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Late Quaternary palaeosol records from subtropical (38°S) to tropical (16°S) South America and palaeoclimatic implications

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Abstract

Loess and palaeosols in the subtropical lowlands of South America (~23–38°S) have a large potential to serve as archives of Late Quaternary environmental and climate changes. At present, mean annual precipitation generally decreases from N to S and from E to W, though with a complex seasonal pattern with austral summer rainfall related to the monsoonal circulation and with austral winter rainfall related to the SE-trades. In this paper, we present results of multiproxy geochemical analyses from three representative eolian/alluvial soil profiles along a S–N transect aiming at the reconstruction of past climate changes: (i) profile "Chasico" at the southern border of the subtropics (38°S), (ii) "D4" in Misiones at the northern border of the subtropics (27°S), and, for comparison, (iii) "Laguna Sucuara" in the savannas of the Bolivian lowlands (16°S). Our results show that before ~16 ka BP, conditions were likely very cold and dry. Except for in "D4", loess or soils are not preserved due to rather scarce vegetation cover and resultant deflation. In "Chasico", accumulation of sands (directly overlying the Tertiary) starts only during the Late Glacial, indicating increasing temperatures and increased monsoonal precipitation (coinciding with the "Tauca" wet phase on the Altiplano). In "D4", a palaeosol is preserved below the Late Glacial sediments and the deflation hiatus. This palaeosol is dated to ~40 ka BP and documents an earlier, but less intensive (southward reaching) phase of monsoonal precipitation ("Inca Huasi" on the Altiplano). Whereas the seasonality during the Late Glacial seems to have been very pronounced, conditions for organic matter production and preservation became much more favourable at "Chasico" and "D4" during the Early Holocene. We suggest that extra-tropical winter precipitation played a more important role than before and than today. Between ~7.5 and 3 ka BP, the expansion of C4 plants along the S–N transect suggests increasing aridity, probably due to a weakening of the extra-tropical circulation in combination with a relatively weak monsoonal circulation. Only after ~3 ka BP climate became more humid again due to the re-strengthening of the monsoon.

1. Introduction

Large parts of South America are covered by Late Quaternary eolian sediments like sands, loess and loess-like materials (Iriondo, 1997; Muhs and Zarate, 2001). Such deposits are well known in the Llanos del Orinoco, NE-Brazil, in the Chaco and in the Pantanal; but they are most extensive in the Pampa covering about 600,000 km^2 (Fig. 1) (Iriondo, 1997; Zárate, 2003). Palaeosols are often developed in the eolian sediments and document past environmental and climate changes (Orgeira et al., 1998; Nabel et al., 1999; Zinck and Sayago, 1999; Smith et al., 2003; Schellenberger and Veit, 2006). In contrast to the Chinese loess records, where loess horizons have been correlated with cold and dry conditions (glacials) and palaeosols with warm and humid ones (interglacials/-stadials), only little is known about the formation of the loess and the palaeosols

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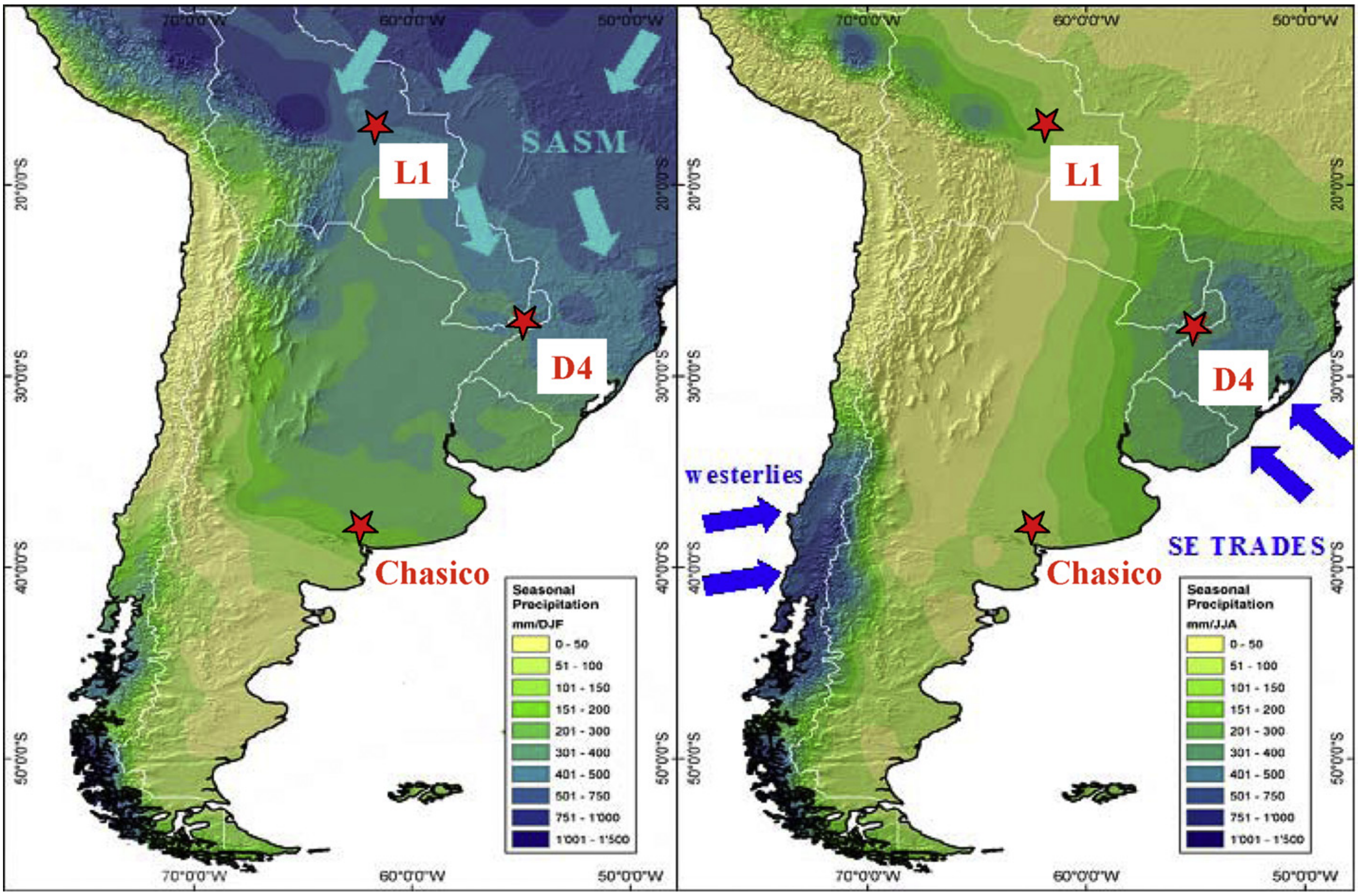

Fig. 1. Location of the three study sites (☆) and seasonal atmospheric circulation patterns providing moisture: Chasico at the southern border of the subtropics, D4 at its northern border, and L1 (Laguna Sucuara) in the tropical lowlands of Bolivia. *Left*: rainfall during austral summer (DJF, December January February), SASM = South American Summer Monsoon. *Right*: rainfall during austral winter (JJA = July June August) (courtesy of J.-H. May).

in subtropical South America. Firstly, more numeric dating control is necessary to establish reliable chronologies (Frechen, 2006; Kemp et al., 2006), and secondly, more detailed geochemical characterization of the sequences may provide better insights into the processes of sediment accumulation and pedogenesis. There is a particularly interesting, since controversial, issue concerning the humidity conditions during the Late Glacial: palynological results suggest that the Last Glacial Maximum (LGM; ~20 ka BP) and the Late Glacial (LG) were cold and dry (Prieto, 2000; Behling, 2002; Iriarte, 2006; Behling et al., 2007), whereas stable isotope analyses ($\delta^{18}O$) of stalagmites in SE-Brazil (Cruz et al., 2005a, b, 2006a, b) and $\delta^{13}C$ values of bulk organic matter and *n*-alkanes (Zech et al., 2008) indicate that the Late Glacial was relatively humid, at least in the northern parts.

