garreaud, R. D.: Intraseasonal variability of moisture and rainfall over the South American Altiplano, Mon. Weather Rev., 128, 3337–3346, 2000.

Garreaud, R. D., Vuille M., and Clement A. C.: The climate of the Altiplano: observed current conditions and mechanisms of past changes, Palaeogeogr. Palaeocl., 194, 5–22, 2003.

Garreaud, R., Barichivich, J., Christie, D. A., and Maldonado, A.: Interannual variability of the coastal fog at Fray Jorge relict forests in semiarid Chile, J. Geophys. Res.-Biogeosciences, 113, G04011, doi:10.1029/2008JG000709, 2008.

Garreaud, R. D., Vuille, M., Compagnucci, R., and Marengo, J.: Present-day South American climate, Palaeogeogr. Palaeocl., 281, 180–195, 2009.

Gayo, E. M., Latorre, C., Jordan, T. E., Nester, P. L., Estay, S. A., Ojeda, K. F., and Santoro, C. M.: Late Quaternary hydrological and ecological changes in the hyperarid core of the northern Atacama Desert (similar to 21° S), Earth-Sci. Rev., 113, 120–140, 2012.

González, Z. I., Krachler, M., Cheburkin, A. K., and Shotyk, W.: Spatial distribution of natural enrichments of arsenic, selenium, and uranium in a mineratrophic peatland, Gola di Lago, Canton Ticino, Switzerland, Environ. Sci. Technol., 40, 6568–6574, 2006.

Gorbahn, H.: The Middle Archaic Site of Pernil Alto, Southern Peru: The beginnings of horticulture and sedentariness in mid-Holocene conditions, Diálogo Andino, 41, 61–82, 2013.

Graf, K.: Untersuchungen zur rezenten Pollen- und Sporenflora in der nördlichen Zentalkordillere Boliviens und Versuch einer Auswertung von Profilen aus postglazialen Torfmooren, Habil., Univ. Zürich, 1979.

Graham, M. C., Gavin, K. G., Farmer, J. G., Kirika, A., and Britton, A.: Processes controlling the retention and release of manganese in the organic-rich catchment of Loch Bradan, SW Scotland, Appl. Geochem., 17, 1061–1067, 2002.

Grosjean, M. and Veit, H.: Water Resources in the Arid Mountains of the Atacama Desert (Northern Chile): Past Climate Changes and Modern Conflicts, in: Global Change and Mountain Regions – An Overview of Current Knowledge, Adv. Glob. Change Res., edited by: Huber, U. M., Bugmann, H. K. M., and Reasoner, M. A. Springer, Heidelberg, 23, 93–104, 2005.

Grosjean, M., van Leeuwen, J. F. N., van der Knaap, W. O., Geyh, M. A., Ammann, B., Tanner, W., Messerli, B., Núñez, L. A., Valero-Garcés, B. L., and Veit, H.: A 22 000 ^{14}C year BP sediment and pollen record of climate change from Laguna Miscanti (23° S), northern Chile, Glob. Planet Change, 28, 35–51, 2001.

Hammer, Ø., Harper, D. A. T., and Paul D. R.: Past: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontologia Electronica, 4, 9 pp., 2001.

Haug, G. H., Hughen, K. A., Sigman, D. M., Peterson, L. C., and Rohl, U.: Southward migration of the intertropical convergence zone through the Holocene, Science, 293, 1304–1308, 2001.

Heusser, C. J.: Pollen and spores of Chile, University of Arizona Press, 167 pp., Tucson, 1971.

Higuera, P. E.: MCAgeDepth 0.1: Probabilistic age-depth models for continuous sediment records, available at: https://code.google.com/p/mcagedepth/downloads/detail?name=MCAgeDepth_UsersGuide.pdf, 2008.

Höfle, B., Griesbaum, L., and Forbriger, M.: GIS-Based Detection of Gullies in Terrestrial LiDAR Data of the Cerro Llamoca Peatland (Peru), Remote Sens., 5, 5851–5870, 2013.

