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

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Abstract

Within palaeoenvironmental studies, high-altitude peatlands of the Andes still remain relatively unexploited, although they offer an excellent opportunity for high-resolution chronologies, on account of their high accumulation rates and abundant carbon for dating. Especially in the central Andes, additional high-quality proxy records are still needed due to the lack of continuous and well-dated records, which show a significant variability on sub-centennial to decadal precision scales.

To widen the current knowledge on climatic and environmental changes in the western Andes of southern Peru, we present a new, high-resolution 8600 year-long record from Cerro Llamoca peatland, a high-altitude Juncaceous cushion peatland in the headwaters of Río Viscas, a tributary to Río Grande de Nasca. A 10.5 m core of peat with intercalated sediment layers was examined for all kinds of microfossils, including fossil charred particles. We chose homogeneous peat sections for pollen analysis at a high temporal resolution. The inorganic geochemistry was analysed in 2 mm resolution using an ITRAX X-ray fluorescence (XRF) core scanner.

We interpret the increase 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 as applicable proxies for in situ palaeo-redox conditions.

The mid-Holocene period of 8.6–5.6 ka is characterized 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 1.8–1.2 ka, which coincides with the florescence of the Nasca culture in the Andean foreland. An abrupt turnover to a sustained dry period occurs at 1.2 ka, which coincides with the collapse of the Nasca/Wari society in the Palpa lowlands. Markedly drier conditions prevail until 0.75 ka, providing evidence for the presence of a Medieval Climate Anomaly. Moister but hydrologically highly variable conditions prevailed again after 0.75 ka, which allowed the re-expansion of tussock grasses in the highlands, increased discharge into the Andean foreland and the re-occupation of the settlements in the lowlands during this so-called Late Intermediate Period.

On a supraregional scale, our findings can ideally be linked to and proofed 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 had led to abrupt changes in temperature, precipitation, and the periodicity of circulation regimes (Jansen et al., 2007; Bird et al., 2011a). This region is particularly sensitive to climatic changes due to steep environmental gradients. It hosts a multitude of microenvironments, which 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 the 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 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, which 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 a coincidence between environmental and cultural changes, the emergence, persistence, and subsequent collapse of pre-Columbian civilizations offer important insights into human-environment interactions (Binford et al., 1997). The success of pre-Columbian civilizations was closely coupled to areas of geo-ecological favourability, which were directly controlled by distinct regional impacts of large-scale circulation mechanisms (Eitel et al., 2005; Mächtle and Eitel, 2012).

A vast number of archaeological sites in the northern part of the Río Grande de Nasca drainage had been 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 in this area, which covers the time from the Archaic Period to the Late Intermediate Period (~ 3760 BC to AD 1450). This exceptional and comprehensive archaeological data source represents a unique pre-requisite to facilitate linkages with palaeoenvironmental records obtained from continuous geo-archives in the nearby Andean highlands.

To supplement and specify the current knowledge on climatic and environmental changes in the western Andes of southern Peru, we present a new, high-resolution 8600-year-long record from Cerro Llamoca peatland (CLP), a high-altitude Juncaceous cushion peatland in the headwater area of Río Viscas, a tributary to Río Grande. Especially for the Nasca culture period, this record provides the highest-resolution palaeoclimatic proxy data for the evaluation of the climate-related cultural changes to date. The record further highlights the quality and potential of high-Andean peat records for the reconstruction of Holocene moisture variations.

2 The study area

2.1 Geographical setting, regional climate and vegetation

The investigated Cerro Llamoca peatland 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 Cerro Llamoca peatland is situated within an area dominated by Tertiary rocks. The Castrovirreyna formation, which formed during the upper Oligocene to early Miocene, consists of andesitic conglomerates intercalated with rhyolithic, 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 (sensu Troll, 1968) an annual rainfall amount based on the data from the Tropical Rainfall Measurement Mission (TRMM) (Bookhagen and Stecker, 2008) of about 200–400 mm yr^{-1} can be 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

practiced since pre-hispanic 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 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 completely occupies the upper valley up to its confluence with a tributary stream channel, which, during heavy rainfall events, repeatedly carries sediment to the vegetated peatland area (Höfle et al., 2013; Schittek et al., 2012). The slopes within the peatland's catchment area, depending on prevailing stable or instable 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). At Cerro Llamoca peatland, the Juncaceae *Distichia muscoides* and *Oxychloe andina* are the dominant peat-accumulating 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 Cerro Llamoca peatland 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 southeast, a dominance of tussock grasses still prevails.