In this paper, we present results from our efforts to contribute to the reconstruction of the Late Quaternary landscape evolution of subtropical South America by studying sediment/palaeosol sequences along a S–N transect from the southern to the northern border of the subtropics, and, for comparison, from the tropical lowlands in Bolivia. Firstly, the chronostratigraphy of the "Chasico" profile (38°S) and the applicability of various geochemical parameters as palaeoenvironmental proxies will be discussed. Then the chronostratigraphy of "D4" in Misiones (27°S) will be described, followed by selected parameters used to infer the palaeoenvironmental conditions. Finally, results from "Laguna Sucuara" in Bolivia (16°S) will be presented. We conclude with a comparison of all three study sites in the context of a proposed palaeoclimate model, which focuses on changes in the atmospheric circulation patterns and related tropical versus extra-tropical precipitation.

2. Materials and methods

2.1. Geographical setting of the study sites

Generally speaking, subtropical South America is dominantly influenced by the South American Summer Monsoon (SASM; Fig. 1), which provides tropical moisture during the austral summer months (Zhou and Lau, 1998). During austral winter, extra-tropical precipitation related to the SE-trades can provide significant amounts of rainfall especially in near-coastal areas (Prohaska, 1976; Cerveny, 1998). More details concerning the present climate of the three study sites are given in

Table 1
General information on research sites

	Chasico	D4 (Misiones)	L1 (Laguna Sucuara)
Location	70 km NW of Bahía Blanca, Argentina	~20 km NE of Oberá, NE Argentina	~120 km NE of Santa Cruz, Bolivian lowlands
Topography	7 m cut on the right side of Rio Chasico	Depression, periodically with stagnant water	Lagoon Sucuara
Longitude	62°51′W	55°31.5′W	62°2.6′W
Latitude	38°24′S	27°23.4′S	16°49.6′S
Altitude (m a.s.l.)	88	330	255
Mean annual precipitation (mm)[a]	~600–700	~1700	~1050
Mean annual temperature (°C)[a]	~15.6	~21	~24
Climate (Köppen and Geiger, 1972)	Cfa	Cfa	Aw
Rain periods	No pronounced seasonality	No pronounced seasonality	During austral summer only
Vegetation	Tall grass, some shrubs	Mesophytic subtropical forest with evergreen species	Semideciduous dry forest

[a] Estimated according to Müller (1979).

Table 1 and in the following brief description of the study site locations (see also Fig. 1).

Profile Chasico is situated at the southern border of subtropical South America, about 70 km NW of Bahía Blanca. A 7-m-thick sequence of fluvial and eolian sediments is exposed on the right banks of River Chasico. At present, mean annual rainfall is ~600–700 mm with no pronounced seasonality. Despite the subhumid conditions, only a tall grass steppe with some shrubs prevails, which is probably due to the intensive land use.

Record D4 is a 4.5 m long sediment core from a basin about 20 km NE of Oberá, NE-Argentina. The surrounding hills consist of Mesozoic basalts (Serra Geral Formation). Controversy exists over the existence of a mantle of "tropical loess" (Iriondo and Kröhling, 1997; Morras et al., 2008). Rainfall (~1700 mm/a) is more or less equally distributed over the whole year, originating between January and August mainly from NW, and from September to December from SE. In contrast to profile Chasico, mean annual precipitation and mean annual temperature are significantly higher (Table 1) supporting the existence of a monsoonal subtropical forest.

For comparison with the subtropical records Chasico and D4, we took sediment samples with a piston corer from the Laguna Sucuara in the lowlands of Bolivia (Table 1, Fig. 1). Sampling depth was 2.0 m. Climatic conditions are characterized by summer rainfalls, correlated with north-westerly winds, and winter dryness, corresponding to an Aw climate according to Köppen and Geiger (1972). The vegetation is a tree savanna.

2.2. Sampling and analyses

Sampling was conducted at high resolution (5–10 cm intervals); the air-dried material was sieved (<2 mm) before analysis. The following proxies were measured:

- *Grain size* of the Chasico samples was determined by sieving and sedimentation (pipette method); grain size of the D4 and L1 samples was analysed with a Mastersizer (MALVERN) after destruction of carbonate (10% HCl) and soil organic matter (H_2O_2).
- *Total organic C, total N and total S* were measured using dry combustion of a finely ground homogeneous 50 mg sub-sample after decalcification (10% HCl) followed by thermal conductivity detection on a VarioEL elemental analyser (Elementar, Hanau, Germany).
- *Magnetic susceptibility* (MS) was determined with a Bartington MS2B susceptibility meter. Aliquots of the air-dried and sieved (2 mm) material were loosely packed into 8-cc plastic boxes.
- *n-Alkanes* were extracted together with free lipids using an accelerated solvent extractor (Dionex ASE 200) with methanol/toluene (7/3) at 9×10^6 Pa and a temperature of 120 °C. Afterwards the *n*-alkanes were separated on columns filled with 2 g activated (5%) Al_2O_3 above 2 g activated (5%) silica and 45 mL hexane/toluene (85/15) as elution solvent according to Zech and Glaser (2008). For separation and quantification of individual *n*-alkanes, we used an HP 6890 GC equipped with a flame ionization detector (FID) and deuterated *n*-alkanes (d42-*n*-C20 and d50-*n*-C24) as internal standards.
- *$\delta^{13}C$ of bulk organic material* ($\delta^{13}C_{TOC}$) was measured after removal of carbonates (10% HCl) using dry combustion of a 40 mg sub-sample with a Carlo Erba NC 2500 elemental analyser coupled to a Delta^{plus} continuous flow isotope ratio mass spectrometer via a Conflow II interface (Thermo Finnigan MAT, Bremen, Germany). Sucrose (CH-6, IAEA, Vienna, Austria) and $CaCO_3$ (NBS 19, Gaithersburg, USA) were used as calibration standards. Natural abundance of carbon stable isotopes is expressed in the usual δ-scale. Precision of repeated sample analysis averaged ~0.15‰.
- *$\delta^{18}O$ and $\delta^{13}C$ values of secondary carbonates* ($\delta^{18}O_{CaCO_3}$, $\delta^{13}C_{CaCO_3}$) were analysed with a Gasbench II coupled to a Delta^{plus} IRMS (both Thermo Finnigan,

Bremen, Germany). Between 0.5 and 2 mg ground and dried sub-samples were placed in 6 mL glass vials into a temperature rack. To minimize any non-calcite effect on results (e.g. from dolomite), the samples were run at room temperature (26.7 °C). Each sample was automatically flushed with He (99.996%) and then a few drops of 100% + orthophosphoric acid were added. The samples were left to react over night. Calibration of obtained results was done with an in-house standard every nine samples. Precision of repeated $\delta^{18}O_{CaCO_3}$ and $\delta^{13}C_{CaCO_3}$ measurements was about 0.1‰.

- *Major and minor elemental compositions* were determined using a Philips 2404 X-ray fluorescence spectrometer.
- *Radiocarbon analyses* (AMS) were performed on total organic carbon (TOC), soluble and alkali insoluble fractions of the organic matter. All radiocarbon ages were corrected for the $^{13}C/^{12}C$ ratio. In the figures, uncalibrated and calibrated (www.calpal-online.de; confidence interval = 68%) ages are shown. In the text, we refer to the uncalibrated ages only in order to enable direct comparison with previously published results.
- *Optical stimulated luminescence* (OSL) dating was performed on the quartz coarse grain fraction (90–200 μm), checking possible feldspar contamination of the quartz extracts by infra-red stimulation (IRSL) after artificial irradiation. Luminescence measurements were carried out on a Ris∅-Reader TL/OSL-DA-15, equipped with blue LEDs (470 ± 30 nm) for stimulation, a Thorn-EMI 9235 photomultiplier combined with a 7.5 mm U-340 Hoya filter (290–370 nm) for detection and a $^{90}Y/^{90}Sr$ β-source (9.16 ± 0.4 Gy/min) for irradiation. The single aliquot regenerative (SAR) dose protocol proposed by Murray and Wintle (2000) was applied to determine the equivalent dose (D_E). Six regeneration cycles were used and shine-down curves were measured for 20 s at elevated temperatures (125 °C) after a preheat of 240 °C (10 s) for the natural and regeneration signals and 160 °C for the test dose signals. The integral of 0–0.4 s of the shine-down curves, after subtracting the background signal from the mean of the 16–20 s integral, was used for D_E determination. All measurements were carried out on small multiple grain aliquots containing ca. 200 grains per aliquot (Fuchs and Wagner, 2003), mounted on aluminium cups using silicon oil. The dose rate ($\dot{D}$) for OSL age calculation was determined by low-level γ-spectrometry. Cosmic-ray dose rates were calculated according to Prescott and Hutton (1994). Results of D_E measurements show a high scatter of equivalent doses for each sample. This high D_E scatter could also be observed for these samples after artificial bleaching, dosing and applying a dose recovery test. Thus, in this case the high scatter is not the result of insufficient bleaching, but due to luminescence properties.