Hoffmann, M., Mikutta, C., and Kretzschmar, R.: Bisulfide reaction with natural organic matter enhances arsenite sorption: Insights from X-ray absorption spectroscopy, Environ. Sci. Technol., 46, 11788–11797, 2012.

Holmgren, C. A., Betancourt, J. L., Rylander, K. A., Roque, J., Tovar, O., Zeballos, H., Linares, E., and Quade, J.: Holocene vegetation history from fossil rodent middens near Arequipa, Peru, Quaternary Res., 56, 242–251, 2001.

Hooghiemstra, H.: Vegetational and climatic history of the high plain of Bogotá, Colombia: a continuous record of the last 3.5 million years, Dissertationes Botanicae, 79, J. Cramer, Vaduz, 138 pp. 1984.

Jansen, E., Overpeck, J., Briffa, K. R., Duplessy, J. C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, D., Peltier, W. R., Rahmstorf, S., Ramesh, R., Raynaud, R., Rind, D., Solomina, O., Villalba, R. and Zhang, D.: Palaeoclimate, in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, T. L.: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Forth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, 433–497, 2007.

Jenny, B., Valero-Garces, B. L., Urrutia, R., Kelts, K., Veit, H., Appleby, P. G., and Geyh, M.: Moisture changes and fluctuations of the Westerlies in Mediterranean Central Chile during the last 2000 years: The Laguna Aculeo record (33°50′ S), Quaternary Int., 87, 3–18, 2002.

Klavins, M., Silamikele, I., Nikodemus, O., Kalnina, L., Kuske, E., Rodinov, V., and Purmalis, O.: Peat properties, major and trace element accumulation in bog peat in Latvia, Baltica, 22, 37–49, 2009.

Kuentz, A., Galán de Mera, A., Ledru, M., and Thouret, J.: Phytogeographical data and modern pollen rain of the puna belt in southern Peru (Nevado Coropuna, Western Cordillera), J. Biogeogr., 34, 1762–1776, 2007.

Kuentz, A., Ledru, M.-P., and Thouret, J.-C.: Environmental changes in the highlands of the western Andean Cordillera, southern Peru, during the Holocene, Holocene, 22, 1215–1226, 2011.

Kumar, B. and Suzuki, K. T.: Arsenic round the world: a review, Talanta, 58, 201–235, 2002.

Lamy, F., Hebbeln, D., Röhl, U., and Wefer, G.: Holocene rainfall variability in southern Chile: A marine record of latitudinal shifts of the Southern Westerlies, Earth Planet. Sci. Lett., 185, 369–382, 2001.

Langner, P., Mikutta, C., and Kretzschmar, R.: Arsenic sequestration by organic sulphur in peat, Nat. Geosci., 5, 66–73, 2012.

Latorre, C., Betancourt, J. L., Rylander, K. A., Quade, J., and Matthei, O.: A vegetation history from the arid prepuna of northern Chile (22–23° S) over the last 13 500 years, Palaeogeogr. Palaeocl., 194, 223–246, 2003.

Ledru, M.-P., Mouruiart, P., and Riccomini, C.: Related changes in biodiversity, insolation and climate in the Atlantic rainforest since the last interglacial, Palaeogeogr. Palaeocl., 271, 140–152, 2009.

Ljungqvist, F. C.: A New Reconstruction Of Temperature Variability In The Extra-Tropical Northern Hemisphere During The Last Two Millennia, Geogr. Ann., 92, 339–351, 2010.

Lopez, P., Navarro, E., Marce, R., Ordoñez, Caputo, L., and Armengol, J.: Elemental ratios in sediments as indicators of ecological processes in Spanish reservoirs, Limnetica, 25, 499–512, 2006.

Mächtle, B.: Geomorphologisch-bodenkundliche Untersuchungen zur Rekonstruktion der holozänen Umweltgeschichte in der nördlichen Atacama im Raum Palpa/Südperu. Ph.D., Heidelberger Geographische Arbeiten, Heidelberg, 123, 227 pp., 2007.

Mächtle, B. and Eitel, B.: Fragile landscapes, fragile civilizations – How climate determined societies in the pre-Columbian south Peruvian Andes, Catena, 103, 62–73, 2013.

