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Quality assessment of chronologies in Latin American pollen records: a contribution to centennial to millennial scale studies of environmental change

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Abstract

The newly updated inventory of the Latin American Pollen Database (LAPD) offers an important overview of data available for multi-proxy and multi-site purposes. However, heterogeneous paleoecological databases are not suitable to be integrated without an uncertainty assessment of existing chronologies. Therefore, we collected all chronological control points and age model metadata from the LAPD literature to create a complementary chronological database of 5116 dates from 1097 pollen records. We start with an overview on chronological dating and reporting in Central and South America. Specific problems and recommendations for chronology reporting are discussed. Subsequently, we implement a temporal quality assessment of pollen records from northwest South-America to support research on climate forcers and responses at a centennial-millennial time-scale. New chronologies are generated for 233 pollen records based on updated calibration curves. Different time windows are discussed on sample resolution and temporal uncertainty. Approximately one in four pollen diagrams depicts < 500 years resolution data at the Younger Dryas/Holocene transition. Overall, our analyses suggest that the temporal resolution of multi-site syntheses of late Pleistocene fossil pollen records in the northwest South-America is ca. 240 years, a resolution which allows analysis of ecological responses to centennial-millennial-scale climate change during the last deglaciation.

1 Introduction

Understanding millennial-scale climate variability during the last glacial is increasingly the focus of current research into past climate change, such as earth-system responses to rapid events (Ammann et al., 2000; Clement and Peterson, 2008; Urrego et al., 2009), teleconnections (Fritz et al., 2010) and the synchronous display of paleoclimate events in different paleo-proxies (Villalba et al., 2009; Austin et al., 2012). The mechanisms of responses to events of rapid climate change provide important insights to develop improved scenarios of ecosystem reactions to future environmental changes. The assessment of ecosystem resilience to millennial-scale climate variability requires a set of high quality databases from different proxies. Integration of proxies can help to determine whether abrupt climatic changes were regionally and altitudinally synchronous, or whether there were significant "leads" and "lags" between and/or within the atmospheric, marine, terrestrial and cryospheric realms (Blockley et al., 2012). Therefore, reconstructions based on multi-proxy datasets at millennial-scale resolution are a keystone for linking important questions on current climate change responses to what we can understand from the past (Urrego et al., 2014).

However, temporal uncertainty remains a challenge in heterogeneous databases of fossil-pollen records (Blois et al., 2011). The demands for precise and accurate chronologies have increased and so have the questions needing high-resolution data with accurate chronologies (Brauer et al., 2014). The increasing number of studies testing for potential synchronous patterns in paleo-proxies (Jennerjahn et al., 2004; Gajewski et al., 2006; Blaauw et al., 2007, 2010; Chambers et al., 2007; Giesecke et al., 2011; Austin et al., 2012), rely heavily on extremely precise correlation between different records. The popular "curve-matching" of proxy data has been the cornerstone on correlating potential teleconnections, but this method neglects time-transgressive climate change (Blaauw, 2012; Lane et al., 2013). To correctly correlate paleoclimate records and integrate results, it is important to identify those few, but growing numbers of records which have relatively precise chronological information (Blois et al., 2011; Seddon et al., 2014; Sundqvist et al., 2014). Within the total spatial coverage of regional pollen databases, such assessment has recently been presented for the European Pollen Database (EPD) (Fyfe et al., 2009; Giesecke et al., 2012) and for the North American pollen database (Blois et al., 2011), but for Latin America this important assessment is still missing. The recently updated Latin America Pollen Database (LAPD; Flantua et al., 2013, 2015; Grimm et al., 2013) shows the vast amount of available palynological sites with geochronological data throughout the continent, but to support multi-site and multi-proxy research on centennial to millennial time-scale, a quality assessment of the chronology is evidently urgent.