3. Results and discussion

3.1. Chasico—southern boarder of the subtropics (~38°S)

3.1.1. Chronostratigraphy

Numeric dating of the Chasico profile suggests that the upper 6.4 m of the sequence represent a more or less continuous paleoenvironmental record since ~15 ka BP (Fig. 2). The basis of the profile, defined here as stratigraphic unit C, consists of very dense and rubified Tertiary loam (personal communication of Dr. Quattrocchio, Geological Department National, University of Bahía Blanca). Unit B—between 640 and 340 cm depth—comprises relatively coarse sediments (mainly silty sands), with a weakly humic Ab horizon at 500–465 cm depth. A thin layer of organic matter at 610 cm depth yielded a radiocarbon age of 14.5 ± 0.05 ka BP (~17 cal ka BP, Fig. 2); in combination with the OSL dates (15.8/13.5/10.7 ka, Fig. 2), these findings show that conditions became favourable enough for sediment accumulation and pedogenesis during the Late Glacial. In contrast, during times of full glacial conditions, deflation and a resultant erosional hiatus is evident in the Chasico record, as it is in many records from the South American subtropics.

Four radiocarbon ages from the upper 340 cm of the profile (unit A) confirm their deposition during the Holocene. Sediments are generally silty indicating less intensive wind strength and more stable landscape conditions than during the Late Glacial. The black Ab horizon at 340–300 cm depth can be correlated with the Early Holocene (10.3 ka BP in 340 cm depth) and likely corresponds to the Puesto Callejón Viejo Palaeosoil described by Fidalgo (1992) (see also Quattrocchio et al., 1998). Sweet water gastropodes occur abundantly at ~300 cm depth (Fig. 2). Borel et al. (2001), studying the pollen and the morphology of fungal palynomorphs of the Chasico record, identified the gastropodes as *Limnaea viator d'Orbigny* and *Littoridina parchappii d'Orbigny*. Their radiocarbon age of 9.93 ± 0.14 ka BP for the Ab horizon (340–300 cm) is in good agreement with our chronology. The sequence of mottled dark grey humic and brown layers between 340 and 225 cm depth (unit A3) indicates hydromorphic and fluvic properties characteristic for humid environments. Also in other parts of the Pampa, the Early Holocene was characterized by warm and humid conditions (Prieto, 1996; Prieto 2000; Prieto et al., 2004).

Between 225 and 125 cm depth, calcic–gypsic layers (unit A2, Fig. 2) document a return to more arid conditions during the Mid Holocene. Intercalated Ab and Bb horizons suggest, however, that humid events may have occurred possibly responsible for the formation of the Puesto Berrondo Palaeosoil identified by Fidalgo (1992) in other parts of the Pampa.

The uppermost 125 cm of the Chasico record represent sediments deposited during the Late Holocene (unit A1, Fig. 2). Between about 3.1 and 1.5 ka BP, the alternation of silt, sand and humic layers documents the fluvic influence

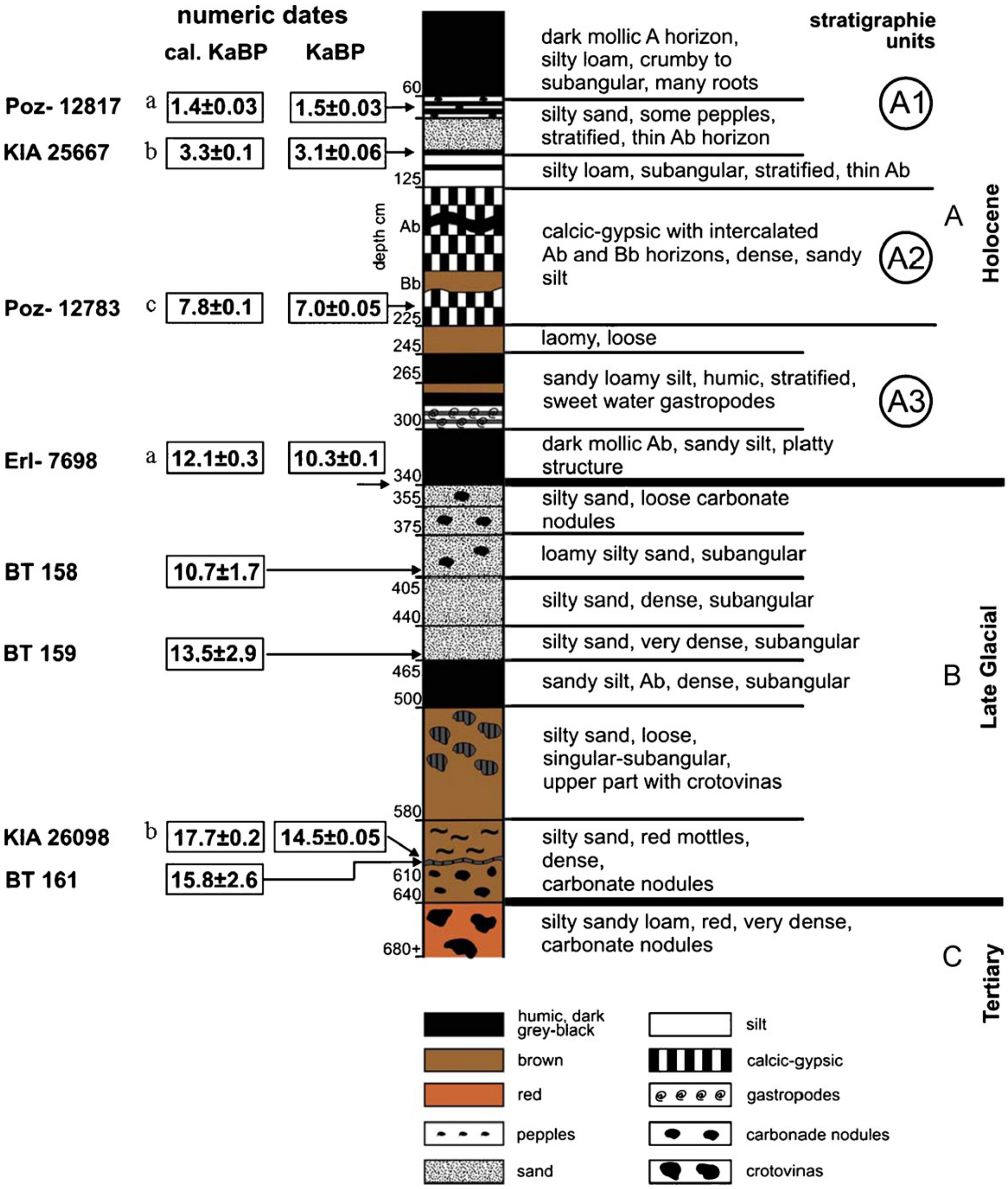

Fig. 2. AMS radiocarbon ages (a = alkali soluble, b = alkali insoluble, c = TOC) and OSL ages (BT-158, -159, -161), some morphological properties, and stratigraphic units of the Chasico record.

on sediment deposition and unstable environmental conditions. Palynological results also show greater climatic variability for this period (Quattrocchio and Borromei, 1998), whereas the thick mollic A horizon of the upper 60 cm of the profile reflects more stability during the last ~1500 years.

3.1.2. Palaeoenvironmental proxies and palaeoclimate

In the following, we present results from geophysical and geochemical analyses of the Chasico record and discuss their potential use as palaeoenvironmental proxies.