2.2 Human settlement history

Pre-Hispanic settlement history in the south Peruvian coastal desert dates back to more than 5000 years (Fig. 5). Earliest 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 (Unkel et al., 2012; Gorbahn, 2013). Here, signs of re-occupation are evident during the Initial Period from 3.41–2.79 ka/1460–840 cal BC, after a 1600 year lasting hiatus.

Along the river oases, periods of cultural florescence followed. The Early Horizon (2.79–2.21 ka/840–260 cal BC) is subdivided into early, middle and late Paracas. 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–80 cal AD) was a very dynamic epoch regarding settlement patterns, ceramic technology and textile craft with enormous population increase, forming the transition from Paracas to Nasca culture (Reindel, 2009). Followed by the Early Intermediate Period (1.87–1.31 ka/80–640 cal AD), that is subdivided in Early, Middle and Late Nasca, the Early Nasca period (1.87–1.65 ka/80–300 cal AD) is a time of high cultural development. Settlement density grew, political structures occurred and ceramic as well as textile production was intensified and professionalized. Systematic agriculture, partly with irrigation systems, and especially the creation of huge geoglyphs, result in enormous landscape changes. In contrast to the Initial Period, settlements evolve in the large floodplains now, close to the valley border and show clear hierarchic features (Reindel, 2009). Highest settlement densities are reached during the Middle Nasca (1.65–1.51 ka/300–440 cal AD), but people also begin to shift their settlements valley-up towards the Andes. This process continues during the Late Nasca phase (1.51–1.31 ka/440–640 cal AD). The Middle Horizon (1.31–1.16 ka/640–790 cal AD), is documented by only few findings in the region (Unkel et al., 2012). Lacking of archaeological material during the next ca. 400 years indicate a second hiatus in the chronology before the beginning of the Late

Intermediate Period (0.77–0.5 ka/1180–1450 cal AD), when human activity markedly rose again along the river oases (Reindel, 2009; Unkel et al., 2012).

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 (ERT) (Schittek et al., 2012). Several transects were measured to receive an insight of the peatland's internal structure and depth to bedrock. Multiple cores were drilled at several sites within the whole peatland range by using a 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 to a depth of 10.5 m. The core was divided into two core-halves, photographed and sedimentologically described at the Paleoecology Laboratory of the Seminar 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 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 Bernd Kromer/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 dataset 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 Intertropical Convergence Zone (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 Cerro Llamoca peatland consists 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 characterize 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, characterized 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 re-deposition 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 re-deposited peat and soil material to the coring site. Ages therefore remain within the same time range.

Nonetheless, especially the peat sections reveal a continuous chronology, allowing a high-resolution palaeoclimate reconstruction. Sample resolution varies between about 10–30 yr cm^{-1} and is highest during periods of peat formation.

4.2 Geochemical variability of the record

The peatland record is characterized 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's 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 biosilification (Servant-Vildary et al., 2001; Seeligmann et al., 2008). Hence, the Si / Ti ratio is used to discern the biogenic silica amount. Manganese (Mn) and iron (Fe) are also of lithogenic origin, but contents further depend on environmental factors, which 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 normalized 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 Cerro Llamoca peatland (as at many other sites of the area) are enriched with As. Recently, wetlands, and in particular peatlands, were identified to act 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 shows the most marked changes at 1050–930 cm (8.6–6.3 ka) with a high variability of values ranging between 10 000–>100 000 cps (Fig. 3). The following section at 930–840 cm (6.3–4.8 ka) is characterized 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), 630–620 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, in correspondence 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 590–530 cm (1.9–1.3 ka), it rises 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 characterized by a high variability between 850–740 cm (5.0–3.9 ka). The 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 630–570 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. Extraregional 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 characterized by a steady presence of Poaceae and *Senecio*-type Asteraceae pollen, both at medium percentage values. Also Caryophyllaceae are 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, Puna belt-typical types gain higher abundances towards the upper part of the zone. Cyperaceae pollen peak at the beginning of zone 2.