Thus, accurate age-depth modelling has been identified as crucial to derive conclusions on climate change signals from paleo-archives (Seddon et al., 2014). Consequently, an increasing number of working groups have declared this their central aim to develop in the present and near future, such as the INTIMATE[1] initiative (Blockley et al., 2012), Neotoma Age Modelling Working Group (Grimm et al., 2014) and the INQUA[1] International Focus group, ACER[1] (Sanchez Goñi and Harrison, 2010). The Latin American version of the latter, LaACER, has proposed to integrate high quality paleo-records to improve our understanding of consequences of millennial-scale variability in the tropics (Urrego et al., 2014). Before correlating different paleo-records, the first step is to assess the chronological quality of individual records. As a contribution to the LaACER initiative (this issue), this paper starts with a brief overview of chronological dating and reporting available from pollen records in Central and South America. We describe the most commonly used dating methods, age modelling and calibration methods, and discuss fields of highest potential improvement in line with international recommendations. Secondly, we assess the chronological quality of pollen records from a specific region of the LAPD, namely the countries from northwest South-America (NW–SA). We evaluate the temporal uncertainty of age models by a conceptual framework proposed by (Giesecke et al., 2012) for ranking the quality of the site chronologies and the individual ^{14}C ages. For internal consistency, all chronologies from the NW–SA are regenerated with updated calibration curves for both the Northern and the Southern Hemisphere going back to 50 kcal BP (IntCal13 and SHCal13; Reimer et al., 2013; Hogg et al., 2013). Subsequently the highest temporal resolution currently possible is estimated from a site specific and synoptic perspective, in which resolution is calculated as the time between two consecutive depths with proxy

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[1] INTIMATE: the INTegration of Ice core, Marine and TErrestrial records of the last termination; INQUA: International Union for Quaternary Science; ACER: Abrupt Climate Changes and Environmental Responses.

information. Based on the combined temporal quality and resolution assessment, the time windows best suitable for inter-site and inter-proxy comparison are discussed. The resulting chronologies are not assumed to be the best age models, but serve as a guidance to discuss the current resolution and temporal quality of South American pollen records for research into centennial to millennial climate variability.

2 Methods

2.1 Geochronological database of Central and South America

To obtain an overview of the control points and age modelling methods used in pollen records throughout the continent, we performed a thorough review of the LAPD and corresponding literature database (Flantua et al., 2015). A total of 1245 publications were checked on their chronological information covering 1369 sites. For 270 sites only biostratigraphic dates were mentioned, no chronological details were provided, or the original publications with specifications were not found. These sites originate primarily from the 1970s and the 1980s, although even some recent publications lack enclosing details on the chronology. All other sites consisting of at least one chronological reference point enter at this stage the geochronological database (Fig. 1). On the chronology the following metadata was collected for each site: *Site Name, Year of Data Preparation, Age Model, Calibration Method, Software, Material Dated, Depth (min, max, mean), Thickness, Laboratory number, pMC (error),* ^{13}*C adjusted* (± *SD),* ^{14}*C date (min, max, errors), Reservoir correction, Calibrated age (min, max, best age, errors), Additional relevant comments from authors.* Furthermore, all additional parameters needed to reconstruct correctly the chronologies, such as presence of hiatus, slumps, contaminated control points and other outliers identified by authors, were included. As a result, the LAPD Geochronological Database (LAPD-ChronDB) currently contains at total 5116 chronological dates from 1097 sites throughout the continent.

2.2 Chronology evaluation for Northwest South America

To assess the temporal uncertainty of chronologies within a specific region of interest, namely NW–SA, the following steps were undertaken: from the LAPD-ChronDB, all sites present in Venezuela, Colombia, Ecuador, Peru and Bolivia were selected (Fig. 1 in grey). When more than one chronological date was available, new chronologies were generated with the updated calibration curves for the northern and the Southern Hemisphere and maintained as closely as possible to the authors' interpretation of the age model (Sect. 2.3). The quality evaluation of age models consists of implementing the method proposed by Giesecke et al. (2012) and will be explained in the Sect. 2.4, followed by temporal resolution estimates at an site specific and synoptic level within different time windows (Sect. 2.5).

2.3 Age model generation

Over 300 publications were consulted for the recalibration of control points and age models of 292 pollen records in the NW–SA.