Mächtle, B., Ross, K., and Eitel, B.: The Khadin water harvesting system of Peru – an ancient example for future adaption to climatic change, in: Hydrogeology of Arid Environments, edited by: Rausch, R., Schüth, C., and Himmelsbach, T., Proceedings, 76–80, 2012.

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R., Hughes, Malcolm K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.: Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256–1260, 2009.

Margalef, O., Canellas-Bolta, N., Pla-Rabes, S., Giralt, S., Pueyo, J. J., Joosten, H., Rull, V., Buchaca, T., Hernandez, A., Valero-Garces, B. L., Moreno, A., and Saez, A.: A 70 000 year multiproxy record of climatic and environmental change from Rano Aroi peatland (Easter Island), Glob. Planet Change, 108, 72–84, 2013.

Markgraf, V. and D'Antoni, H. L.: Pollen flora of Argentina. University of Arizona Press, 208 pp., 1978.

McCormac, F. G., Hogg, A. G., Blackwell, P. G., Buck, C. E., Higham, T. F. G., and Reimer, P. J.: SHCal04 Southern Hemisphere calibration, 0–11.0 cal kyr BP, Radiocarbon, 46, 1087–1092, 2004.

Maslin, M. A. and Burns, S. J.: Reconstruction of the Amazon Basin effective moisture availability over the past 14 000 years, Science, 290, 2285–2287, 2002.

Maslin, M. A., Ettwein, V. E., Wilson, K. E., Guilderson, T. P., Burns, S. J., and Leng, M. J.: Dynamic boundary-monsoon intensity hypothesis: evidence from the deglacial Amazon River discharge record, Quaternary Sci. Rev., 30, 3823–3833, 2011.

Morales, M.S., Christie, D. A., Villalba, R., Argollo, J., Pacajes, J., Silva, J. Z., Alvarez, C. A., Llancabure, J. C., and Soliz Gamboa, C. C.: Precipitation changes in the South American Altiplano since 1300 AD reconstructed by tree-rings, Clim. Past, 8, 653–666, doi:10.5194/cp-8-653-2012, 2012.

Moreno, A., Giralt, S., Valero-Garcés, B., Sáez, A., Bao, R., Prego, R., Pueyo, J. J., González-Sampériz, P., and Taberner, C.: A 14 kyr record of the tropical Andes: The Lago Chungará sequence (18° S, northern Chilean Altiplano), Quat. Int., 161, 4–21, 2007.

Muller, J., Wüst, R. A. J., Weiss, D., and Hu, Y.: Geochemical and stratigraphic evidence of environmental change at Lynch's Crater, Queensland, Australia, Glob. Planet Change 53, 269–277, 2006.

Muller, J., Kylander, M., Wüst, R. A. J., Weiss, D., Martinez Cortizas, A., LeGrande, A. N., Jennerjahn, T., Behling, H., Anderson, W. T., and Jacobson, G.: Possible evidence for wet Heinrich phases in tropical NE Australia: the Lynch's Crater deposit, Quaternary Sci. Rev., 27, 468–475, 2008.

Placzek, C. J., Quade, J., and Patchett, P. J.: Isotopic tracers of paleohydrologic change in large lakes of the Bolivian Altiplano, Quat. Res., 75, 231–244, 2011.

Rauh, W: Tropische Hochgebirgspflanzen: Wuchs- und Lebensformen, Springer-Verlag, 206 pp., 1988.

Reese, C. A. and Liu, K.: A modern pollen rain study from the central Andes region of South America, J. Biogeogr., 32, 709–718, 2005.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A. Beck, J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E., Burr, G. S., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Mccormac, F. G., Manning, S. W., Reimer, R. W., Richards, D. A., Southon, J. R., Talamo, S., Turney, C. S. M., Van Der Plicht, J. M., and Weyhenmeyer, C. E.: IntCal09 and Marine09 radiocarbon age calibration curves, 0–50 000 years cal BP, Radiocarbon, 51, 1111–1150, 2009.

Rein, B., Luckge, A., and Sirocko, F.: A major Holocene ENSO anomaly during the Medieval period, Geophys. Res. Lett, 31, L17211, doi:10.1029/2004GL020161, 2004.