Magnetic susceptibility shows a maximum in 570–580 cm depth (Fig. 3). The values decrease during the Late Glacial more or less continuously towards 380 cm depth. A second maximum appears in 370 cm. The Early Holocene materials generally have low MS values apart from the brown sandy loamy layer between 225 and 245 cm depth and the sandy layer in ~100 cm depth. Since MS is significantly positively correlated with the sand fraction 63–125 μm, but negatively with the finer textural fraction <20.7 μm (Fig. 3), it can be assumed that the wind vigour model (Evans and Heller, 2001; Evans et al., 2003) is of relevance. Accordingly, higher MS values are due to relatively dense,

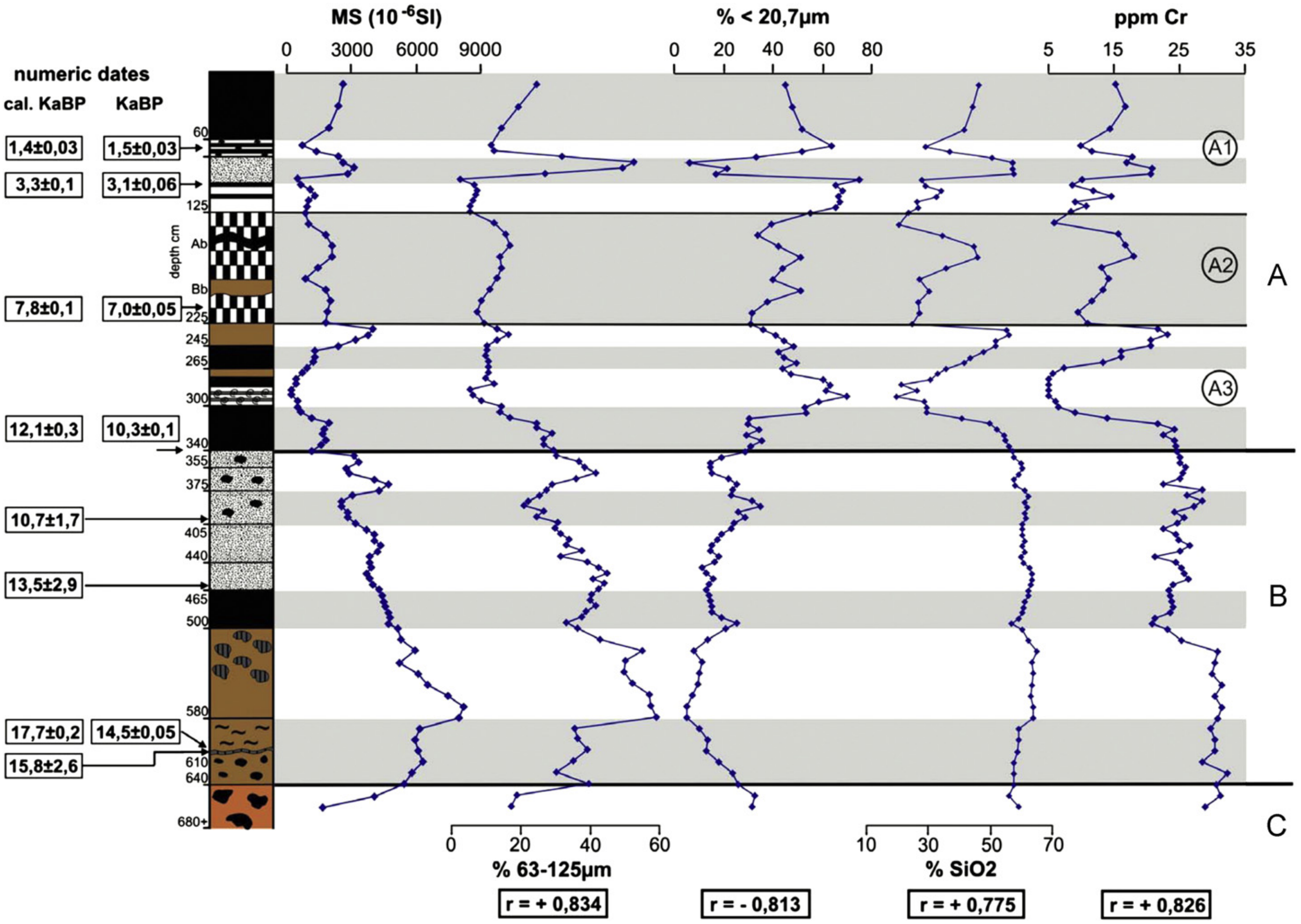

Fig. 3. Depth function of magnetic susceptibility (MS), grain size, SiO_2- and Cr-contents of the Chasico record. The correlation coefficients (*r*) describe the statistical relationship between the respective parameter and MS.

heavy SiO_2- and Cr-rich big particles (Fig. 3) that can be transported only by strong winds, indicating cold and/or dry periods. The applicability of the wind vigour model to the Pampean loess was recently also advocated by Schellenberger et al. (2003) and Bidegain et al. (2005). Apparently, the MS values of the Pampa sediments seem to behave similar to the eolian deposits in Siberia (Chlachula et al., 1998) and they do not follow the pedogenetic model as in Chinese (Heller and Liu, 1982) and Eastern European loess records (Buggle et al., 2007), where during warm periods very small super paramagnetic particles are produced and increase the MS signal.

Concerning *organic matter* in the Chasico record, information about biomass productivity, preservation and palaeovegetation can be derived (Fig. 4): The Late Glacial sediments in unit B contain only traces of TOC and total N. Even the buried A horizon in 465–500 cm depth and the crotovinas below show only slightly higher TOC values (up to 0.09%). Climate conditions were probably still too cold and at least seasonally too dry to allow significant biomass production or preservation. Most likely, only few drought-tolerant shrubs prevailed. This interpretation is in agreement with palynological findings (Prieto, 1996; Prieto, 2000; Muhs and Zarate, 2001) and is corroborated by biomarker analyses: low C31/C29 ratios of the *n*-alkanes in unit B indicate that shrub leaf waxes (mainly C29) dominated those derived from grass and herbs (mainly C31) (Schwark et al., 2002).

Biomass production increased significantly during the Early Holocene (unit A3, Fig. 4). Warmer and probably more humid conditions also led to a shift in vegetation composition. The high C31/C29 ratios show that grasses and herbs expanded. The Mid Holocene deposits (unit A2, Fig. 4) are, however, again poor in TOC and N, coinciding with lower C31/29 ratios. Aridity is also reflected in accumulation of carbonate and gypsum as indicated by high S contents. The Late Holocene sediments (unit A1, Fig. 4) display a pronounced fluctuation of TOC, N and C31/C29 between 60 and 125 cm due to unstable environmental conditions.

Although *stable isotopes* are sometimes complicated to interpret due to multiple factors influencing their composition (Glaser, 2005; Glaser and Zech, 2005), their potential to reconstruct vegetation ($\delta^{13}C_{TOC} \rightarrow C3$ versus C4) and