Chronology control points: The most common control points are radiocarbon dates. For the age model generation we included the reported uncertainty of a date regardless of its origin (conventional dates or Accelerator Mass Spectrometry (AMS) date). Additional important control points in constructing chronologies are ages derived from tephra layers from volcanic material, radioactive isotope of lead (^{210}Pb) and fission track dates.

Biostratigraphic dates: Before exact dating by ^{14}C became available and more affordable, many records relied on the identification of presumably synchronous onsets of the Lateglacial, such as numerous pollen records from the Valle de Lagunillas (González et al., 1966) and Sierra Nevada (Van der Hammen, 1984). The transition of the Pleistocene/Holocene is often mentioned as an important reference point in diagrams, as is the Younger Dryas (YD). The onset of the Bølling/Allerød is less frequently used, whereas referring and correlating regionally defined stadials and interstadials is more popular. For example, the “Guantiva interstadial” (Van der Hammen and González, 1965; Van Geel and Van der Hammen, 1973) and “El Abra stadial” (Kuhry et al., 1993; Van der Hammen and Hooghiemstra, 1995) are commonly used biostratigraphic dates within Colombia, being the first considered to be an equivalent to the European Allerød Interstadial and the latter the Younger Dryas sequence (Van der Hammen and Hooghiemstra, 1995). Similarly in the tropical Venezuelan Andes, the “Anteojos” cold phase was proposed as equivalent to the cold reversal of the YD and in some aspects comparable to El Abra (Rull et al., 2010).

Although high resolution well dated pollen records are becoming available, for the generation of the recalibrated age models we did not use stratigraphic dates. Use of these layers would ignore the possibility that for example the palynologically-detectable onset of the Holocene was asynchronous throughout northern South America. Therefore any further inferences on spatial leads, lags or synchroneity would become flawed. Especially older pollen records relied heavily on this method of record matching without accurate chronological background.

Core tops and basal ages: The sediment surface can be assigned to the year of sampling, if explicitly mentioned by the authors as the result of being the youngest sample in an undisturbed way. Frequently however, assigning depths to core tops adds a factor of uncertainty because the uppermost sediments have not been consolidated and are recurrently lost during coring. Uncertainties of core top ages are hard to estimate but are here put at 50 yr (1 SD). The age of core tops estimated by extrapolation were not included but replaced by the estimates provided by the new age model method. Extrapolations from the new chronologies that went beyond −50 yr BP (years before AD 1950) were not used. Similarly we did not use the basal ages of the authors when based on extrapolations, but allowed the recalibrated age model produce new down-core ages.

Calibration curves: The South American continent covers both the Northern Hemisphere (NH) as well as the Southern Hemisphere (SH). The previous SH calibration curve (SHCal04) only extended to 11 kcal BP. In age model tools like CLAM (Blaauw, 2010), options were provided to “glue” the NH calibration curve to the SH curve to extend back to 50 kcal BP. However, recently the SH calibration curve was updated with new datasets (Hogg et al., 2013) and now replaces the need to use the NH curve for older dates in the SH. This provides new opportunities to recalibrate age models with updated calibration information and produce additional sample ages for reevaluation. Nevertheless, tropical regions still face an uncertainty factor open for discussion, namely the southern limit of the Intertropical Convergence Zone (ITZC). McCormac et al. (2004) defined this limit to be the boundary between NH–SH, but models need additional data to better determine its exact location through time (McGee et al., 2014). For internal consistency we assigned the curve according to the general delimitation by Hogg et al. (2013) and Hua et al. (2013), or used the preferred calibration curve by the authors for the creation of the chronology. Mayle et al. (2000) for example, explicitly explain why their site in the Bolivian Amazonia experiences NH influences. Finally, a total of 13 sites include post-bomb dating for which 5 different regional curves options exist (Hua et al., 2013). Post-bomb calibration curves were as used by original authors or assigned according to Hua et al. (2013).