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 630–540 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 whole record here. Peatland pollen types show increases of Gentianaceae, Cyperaceae and *Plantago* values. The later nearly disappears from the record afterwards, whereas Azorella, Brassicaceae, Malvaceae and *Isoetes* start to appear more frequently and in higher abundances from now 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 re-deposition. 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, but 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 sulphur-rich anoxic environments. They postulate that covalent binding of trivalent As to NOM via organic sulphur species is the primary mechanism of As-NOM interactions under sulphate-reducing conditions. Therefore, As mobilization is suppressed by the sorption of As to NOM by formation of stable inner-sphere complexes.

However, the CLP record shows several significant As peaks. Concerning the last 4000 years, the modelled periods of these As-peaking events 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 from Latvia. The formation of humic acids leads to an increase of functional groups, and therefore, to an increasing sorption capacity.

Cloy et al. (2009) and Rothwell et al. (2009, 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 re-wetting of peat after significant water table draw-down. Blodau et al. (2008) demonstrate that re-wetting of previously dry minerotrophic peat leads to the rapid release of As and Fe into pore waters coupled to 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, up to now, 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 for (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) found out 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 naturally is 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 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 Intertropical Convergence Zone (ITCZ) (Haug et al., 2001; Ledru et al., 2009; Bird et al., 2011a, b; Vuille et al., 2012). Similarities in the δ^{18}O isotopic signatures from speleothems (Cruz et al., 2005; van Breukelen et al., 2008; 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 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 palaeoclimates 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 being the driest episode of the Chungará lake record in the northern Chilean Altiplano. They point out that dry conditions were not constant, but characterized 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 repeatedly were 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 central problem 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 Pumacocha 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 Cerro Llamoca peatland during the Middle Holocene as visible by the episodically higher levels of Si / Ti and Mn / Fe ratios.

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 5.4 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 recognized 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 the expansion of Quellcaya ice cap (Thompson et al., 2006) and water levels at Lake Titicaca increased (Baker et al., 2001). The conditions promoted massive peat growth at CLP, but had remained highly variable and unstable as evident by the high fluctuations of the pollen and Mn / Fe ratio records. Probably, the humid period between 5.4 and 4.9 ka culminated in the formation of a palaeosoil within a loess sequence in the desert-margin area of southern Peru, which indicates stable conditions with weathering processes and a dense vegetation cover in an area now characterized by extremely arid conditions (Mächtle and Eitel, 2012).

The cool and wet period is followed be 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 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 1.75 ka. Elevated As contents at the same period 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, sedimentological and diatom-assemblage data derived from sediment cores extracted from Laguna Acuelo (Central Chile). Similar observations had also been made by Chepstow-Lusty et al. (2003), who evidenced the RWP as a period of one to two hundred years of relative warmth and dryness, in comparison to the periods before and after. Interestingly, the pollen record at CLP does not show evidence of that short, dry period.

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’s 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 lithics concentrations, they identified this period as characterized by a lack of strong flooding, because of reduced river runoff, from 1.15–0.7 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 “Medieval Climate Anomaly” and a northward position of the Atlantic ITCZ.

Starting shortly after 0.75 ka, grass pollen abundance at CLP is back to levels > 90 % and remain being highly abundant until about 0.5 ka. Mn / Fe ratios indicate variable redox conditions in the peatland. A significant low stand of the Mn / Fe ratios 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., 2009).

After 0.5 ka, the proxy signals of CLP underlie strong and repeated shifts. These changes are likely to be linked to the instabilisation 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 occur during periods of slow vegetation growth on the slopes of the water catchment area because of climatic changes and/or soil degradation by overgrazing (Schittek et al., 2012).

Bird et al. (2011b) noted a pronounced decrease in Pumacocha δ^{18}O between 0.55–0.13 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 destabilization. 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 oxidized 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. 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 El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) 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 changes on pre-Columbian population history

The earliest settlements in the Río Grande de Nasca drainage are situated in the middle section of the Río Grande valley on the foothill of the Andes and are related to the Archaic and Initial Period. At the site Pernil Alto, two different occupation periods were detected (Reindel, 2009; Unkel et al., 2012). The earlier occupation dates back to 5.25–5.0 ka, a period that is characterized by a transition to wetter conditions. It remains speculative if the pronounced climate change at 5.0–4.9 ka led to the abandonment of Pernil Alto.