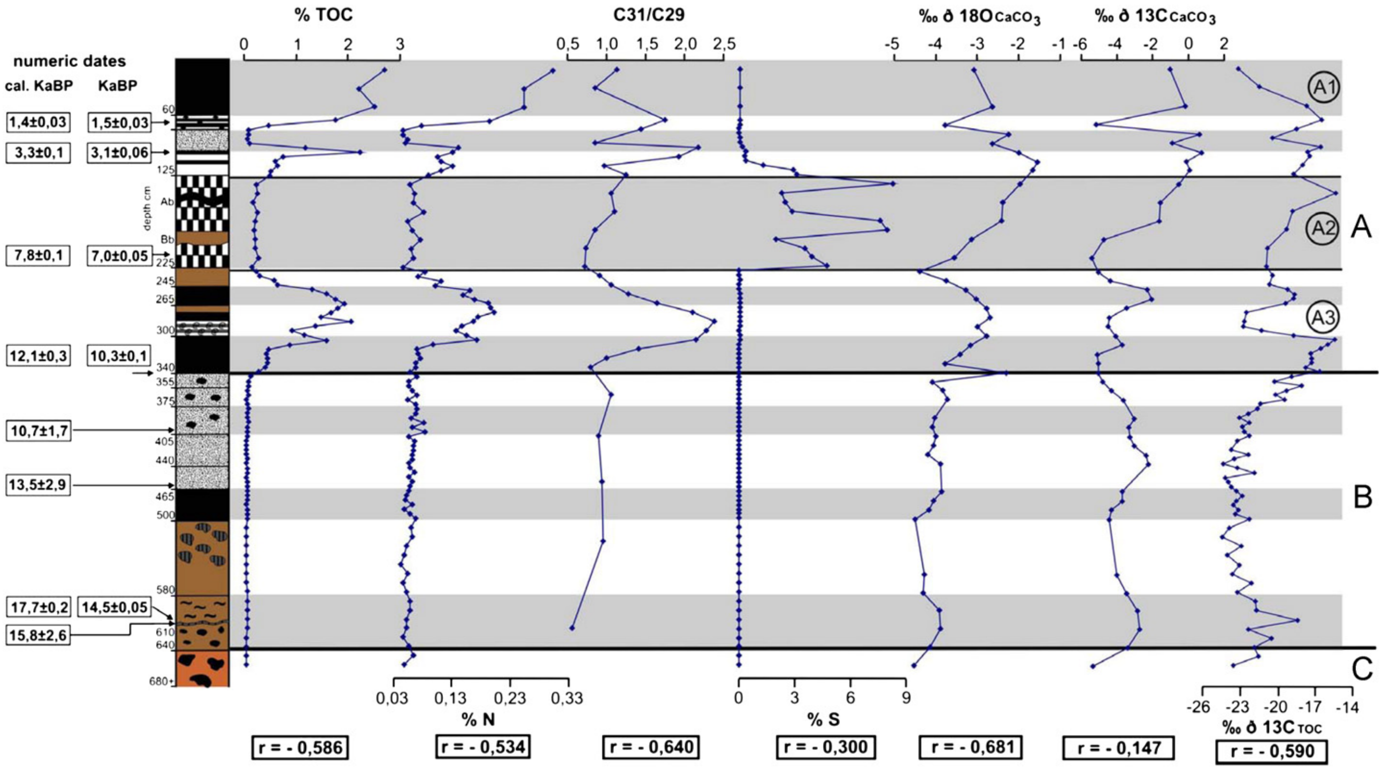

Fig. 4. Depth function of total organic carbon (TOC), total nitrogen (N), total sulphur (S), the ratio of *n*-alkanes C31 and C29, $\delta^{18}O$ and $\delta^{13}C$ carbonate and $\delta^{13}C_{TOC}$ of the Chasico record. The correlation coefficients (r) describe the statistical relationship between the respective parameter and MS.

climate ($\delta^{18}O \rightarrow$ temperature) has been shown in numerous studies. $\delta^{13}C_{TOC}$ values in the Late Glacial sediments (unit B) vary around −23‰ (Fig. 4). This is consistent with C3 shrub vegetation inferred from the *n*-alkane and pollen results. During the Early Holocene, values increase to −15‰, which can be explained by the invasion of C4 grasses. The lacustrine sediments between 265 and 300 cm depth exhibit again more negative $\delta^{13}C_{TOC}$ values of −23‰. A positive value of −15‰ characterizes the buried A horizon in 150 cm depth, while the other Mid Holocene deposits revealed $\delta^{13}C_{TOC}$ values between −19‰ and −21‰, probably due to a mixed C3/C4 vegetation with predominance of drought-resistant shrubs (C31/C29 ratios in Fig. 4). The uppermost 125 cm of the profile show in its lower part (~70–125 cm) varying $\delta^{13}C_{TOC}$ values with a decreasing trend in its upper part. The surface layer has a $\delta^{13}C_{TOC}$ value of −23‰, which reflects the actual shrub vegetation. Note that minor shifts in $\delta^{13}C_{TOC}$ may indicate water stress or differences in preservation, but shifts as pronounced as in the Chasico record should be related to the invasion of C4 plants from southern Brazil as identified also by pollen studies (Quattrocchio and Borromei, 1998).

Concerning the oxygen isotopic composition, we note that the analysed pedogenic carbonates may not have formed directly at the palaeosurface, but post-depositionally in sub-surface horizons. This is indicated by the poor correlation ($r = 0.208$) between $\delta^{13}C_{TOC}$ and $\delta^{13}C_{CaCO_3}$. Nevertheless, their analysis may provide a first-order estimation of relevant palaeoclimatic changes, i.e. the precipitation input and evapotranspiration. In the Late Glacial unit B $\delta^{18}O_{CaCO_3}$ values vary around −4‰, in the Early Holocene unit A3 they increase up to −3‰. In the Mid Holocene deposits $\delta^{18}O_{CaCO_3}$ continuously increases from about −4‰ in 225 cm depth to −2‰ in 125 cm depth. In the upper 100 cm of the profile $\delta^{13}O_{CaCO_3}$ becomes more negative (~−3‰) again. Assuming that the $\delta^{18}O_{CaCO_3}$ values are mainly influenced by the $\delta^{18}O$ signature of the soil water, the following interpretation is suggested: The negative values of about −4‰ in unit B reflect the cold Late Glacial climate with reduced evapotranspiration. The increase in subunit A3 could be due to (i) the Holocene warming and resultant higher evapotranspiration, or (ii) a higher contribution of relatively enriched "short distance rains" from the adjacent Southern Atlantic Ocean—in contrast to more depleted tropical monsoonal precipitation. Changes in the monsoon intensity have recently been proposed based on high-resolution speleothem data from SE-Brazil (Cruz et al., 2005a, b, 2006a, b; Wang et al., 2006), but also the transgression of the sea (Muhs and Zarate, 2001) should be considered. The continuous increase of $\delta^{18}O_{CaCO_3}$ in the Mid Holocene deposits from −4‰ (225 cm depth) to −2‰ (125 cm depth) could be related to the aridity during this period.

In summary, the Chasico record documents warming and—at least seasonally—an increase in precipitation during the Late Glacial compared with cold and dry full glacial conditions. The scarce vegetation consisted mainly of shrubs. A dramatic climatic amelioration with increasing temperatures and precipitation (all year round) occurred during the Early Holocene. The Mid Holocene became drier again, supporting the formation of calcic–gypsic horizons. The Late Holocene started with a pronounced climatic instability, during the last ~1500 years a thick mollic A horizon developed under more stable conditions.

3.2. *Misiones (D4)—northern border of the subtropics (~27°S)*

3.2.1. *Chronostratigraphy*

Numeric dating results from record D4 in Misiones suggest that the palaeoenvironmental archive reaches back to ~40 ka BP (for ages and a brief morphological description see Fig. 5). Homogeneity tests using the major and minor elemental composition reveal that the profile can be subdivided into three stratigraphic units (Zech et al., 2008).

Unit C is radiocarbon dated to 34.5–41.4 ka BP, i.e. Marine Isotope Stage (MIS) 3. This chronology is corroborated by another age obtained from organic material in 250 cm depth in a neighbouring basin (D2: 32 ka BP). The brown subunit C4 (>400 cm depth) may be a truncated *in situ* B horizon, or re-deposited soil material. The bleached, light grey, mottled subunit C3 documents humid conditions during MIS3, followed upwards by a grey silty clay loam which we interpret as a transitional layer (= subunit C2, 360–320 cm). It contains more organic matter (OM) than subunit C3 but less than C1 (320–290 cm) indicating that biomass production and/or OM conservation improved from C4 to C1 (Zech et al., 2008). At 290 cm depth, a hiatus suggests that either the environmental conditions became unfavourable for sedimentation at the end of MIS3 or that the profile was truncated—probably by deflation—during the LGM.

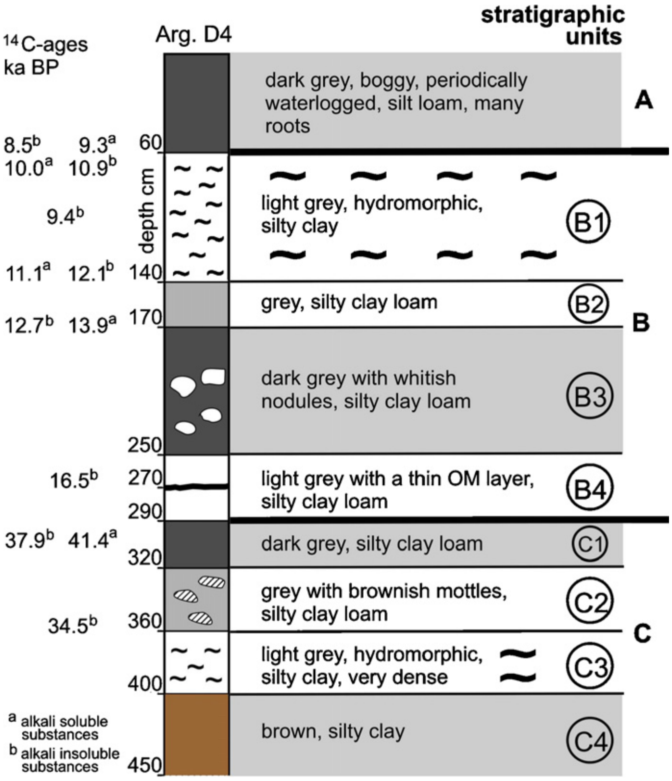

Fig. 5. AMS radiocarbon ages of alkali soluble and alkali insoluble organic substances, some morphological properties and stratigraphic units of the D4 record.