Age model method: Depending on the number of available control points, two age-depth models were created per site. All age-depth relationships were reconstructed using the R-code CLAM version 2.2 (Blaauw, 2010; R Development Core Team, 2014), which is an R code for "classic age-modelling" (Blaauw and Heegaard, 2012). The simplest age model possible, namely the *linear interpolation* method, produces a straightforward interpolation. It connects individual control points with straight lines which is in most cases unrealistic as it assumes abrupt changes in sedimentation rates at the dated depth in the sediment core. The second age model method we used is the *smoothing spline*, with a default smoothing factor of 0.3. This interpolation method produces a curve between two points that is also influenced by more distant control points. This method provides a smoother outline of age model and is considered to produce a more realistic model of the sedimentation process compared to the linear interpolation method. However, smoothing spline can only be performed at sites that present 4 or more control points. Furthermore, age models were not run on cores that were problematic from the start. Examples are: cores where a hiatus/slump disrupts the age model in a way that no linear interpolation is possible; cores with many age reversals, when an older date lies above a younger date with limited dates collected; and cores with many radiocarbon dates nearly identical regardless of depth. The two newly produced models were evaluated, selecting the more appropriate one in accordance to the authors' description, with a general preference for the smoothing spline.

The sample depths were derived from either the raw dataset or from the specifications and figures in the original publication. In a few cases, neither were available, so a 10 cm sample interval was assigned. The sample age is obtained as the highest-probability age based on the distribution of estimated ages from 1000 Monte Carlo runs and the uncertainties are provided as 95 % confidence intervals.

2.4 Age model evaluation

We followed the age model evaluation proposed by Giesecke et al. (2012) to define the temporal quality and uncertainty of the chronologies. An uncertainty classification based on the assignation of semi-quantitative "stars" focuses on the density of control point. The classification is additive and samples are assigned to the lowest class (a single star) where the estimated sample age is within 2000 years of the nearest control point. Additive stars are given at 1000 and 500 year proximity to the nearest control point (Table 1). In addition to the three stars that characterize proximity to the nearest control point, an extra star is given to samples that are situated in a straight section of the sequence. The "straightness" star is given to a sample where, within the nearest four control points, the modelled sediment accumulation rate changes less than 20 %. Only sequences with at least four control points can obtain such an additional star. The evaluation is based on the position of the sample relative to the control points and is independent of the interpolation procedure. Therefore stars are assigned to both the linear interpolation and smooth spline output unless insufficient control points are available for the latter.

2.5 Time window assessment

Rapid climate change events occurred during the Dansgaard–Oescher (D–O) cycles spanning the last glacial cycle and during the Holocene. Changes in ocean currents and deep circulation probably play a major role in either triggering or amplifying rapid climate changes on the South American continent. The most dramatic rapid changes were initially observed in the mid to high latitude regions of the North Atlantic Ocean, and therefore much research during the 1990s on the links between ocean circulation and millennial-scale climate change was focused there (Anderson et al., 2013). Now recent studies, like at Lake Titicaca, Bolivia (Fritz et al., 2010) and Lake Fúquene, Colombia (Groot et al., 2011) show clear evidence of millennial climate variability of large-amplitude during Marine Isotope Stages (MISs) 4 to 2. It is important not only to identify those pollen records that extend back to specific events of interest, but also to assess the temporal quality and the sample resolution available. Therefore, we focused on the following time windows: MIS 5 (c. 130–70 kyr BP) thousand years (kyr BP), MIS 3 (c. 60–27 kyr BP), Heinrich event 1 (H1; c. 18–15 kyr BP), and the YD/Holocene transition (c. 12.86–11.65 kyr BP). We will discuss both the temporal resolution and control-point density (the star classification system) at these stages or events for a conclusive overview for paleoclimate reconstructions at millennial time-scale. All statistical calculations were done with the use of R (R Development Core Team, 2014).

3 Results

Chronological data in Central and South America

The number of available pollen records has increased considerably in the last 20 years (Flantua et al., 2015). During recent years, the number of ages used for stratigraphic age models has trended upwards; since 2010, the mean and median number of dates per published pollen site has been five and three, respectively (Flantua et al., 2015).