Reindel, M.: Life at the Edge of the Desert – Archaeological Reconstruction of the Settlement History in the Valley of Palpa, Peru, in: New Technologies for Archaeology, Natural Science in Archaeology, Reindel, M., and Wagner, G. A., 25, Springer-Verlag Berlin Heidelberg, 439–461, 2009.

Reindel, M. and Isla, J.: Cambio climático y patrones de asentamiento en la vertiente occidental de los Andes del sur del Perú, Diálogo Andino, 41, 83–99, 2013.

Reuter, J., Stott, L., Khider, D., Sinha, A., Cheng, H., and Edwards, R. l.: A new perspective on the hydroclimate variability in northern South America during the Little Ice Age, Geophys. Res. Lett., 36, L21706, doi:10.1111/j.1365-2699.2005.01183.x, 2009.

Rothwell, J. J., Dise, N. B., Taylor, K.G., Allott, T. E. H., Scholefield, P., Davies, H., and Neal, C.: A spatial and seasonal assessment of river water chemistry across North West England, Sci. Total Environ., 408, 841–855, 2009.

Rothwell, J. J., Taylor, K. G., Chenery, S. R. N., Evans, M. G., and Allott, T. E. H.: Storage and Behaviour of As, Sb, Pb, and Cu in Ombotrophic Peat Bogs under Constrasting Water Table Conditions, Environ. Sci. Technol., 44, 8497–8502, 2010.

Rowe, H. D., Guilderson, T. P., Dunbar, R. B., Southon, J. R., Seltzer, G. O., Mucciarone, D. A., Fritz, S. C., and Baker P. A.: Late Quaternary lake-level changes constrained by radiocarbon and stable isotope studies on sediment cores from Lake Titicaca, South America, Glob. Planet Change, 38, 273–290, 2003.

Ruthsatz, B.: Pflanzengesellschaften und ihre Lebensbedingungen in den Andinen Halbwüsten Nordwest-Argentiniens. Dissertationes Botanicae, 39, J. Cramer, Vaduz, 168 pp., 1977.

Ruthsatz, B.: Die Hartpolstermoore der Hochanden und ihre Artenvielfalt, Berichte der Reinhold-Tüxen-Gesellschaft, 12, 351–371, 2000.

Sandoval, A. P., Marconi, L., and Ortuno, T.: Flora Polínica de Bofedales y Áreas Aldanas del Tuni Condoriri, Herbario Nacional de Bolivia, Weinberg S.R.L., no. 4-2-2908-10, La Paz, 2010.

Schittek, K., Forbriger, M., Schäbitz, F., and Eitel, B.: Cushion Peatlands – Fragile Water Resources in the High Andes of Southern Peru, in: Water – Contributions to Sustainable Supply and Use, Landscape and Sustainable Development, Workinggroup Landscape and Sustainable Development, edited by: Weingartner, H., Blumenstein, O., and Vavelidis, M., Salzburg, Austria, 63–84, 2012.

Seltzer, G. O. and Hastorf, C. A.: Climatic Change and its Effect on Prehispanic Agriculture in the Central Peruvian Andes, J. Field Archaeol., 17, 397–414, 1990.

Seltzer, G. O., Baker, P., Cross, S., Dunbar, R., and Fritz, S.: High-resolution seismic reflection profiles from Lake Titicaca, Peru-Bolivia: Evidence for Holocene aridity in the tropical Andes, Geology, 26, 167–170, 1998.

Servant-Vildary, S., Servant, M., and Jimenez, O.: Holocene hydrological and climatic changes in the southern Bolivian Altiplano according to diatom assemblages in paleowetlands, Develop. Hydrobiol., 162, 267–277, 2001.

Squeo, F. A., Warner, B. G., Aravena, R., and Espinoza, D.: Bofedales: High altitude peatlands of the central Andes, Rev. Chil. Hist. Nat., 79, 245–255, 2006.

Sossna, V.: Los patrones de asentamiento del Periodo Intermedio Temprano en Palpa, costa sur del Perú, Zeitschrift für Archäologie Außereuropäischer Kulturen, 4, 207–280, 2012.