Unit B documents the re-onset of sedimentation. The light grey subunit B4 (290–250 cm) contains a thin layer of OM and could be dated to 16.5 ka BP (~20 cal ka BP). Several more radiocarbon ages are available from the horizons above and show that the sediments between 250 and 60 cm were deposited during the Late Glacial. Their lower part (subunit B3) is OM rich, but towards the surface the dark grey colour continuously decreases. The bleached hydromorphic clayey subunit B1 probably reflects lacustrine, though not perennial, conditions. This interpretation is corroborated by maxima of short- and mid-chain alkanes deriving from algae and submerged plants and from OM preservation indices (Zech et al., 2008).

The OM rich and silty unit A was deposited during the Holocene. Morphologically (see below), this unit cannot be subdivided into a humid Early Holocene, a dry Mid Holocene and a Late Holocene section like the Chasico Record (Fig. 2).

3.2.2. *Palaeoenvironmental proxies and palaeoclimate*

The *MS* record of D4 shows a very similar pattern as the Chasico profile, although the absolute values are by an order of magnitude lower. High values characterize the sediments deposited during MIS2 (~17 ka BP, subunit B4); the values decrease almost continuously during the Late Glacial and are relatively low during the Holocene. According to the wind vigour model, this again suggests stronger winds during the LGM and the Late Glacial compared with the Holocene. Intermediate and fluctuating MS values in unit C suggest varying wind-strengths during MIS3. In contrast to the Chasico profile, no strong correlation exists, however, with grain size considering the complete profile (= units A+B+C; Fig. 6). This is probably due to clay enrichment in the lacustrine subunit B1. Since in general the dominant grain size class is silt (fraction 2–63 μm = 60–80%, see Fig. 6), we argue that eolian sediments were brought by westerly winds from the Chaco and trapped in the D4 depression. This is in agreement with the hypothesis of a young Quaternary "tropical loess" sheet covering the basaltic landscape in Misiones (Iriondo and Kröhling, 1997), but we should mention that this hypothesis is not generally accepted. Morras et al. (2008) show that the basaltic plateaus and hills in Misiones are not covered by a uniform eolian Late Pleistocene mantle. Small amounts of eolian input may, however, accumulate in depressions due to hillwash. Note that MS values correlate very well with the SiO_2/R_2O_3 ratios in units B and C ($r = 0.865$) probably reflecting higher eolian inputs of silica-rich material during less

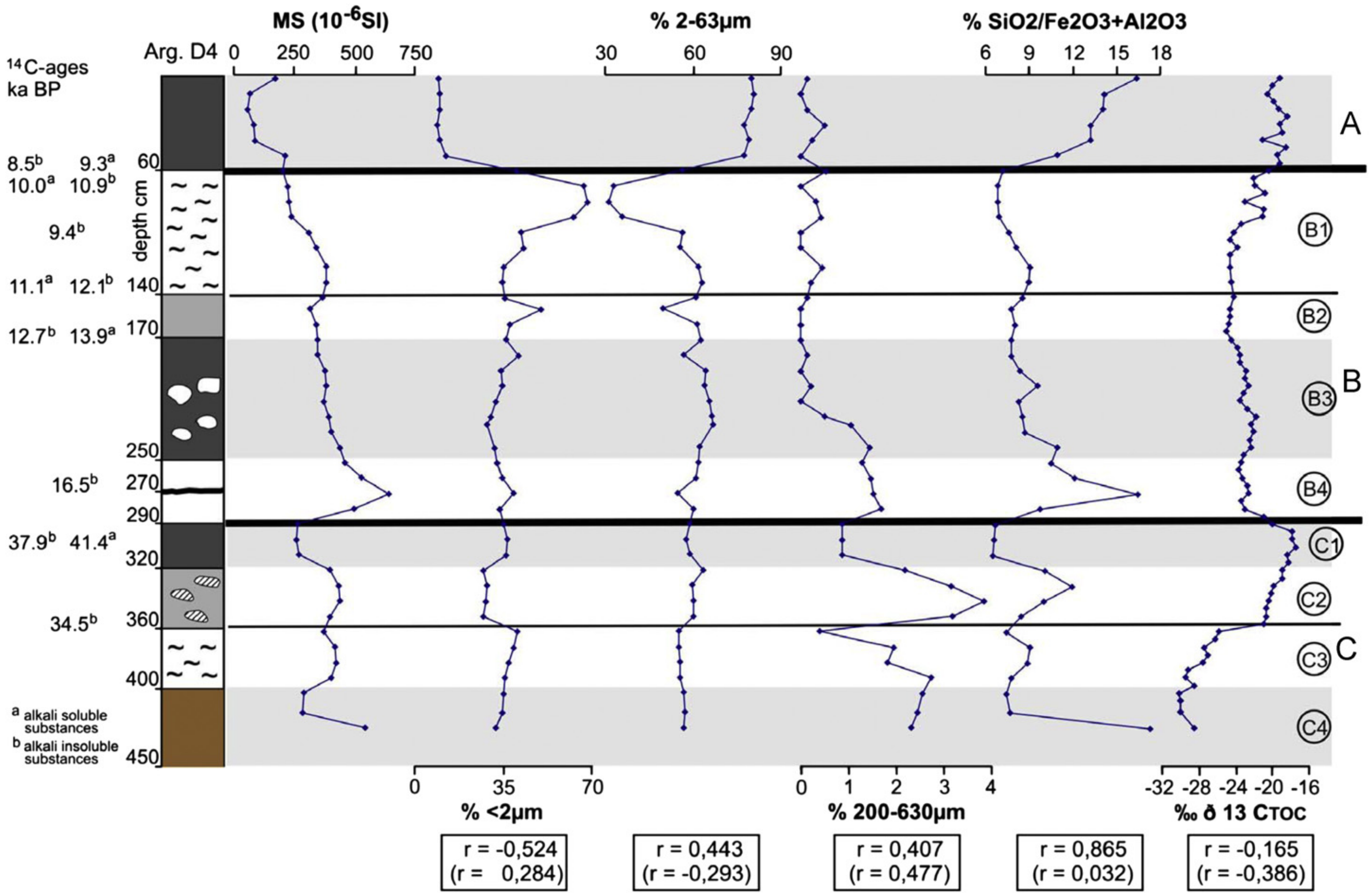

Fig. 6. Depth function of magnetic susceptibility (MS), grain size, SiO_2/R_2O_3 ratios, and $\delta^{13}C_{TOC}$ of the D4 record. The correlation coefficients "*r*" describe the statistical relationship between the respective parameter (unit B and C only) and MS. For comparison, "*r*" in parentheses refers to the correlation including unit A.

favourable climatic conditions. This correlation fails, however, completely for the Holocene part of the profile, where low MS values correlate with high SiO_2/R_2O_3 ratios. We speculate that changes of the sediment sources and/or changes in the sediment source areas occurred at the Pleistocene–Holocene transition, which coincides with a drop in accumulation rate (unit B: ~20 cm/ka, unit A: ~6 cm/ka).