After the 1600 year-long occupation hiatus, which includes a sustained dry period between 4.6–4.2 ka, the site was re-occupied in the Initial Period (3.4–2.8 ka).

Here, a period of cultural florescence occurred during Paracas (Early Horizon) and Nasca (Early Intermediate Period) times (2.8–1.3 ka). The Nasca period coincides with a period of pronounced stability at CLP, which enforced moisture availability and river runoff in the Palpa/Nasca valleys, which led to a concentration of settlements along the river oases (Eitel and Mächtle, 2009). Presumably, a short dry phase at around 1.3 ka caused a general crisis of the Nasca, which led to an increasing dependence on imports from the more stable highland regions and resulted in a growing cultural and political influence of the Wari culture (Sossna, 2012).

After 1.2 ka, dry conditions prevailed and the region was largely abandoned (Reindel, 2009). During the Late Intermediate Period (LIP; ca. 0.75–0.5 ka), climatic improvement triggered a massive migration from the highlands to the ecologically favourable river oases (Fehren-Schmitz et al., 2010).

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 hence, a stronger easterly moisture transport towards the western range of the Andes. Since the mid-Holocene, increased moisture flux had repeatedly reached the headwaters of some rivers, which drain to the Pacific and bring water to the lowland river oases. Here, in strong dependence on the moisture derived from across the Andes, pre-Columbian cultures boomed or declined.

The sediment deposits of Cerro Llamoca peatland (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 had led to repeated fan aggradation upon the peat-accumulating area.

Arsenic contents and Mn / Fe ratios turned out as valuable, new proxies for in situ palaeo-redox 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 characterized by highly variable moisture conditions with a series of episodic dry spells alternating with spells that are more humid. After a pronounced cool and humid spell at 5.0–4.9 ka, conditions generally remained instable, 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 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 of the Palpa-Nasca river oases at the foot of the western Andean range.

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Table 1. Radiocarbon ages of core Pe852. The calibrated age ranges were calculated using CALIB 6.0.1 and the Intcal 09 dataset (Reimer et al., 2009). The modelled ages are the result of a probabilistic age-depth model using MCAgeDepth (Higuera, 2008). The range represents the 2-σ values, and the median ages are in parentheses.

Lab #	Depth (cm)	Measured ^{14}C	Measured error (±)	2 σ 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.

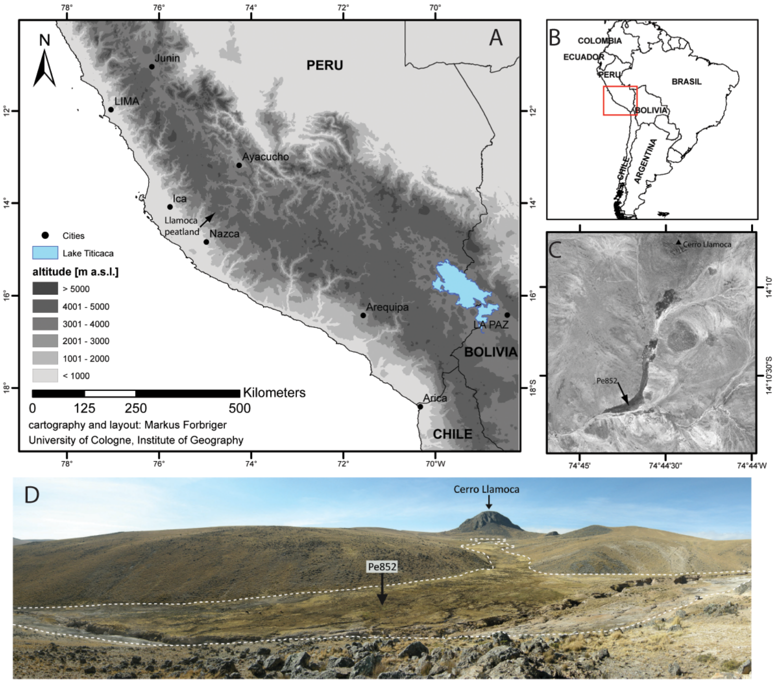

Fig. 1. (A) The location of Cerro Llamoca peatland in the western Andes of southern Peru (data source: DGM-GTOPO 30). **(B)** Map of Peru and adjacent countries (data source: GLCF World Data). **(C)** Aerial photograph of Cerro Llamoca peatland with Cerro Llamoca in the north and location of the coring site of core Pe852 (Servicio Aerofotográfico Nacional – SAN, Lima). **(D)** Panorama of Cerro Llamoca peatland 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.