Here we enter in more detail on the available chronologies, describing the most commonly used control points for dating, age modelling and calibration methods.

3.1 Control points

Radiocarbon dates

The LAPD-ChronDB stores a total of 5116 dates of which the most common control points are radiocarbon dates. Radiocarbon (^{14}C) dating has been used to date pollen records for more than five decades now. The first dated records in South America came from the Orinoco delta of Venezuela (Muller, 1959), and from Colombia sites such as Ciudad Universitaria, Laguna de la América, and Páramo Palacio (Van der Hammen and González, 1960) and Laguna de Petenxil in Guatemala (Tsudaka, 1967). These first control points, and many that followed in the initial decades, were estimated by patiently counting beta particles (could take days to months of counting time), i.e. the product of decay of ^{14}C atoms. In the early stages of ^{14}C measurement, this technique required a minimal sample size of 0.5 g carbon (Povinec et al., 2009), while sample sizes differed greatly among materials (Bowman, 1990). In paleoecological research, this has always been a limiting factor as natural samples generally present a small ^{14}C/C ratio. As a consequence material to obtain a ^{14}C date sometimes originated from a wide depth interval of the sediment core. Sites like Cala Conto, Bolivia (Graf, 1992), Lago Mascardi-Gutierrez, Argentina (Markgraf, 1983) and several sites from the Venezuelan Tepuys (Rull, 1991) mention a sample thickness of 50 cm and more (i.e. spanning several centuries of sedimentation) to obtain one single ^{14}C control point. Even some recent sites at Trinidad and Tobago, namely Nariva Sand Hill West and Trough (Ramcharan, 2004) needed more than a meter of section for dating material. Therefore, conventional radiocarbon dating based on bulk samples of lake sediments is often a high risk undertaking as it can result in a substantial uncertainty and puzzling date estimates. (Vaughan et al., 1985) endured the consequences for Lake Petén:

29 ^{14}C measurements were rejected as meaningless due to various existing dating difficulties.

The great breakthrough came from the development of AMS dating in 1977 that consisted of direct counting of the ^{14}C atoms present in a sample (Bowman, 1990; Povinec et al., 2009). This technique reduced the requirements for sample size and therefore improved the accuracy of samples. Furthermore, the required counting time was reduced to minutes. It took some time for AMS dating to appear in Central and South America. It was not until the early 1990s that AMS dating was used in sites as Lake Miragoane, Haiti (Brenner and Binford, 1988), Laguna de Genovesa, Ecuador (Steinitz-Kannan et al., 1998) and Lake Quexil, Guatemala (Leyden et al., 1993). Ever since an increasing number of sites report AMS dates to support their chronologies with higher precision. Nevertheless, even in a recent record with AMS ages, authors have been struggling to compile a consistent age model due to low carbon content of the samples (Groot et al., 2014). The advantages of using ^{14}C as dating method, having broad applicability on many different sample materials and covering the most prevalent time range (50 kyr BP), surpasses other methods and therefore remains to be the most commonly applied scientific dating method.

Currently ca. 68 % of the geochronological dates in the LAPD fall within the last 10 kyr, 20 % during the 20–10 kyr BP and 4 % during the 30–20 kyr BP. A wide range of materials is used for dating: cellulose-containing materials (woods, seeds, achenes, plant remains, insect chitin; $n = 1732$); charcoal and charred material ($n = 191$); carbonates (shells and calcite; $n = 118$), collagen-containing materials (bones and coprolites; $n = 48$); bulk sediments from different materials ($n = 1074$).