Low $\delta^{13}C$ values of the bulk organic matter (<-26‰) indicate that during the sedimentation of subunits C4 and C3 a pure C3 vegetation cover existed, documenting a humid period during MIS3. This is in agreement with palynological results from Southern Brazil (Salgado-Labouriau, 1997; Behling et al., 2004), with recently published $\delta^{18}O_{CaCO_3}$ findings from SE-Brazil (Cruz et al., 2005a, b, 2006a, b; Wang et al., 2006), and with lake sediment studies carried out on the Bolivian Altiplano where this wet phase is named "Inca Huasi" (Baker et al., 2001; Fritz et al., 2004; Placzek et al., 2006). A sharp increase characterizes the transition to higher $\delta^{13}C_{TOC}$ values in subunit C2 and C1 (-18‰). Without doubt C4 grasses and/or CAM plants expanded indicating a savanna like climate with a pronounced dry season. Increasingly dry conditions after the wet phase during MIS3 are ultimately reflected in the hiatus in the D4 record at 290 cm depth (Zech et al., 2008). The re-onset of sedimentation does not start before ~19 ka BP. Inferred dry and cold conditions during this hiatus period are again in agreement with palynological results from SE-Brazil (Behling, 2002) and with the speleothem records in SE-Brazil. Kröhling (1999) also described arid conditions between 36 and 16 ka BP in the Santa Fé and Córdoba provinces of Argentina.

Intermediate $\delta^{13}C_{TOC}$ values (-24‰) during the LGM (subunit B4), in combination with *n*-alkane data (not shown here), have been interpreted to still document cold and dry conditions allowing the growth of a predominantly C3 grass vegetation (Zech et al., 2008). In comparison with subunit C1, C4 grasses may not have been competitive enough because it was too cold. The gradual transition towards more favourable conditions during the Late Glacial, which we have deduced from decreasing MS, sand, and SiO_2/R_2O_3 values above, is also evident in the organic parameters: although $\delta^{13}C_{TOC}$ shows only a minor shift towards more negative values indicating still mainly C3-derived organic matter, gradual expansion of forests versus grass can be deduced from *n*-alkane analysis (Zech et al., 2008). The constellation of these proxies (in combination with the increasing accumulation of SOM and some secondary carbonate in subunit B3) suggests that after the LGM, conditions were getting warmer, but also wetter. The fact that TOC is decreasing in subunit B1 probably reflects the seasonally desiccating lacustrine conditions as indicated by the high clay contents; besides, hydromorphic features become abundant.

More humid conditions in southern tropical/subtropical South America during the Late Glacial can also be deduced from the $\delta^{18}O$ composition of the stalagmites in SE-Brazil (Cruz et al., 2006a, b), from the Late Glacial forest expansion in NE-Brazil and southern Amazon (Behling, 1998; Freitas et al., 2001; Behling, 2002; Behling et al., 2002), and from lake sediment studies on the Bolivian Altiplano during the "Tauca" and "Coiposa" wet phases (Placzek et al., 2006). The palaeoclimatic explanation of this observed Late Glacial wet phase is an intensification of the monsoonal circulation, which is in principal driven by insolation on orbital time scales and by temperature changes at high latitudes on millennial time scales (Zech et al., 2008).

Finally, unit A is characterized by a minor increase in $\delta^{13}C_{TOC}$ (~-20‰) indicating the expansion of C4 savanna grasses and/or CAM plants. Although D4 seems to lack the resolution to identify the Mid Holocene dry period, there is some evidence from profiles on nearby slopes and plateaus (see Morras et al., 2008). The $\delta^{13}C_{TOC}$ values of profile M0, for example, show maxima of ~-16‰ between 100 and 200 cm soil depth (Fig. 7). Radiocarbon ages of the alkali soluble organic compounds are 3.1 and 7.1 ka BP (3.3 and 7.9 cal. ka BP, respectively), thus confirming that the Mid Holocene dry period identified in the Chasico record (Fig. 2) not only affected the southern border of subtropical Argentina but also the northern border. Additionally, the ratios of the lignin compounds syringyl/vanillyl (= S/V) and coumaryl/vanillyl (= C/V) indicate that the $\delta^{13}C_{TOC}$ value of ~-16‰ in 100 cm depth mainly derived from grass organic matter, whereas at the soil surface in 5 cm the more negative $\delta^{13}C_{TOC}$ values of ~-21‰ are strongly influenced by angiosperm organic matter (Goñi et al., 1998).

3.3. Laguna sucuara (L1)

The northernmost record of our transect is Laguna Sucuara (L1) located in the Bolivian savanna (Fig. 1). It comprises sediments from the Holocene and perhaps the youngest section of the Late Glacial (Fig. 8). The lower third of the profile is characterized by strongly fluctuating sandy–silty grain size, varying MS values, and $\delta^{13}C_{TOC}$ values of −23 to −21‰. Towards the middle part of the profile, sand contents decrease, the silt fraction 2–63 μm increases and the pronounced fluctuations of the grain size

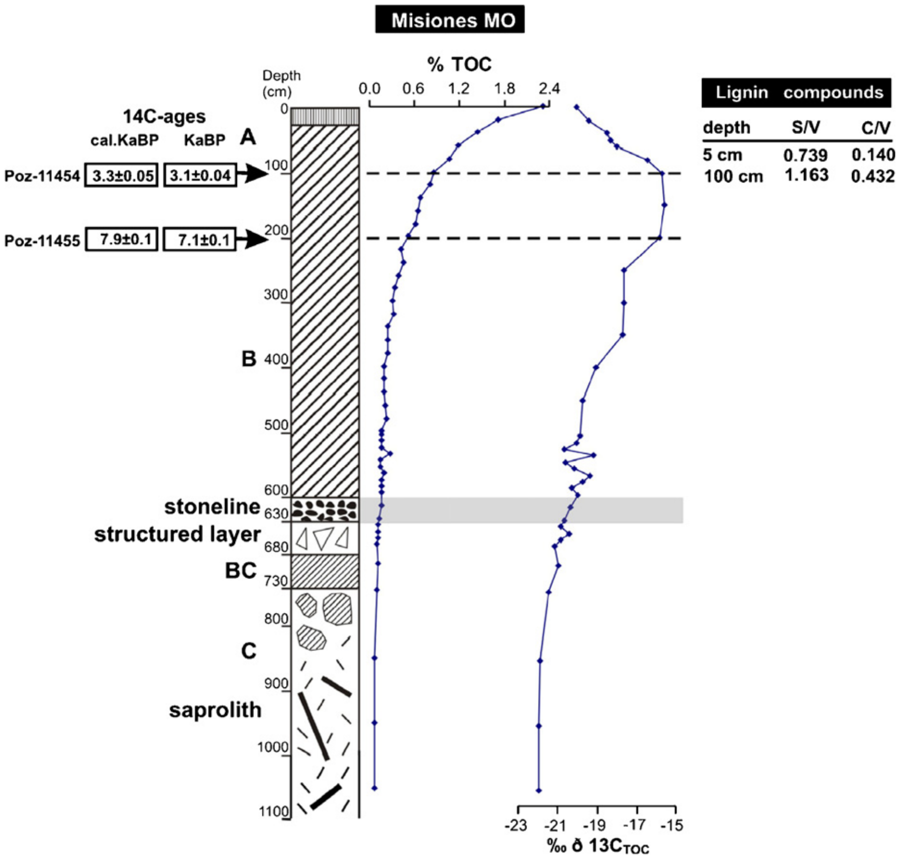

Fig. 7. Depth function of total organic carbon (TOC) and $\delta^{13}C_{TOC}$ of profile M0. S, C and V are the lignin compounds syringyl, coumaryl and vanillyl, respectively. ^{14}C ages refer to alkali-soluble organic matter.