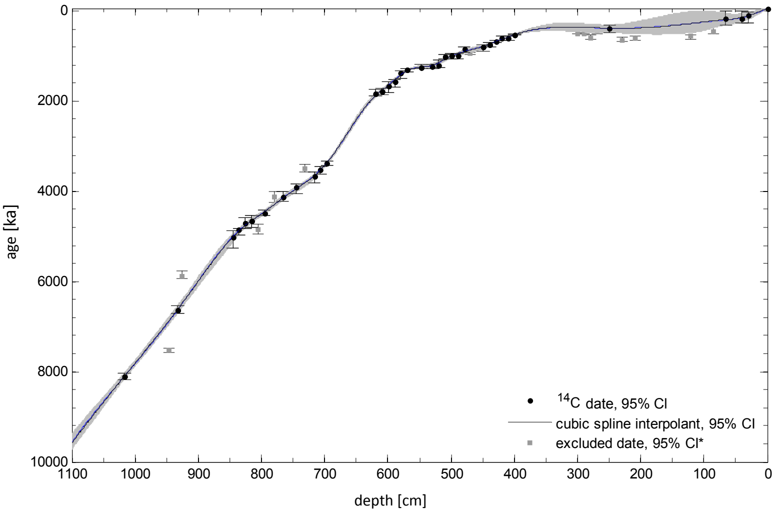

Fig. 2. Age-versus-depth model for core Pe852 retrieved from Cerro Llamoca peatland based on 35 ^{14}C dates. The grey band represents the modelled range of dates and the black line the 50th percentile of all runs. 15 dates were excluded from the model.

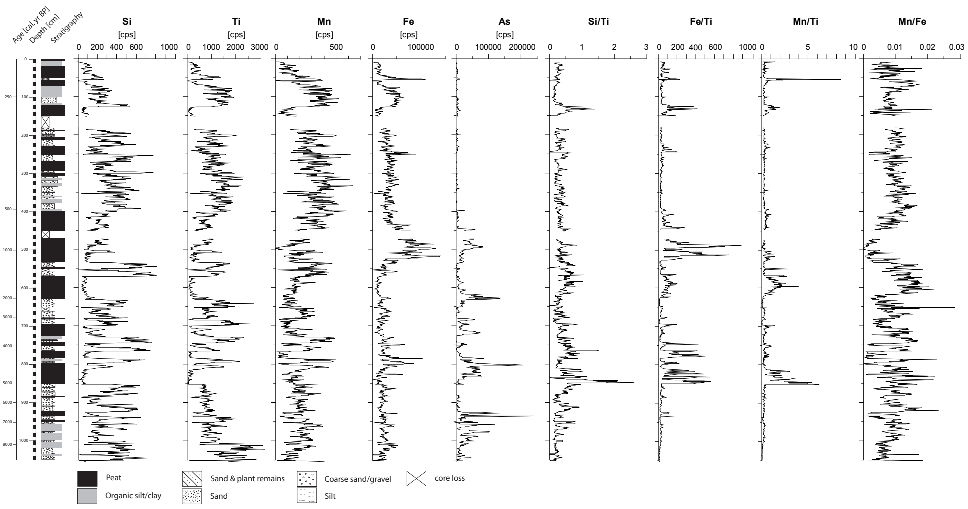

Fig. 3. Stratigraphy and selection of elements and elemental ratios measured by the XRFcore scanner for core Pe852 of Cerro Llamoca peatland. All measurements are in counts per second (cps).