Tephrochronology

The terminology *Tephrochronology* actually means use of tephra layers as isochrons (time-parallel marker beds) to connect and synchronize sequences and to transfer relative or numerical ages to them using stratigraphy and other tools (Lowe, 2011). The pro-

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cess of obtaining a numerical age or date for a tephra layer deposited after a volcanic eruption either directly or indirectly is called *Tephrochronometry* (Lowe, 2011). Primary minerals, such as zircon, K-feldspar and quartz, can be used to date tephras directly. Indirect methods include different applications such as radiometric dating (radiocarbon dating, fission-track dating, argon isotopes K/Ar, Ar/Ar, luminescence dating, *U* series, ^{238}U/^{238}Th zircon dating), and incremental dating (annually banded found in the layering of ice cores) (Lowe, 2011). This field of advanced chronology is of essential importance in the search for precise dates for high-resolution paleoenvironmental records and research (Davies et al., 2012). Tephrochronology has become increasingly popular across a range of disciplines in the Quaternary field (Lowe, 2011; Bronk Ramsey et al., 2015), especially for linking and synchronizing paleorecords accurately along longer timescales. Although not extensive, we provide here an overview of sediment cores that welcomed this technology for improved chronological purposes.

In Central and South America, there are regions of increased volcanic activities where frequent tephra layers can be found. Mexico's active seismic zones have numerous active volcanoes in the so-called "Mexico's Volcanic Axis" or "Trans-Mexican Volcanic Belt" (eje. *Volcánico Transversal*). Ortega-Guerrero and Newton (1998) collected tephra layers in southern Mexico specifically aimed to produce stratigraphic markers for palaeoenvironmental research. Tephra layers called Tlácuac, Tlapacoya and Toluco can be found in different pollen records such as Lake Texcoco (Lozano-García and Ortega-Guerrero, 1998) and Lake Chalco Lozano (Lozano-García et al., 1993). Additional tephra layers played an important role in the chronology of Lake Peten-Itza PI6, Guatemala (80 kyr BP; Hodell et al., 2008) and Laguna Llano del Espino and Laguna Verde, El Salvador (Dull, 2004a, b).

The northern Andes forms part of the "Northern Volcanic Zone" (Stern, 2004; Rodriguez-Vargas et al., 2005) and is shared by Colombia and Ecuador. In the Ruiz-Tolima region (Central Cordillera of Colombia), Herd (1982) identified 28 eruptive events during the last 14 000 years. Sites like Puente Largo and Llano Grande (Velásquez-R et al., 1999) make use in their chronologies of these events. Even sites along the Eastern Cordillera capture these volcanic ashes, like Funza (Andriessen et al., 1994; Torres et al., 2005) and El Abra (Kuhry et al., 1993), while the ridge itself lacks volcanic activities (Rodriguez-Vargas et al., 2005). Otoño-Manizales Enea (Cleef et al., 1995) reports 5 events between 44 and 28.5 kyr BP and Fúquene another 6 events between 30 and 21 kyr BP (Van Geel and Van der Hammen, 1973). Fission-track ages on sparse zircons were obtained for the long cores of Funza I, Rio Frío and Facatativá (Andriessen et al., 1994; Wijninga, 1996).

Ecuador is evenly well known for its very active volcanic region. Two eruptions of the Guagua Pichincha and one of the Quilotoa were seen at pollen site Papallacta (Ledru et al., 2013). Thanks to four radiometric ^{40}Ar–^{39}Ar dates from tephra deposits, the chronology of the Erazo pollen record was placed within the middle Pleistocene period (Cardenas et al., 2011). An important overview of tephrochronology in southern Ecuador was provided by Rodbell et al. (2002).

The central Andes forms part of the “Central Volcanic Zone” (Stern, 2004; Rodriguez-Vargas et al., 2005) and is shared by Peru and Bolivia. Several ice cores from the Sajama Ice Cap in Bolivia use ash layers from Volcán Huaynaputina in Peru as dating control (Reese, 2003). To support the chronology of the long core of Lake Titicaca, nine aragonite-rich layers for U/Th helped correlation with the last interglacial period, MIS5e (Fritz et al., 2007).