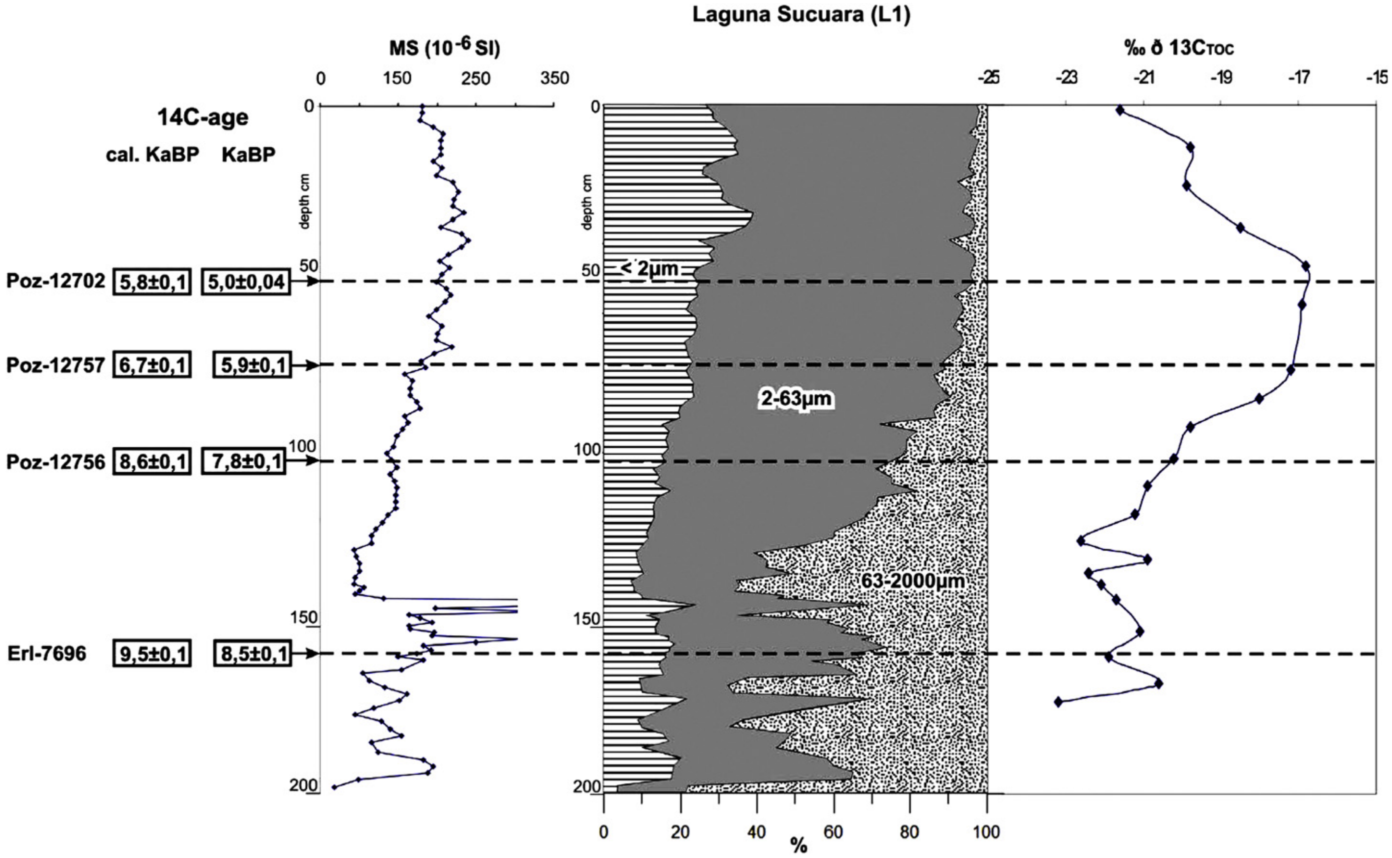

Fig. 8. AMS radiocarbon ages (5.0, 5.9 and 7.8 ka BP refers to TOC; 8.5 ka BP refers to alkali soluble organic matter), magnetic susceptibility, grain size and $\delta^{13}C_{TOC}$ of core L1.

classes, of MS and $\delta^{13}C_{TOC}$ diminish. The $\delta^{13}C_{TOC}$ values increase to ~−17‰ between ~80 and 50 cm depth, i.e. at about 5 ka BP according to the radiocarbon chronology. In the upper 50 cm of the profile, $\delta^{13}C_{TOC}$ and MS values decrease again, and clay contents show maxima of nearly 40%.

From these results, we conclude that the environmental conditions at the Pleistocene–Holocene transition were probably unfavourable for the accumulation of organic material. Pronounced seasonality of rainfall may have been responsible for the formation of the strongly stratified fluvic silty sands in the lower third of the record; and we tentatively suggest that although the monsoonal precipitation was reduced, the extra-tropical winter precipitation was responsible for the growth of mainly C3 plants. Towards the Mid Holocene aridity increased and C4 savanna grasses expanded. At the same time, eolian silt inputs into the lagoon increased. At about 4 ka BP, it became more humid again due to the re-strengthening of the tropical circulation and the present day tree savanna established in the catchment. This interpretation is supported by even more negative $\delta^{13}C_{TOC}$ values of −25‰ in the surface layers of a second lagoon called Lagoon Bazán, located adjacent to Lagoon Sucuara. Mayle et al. (2000), studying the shift of the Amazonian rain forest to savanna boundaries in Eastern Bolivia during the Late Quaternary, also found that the Late Holocene was more humid than the Mid Holocene. Their palynological findings show that the present day limit of the humid evergreen rainforest represents the southernmost extent of Amazonian rainforest over at least the past 50,000 years.

4. Synthesis and conclusions

The lack of Quaternary sediments older than ~16 ka BP in our southern subtropical profile Chasico provides evidence for pronounced eolian denudation during and possibly also before the LGM. We explain that with low temperatures combined with very dry conditions. Also marine regression may have favoured erosion along the valleys. Whereas reliably dated and consistent palaeoenvironmental records of the MIS3 from the southern border of the subtropics in SE-South America are missing, a wetter phase at ~34–40 ka BP (correlated with the "Inca Huasi" wet phase on the Altiplano) is well documented to the north, both in our D4 profile and in several other paleoclimate archives, like the speleothems, pollen and lacustrine sediments. Although intensive erosion during the LGM may have truncated former soils or loess, we suggest that the tropical monsoonal circulation, which dominantly controls the moisture fluctuations in tropical and subtropical South America, did not reach far enough south at

~40 ka to allow loess or soil formation at the study site Chasico.

Note that although insolation is modulating monsoon intensity on orbital time scales, it has been recognized that millennial-scale high-latitude temperatures are important too. Therefore, the insolation maximum at ~20 ka BP is not necessarily in contradiction with the extremely dry and erosive conditions at that time. Despite declining insolation, there is plenty of evidence for a pronounced wet phase during the Late Glacial: The re-onset of sedimentation at ~16 ka BP is not only documented in the D4, but also in the Chasico record, i.e. much further south than during the earlier (~40 ka) wet phase. This is in agreement with lake transgressions on the Altiplano (“Tauca” and “Coipasa”) and the strongly depleted isotope signature in the SE-Brazilian speleothems. An interesting feature is, however, that (i) organic matter accumulation is almost negligible in the sandy deposits of the Chasico record as well as in the lacustrine sediments in D4, and (ii) there seem to be major disagreements with palynological results from the subtropics, which are interpreted to indicate dry Late Glacial conditions (Quattrocchio and Borromei, 1998; Prieto, 2000; Behling, 2002; Behling et al., 2002, 2007). We suggest taking seasonality of precipitation into account is crucial to solve the above issues. High summer precipitation during the Late Glacial probably coincided with low winter precipitation. Thus, only drought-resistant shrubs and grasses, but no trees, prevail and stabilize the landscape. Eolian sands and silts are trapped and accumulate—in depressions even lacustrine clays (as in D4)—but the pronounced dry winter season causes desiccation and oxidation of organic matter.

Preservation of organic matter at the Chasico and the D4 location during the Early Holocene suggests that extra-tropical winter precipitation increased. The north–westward influence may, however, have been limited according to our results from L1 and the palynological findings of Mayle et al. (2000) in Bolivia. With the Pleistocene–Holocene transition, the tropical monsoonal precipitation probably dropped significantly, coinciding with a northward shift of the ITCZ (Wang et al., 2006). All three of our records under study document the Mid Holocene dry period, which has extensively been described for tropical and subtropical South America (Mayle et al., 2000; Bradbury et al., 2001; Freitas et al., 2001; Fritz et al., 2001; Muhs and Zarate, 2001; Behling et al., 2004; Iriarte, 2006). Neither the extra-tropical nor tropical precipitation seems to have been high at that time. The south-ward shift and/or intensification of the monsoon during the Late Holocene is then documented along the whole N–S transect.

Our results show that a complex interplay between the tropical and the extra-tropical precipitation controlled the humidity conditions along the N–S transect in tropical–subtropical South America. Changes in the atmospheric circulation patterns in the course of the Late Quaternary had their imprint on vegetation, loess deposition and soil formation. Future work should focus on (i) the spatial distribution of the individual pedo-facies, (ii) the exact timing of the environmental changes, (iii) the development of more quantitative proxies, e.g. deuterium and oxygen isotopes in pedogenic carbonates and organic matter, and finally (iv) the search of records that reach further back in time.

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