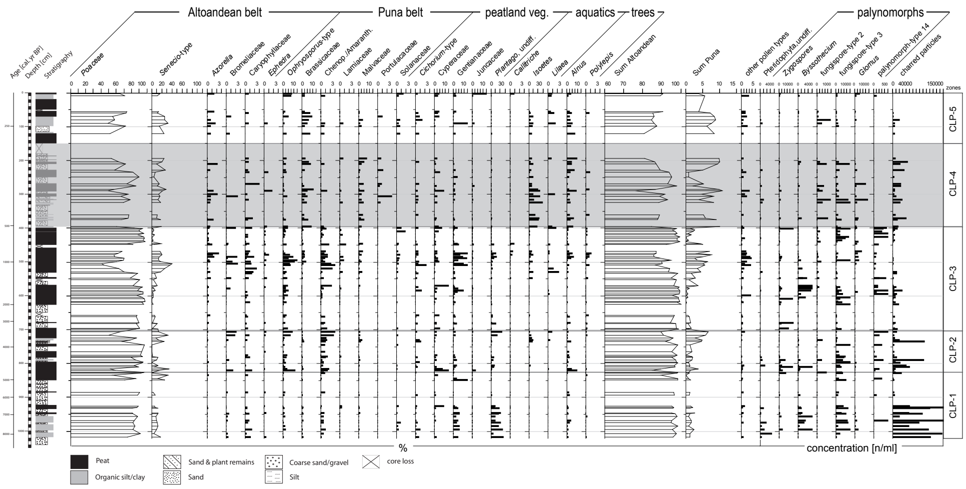

Fig. 4. Pollen, palynomorphs and charred particles diagram for Cerro Llamoca peatland, plotted against depth. Peatland vegetation and aquatic types were excluded from the pollen sum.

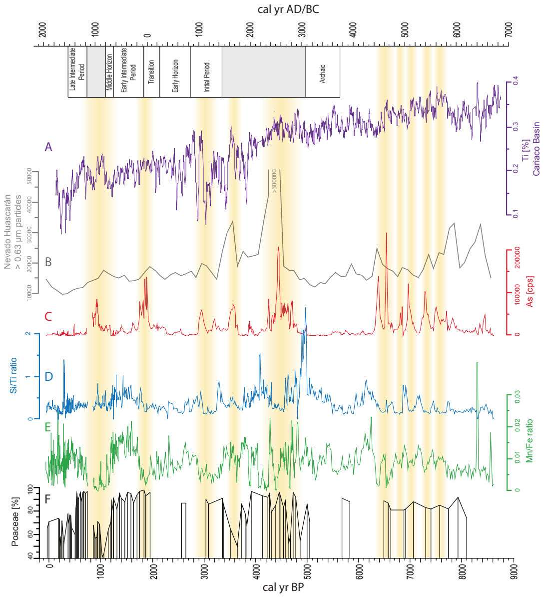

Fig. 5. The archaeological chronology for the pre-Columbian cultures in the Palpa valleys (Unkel et al., 2012) in comparison with in situ geochemical parameters **(C, D, E)** and the Poaceae pollen record **(F)** of Cerro Llamoca peatland. The records are further compared with the bulk Ti content of Cariaco Basin sediments (**A**; Haug et al., 2001) and dust particle concentrations of Huascarán ice core (**B**; Thompson et al., 1995).

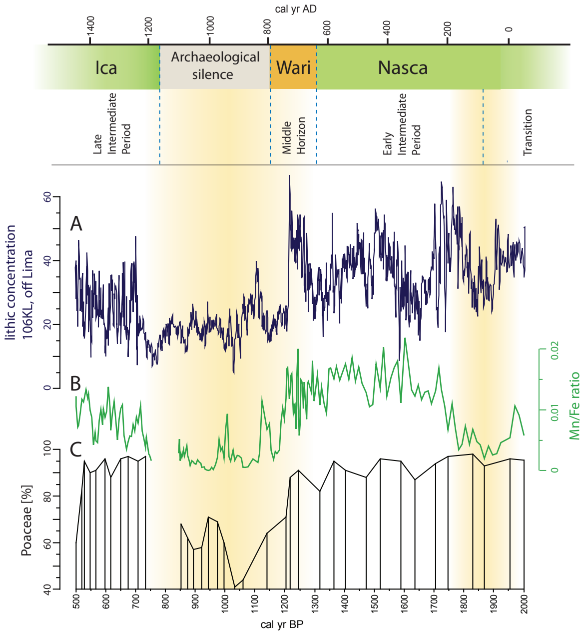

Fig. 6. The archaeological chronology of the last 2000 years in the Palpa valleys (Unkel et al., 2012) in comparison with lithics concentrations of a marine core from the Peruvian shelf west of Lima (**A**; Rein et al., 2004), Mn / Fe ratios **(B)** and Poaceae pollen percentages **(C)** from Cerro Llamoca peatland.