Sossna, V.: Impacts of Climate Variability on Pre-Hispanic Settlement Behavior in South Peru – The Northern Río Grande de Nasca Drainage between 1500 BCE and 1532 CE. Ph.D., Christian-Albrechts-Universität zu Kiel, 293 pp., 2014.

Street-Perrott, F. and Barker, P.: Biogenic silica: a neglected component of the coupled global continental biogeochemical cycles of carbon and silicon. Earth Surf. Process. Landforms, 33, 1436–1457, 2008.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P.-N., Henderson, K. A., Cole-Dai, J., Bolzan, J. F., and Liu, K.-B.: Late Glacial Stage and Holocene Tropical Ice Core Records from Huascarán, Peru, Science, 269, 46–50, 1995.

Thompson, L. G., Davis, M. E., Mosley-Thompson, E., Sowers, T. A., Henderson, K. A., Zagorodnov, V. S., Lin, P. N., Mikhalenko, V. N., Campen, R. K., Bolzen, J. F., Cole-Dai, J., and Francou, B.: A 25 000-year tropical climate history from Bolivian ice cores, Science, 282, 1858–1864, 1998.

Thompson, L. G., Mosley-Thompson, E., Brecher, H., Davis, M., León, B., Les, D., Lin, P.-N., Mashiotta, T., and Mountain, K.: Abrupt tropical climate change: Past and present, Proc. Natl. Acad. Sci. USA, 103, 10536–10543, 2006.

Torres, G. R., Lupo, L. C., Sánchez, A. C., and Schittek, K.: Aportes a la flora polínica de turberas altoandinas, Provincia de Jujuy, noroeste argentino, Gayana Bot., 69, 30–36, 2012.

Troll, C.: The cordilleras of the tropical Andes. Aspects of climatic, phytogeographical and agrarian ecology, in: Geo-Ecology of the mountainous regions of the tropical Americas, Troll, C., Colloquium Geographicum, 9, Bonn, 1968.

Unkel, I., Reindel, M., Gorbahn, H., Isla Cuadrado, J., Kromer, B., and Sossna, V.: A comprehensive numerical chronology for the pre-Columbian cultures of the Palpa valleys, south coast of Peru, J. Archaeol. Sci., 39, 2294–2303, 2012.

van Breukelen, M. R., Vonhof, H. B., Hellstrom, J. C., Wester, W. C. G., and Kroon, D.: Fossil dripwater in stalagmites reveals Holocene temperature and rainfall variation in Amazonia, Earth Planet Sc. Lett., 275, 54–60, 2008.

Vinther, B. M., Burchardt, S. L., Clausen, H. B., Dahl-Jensen, D., Johnsen, S. J., Fisher, D. A., Koerner, R. M., Raynaud, D., Lipenkov, V., Andersen, K. K., Blunier, T., Rasmussen, S. O., Steffensen, J. P., and Svensson, A. M.: Holocene thinning of the Greenland ice sheet, Nature, 461, 385–388, 2009.

Vuille, M.: Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation, Int. J. Climatol., 19, 1579–1600, 1999.

Vuille, M., Burns, S. J., Taylor B. L., Cruz, F. W., Bird, B. W., Abbott, M. B, Kanner, L. C., Cheng, H., and Novello, V. F.: A review of the South American Monsoon history as recorded in stable isotopic proxies over the past two millennia, Clim. Past, 8, 1309–1321, doi:10.5194/cp-8-1309-2012, 2012.

Wright Jr., H. E.: Late Glacial and late Holocene moraines in the Cerros Cuchpanga, central Peru, Quat. Res, 21, 275–285, 1984.

Zhou, J. and Lau, K. M.: Does a Monsoon Climate Exist over South America?, J. Climate, 11, 1020–1040, 1998.

Zolitschka, B., Behre, K. E., and Schneider, J.: Human and climatic impact on the environment as derived from colluvial, fluvial and lacustrine archives – examples from the Bronze Age to the Migration Period, Germany, Quat. Sci. Rev., 22, 81–100, 2003.