Finally, towards the south, the “Southern Volcanic Zone” covers Chile and Argentina (Stern, 2004). An overview of the Holocene tephrochronology of an important part of this volcanic zone is presented in Naranjo and Stern (2004). The Pleistocene-Holocene transition has shown similarity in timing with an increase in volcanic activity in southern Chile (Abarzúa and Moreno, 2008). Jara and Moreno (2014) assessed the potential of volcanic events as being a driver of vegetation changes at a (sub-) millennial timescale based on 30 tephra layers since 13.5 kyr BP. Other sites with tephras to support their chronology are at Puerto del Hambre in Chile (Clapperton et al., 1995) and Rio Rubens in Argentina (Markgraf and Huber, 2010), among others.

Other dating techniques

An exceptional dating method was used at Ciama 2 in Brazil, through Optically Stimulated Luminescence (OSL) encompassing the period between the MIS3 (unfortunately MIS5 ages were discharged) and the last millennium (de Oliveira et al., 2012). The same technique was used at the Potrok Aike lake in Patagonia. A 65 kyr-long sediment core was recovered by the Potrok Aike Maar Lake Sediment Archive Drilling Project (PASADO; Recasens et al., 2012), where they use a combination of OSL, tephra and ^{14}C to establish their chronology (Buylaert et al., 2013; Recasens et al., 2015). The pollen record from this multi-proxy study is to be published soon and will be an important comparison to other long cores from South America on Late Quaternary climate variability research.

There are two very important records that serve in South America as a key reference for regional chronology testing, which are Fúquene-9C (Groot et al., 2014) and MD03-2622 marine core from the Cariaco basin (González et al., 2008). Both cores were analysed at high resolution (Fq-9C: 60 yr; Cariaco: 350 yr) and cover 284–27 and 68–28 kyr BP, respectively. No recalibrated age model or star classification was produced as both sites implement different kinds of age models, namely frequency analyses of arboreal pollen % and orbital tuning (Fq-9C) and tuning to reflectance curve of another marine core (Cariaco, which itself has been tuned to Hulu Cave in China). Therefore the longest cores considered in this study are from Titicaca: LT01-2B and LT01-3A (Hanselman et al., 2005, 2011; Fritz et al., 2007; Gosling et al., 2008, 2009).

Seismic activities

In some cases, significant seismic events can be observed synchronously in various pollen records. For example, over a large area in the Chocó Biogeographic region, synchronous gaps in records were probably caused by a floodplain subsidence of a delta in the Colombian Pacific region (Berrío et al., 2000; González and Correa, 2001; Urrego Giraldo and del Valle, 2002; Urrego et al., 2006). These events of high seismic activities can provide additional support for pinpointing chronologies when recorded as analogues events in different records.

3.2 Reporting of ^{14}C measurements and corrections

Through the years the radiocarbon community has presented a series of papers indicating the proper way of reporting ^{14}C data (Stuiver and Polach, 1977; Mook and Van der Plicht, 1999; Reimer et al., 2004a). In the early days, the world's laboratories reported all of their produced radiocarbon dates in the journal *Radiocarbon*, a journal then dedicated to compile these overviews. Probably the earliest radiocarbon dates from Central and South America can be found in Vogel and Lerman (1969) describing in detail dates produced from Cuba, Jamaica, Colombia, Guyana, Surinam, Peru and Argentina. However, this system could not keep up with the increasing number of both laboratories and studies reporting radiocarbon dates. Since then the correct reporting of ^{14}C dates relied completely on the experience and willingness of the researchers.

Measured radiocarbon concentrations require an additional correction due to mass fractionation of ^{14}C atoms during natural bio-geochemical processes and sample preparation and measurement. This is a δ^{13}C based correction which has a default value of −25 ‰ based on wood (Stuiver and Polach, 1977). In the LAPD-ChronDB there are 1283 reported ^{14}C with fractionation correction ranging from −42 to 30.2 ‰. This number represents a quarter of the total number of radiocarbon dates in the database, meaning that over 600 studies neglect to report this fractionation correction at all.

Studies specifying additional corrections such as the possible reservoir age are rare. Although organic material potentially presents this ^{14}C offset, it is rarely identified in terrestrial pollen records of the LAPD. For the marine reservoir correction, the marine calibration curves incorporate a global ocean reservoir correction of ca. 400 yr. Nevertheless, regional differences in reservoir values should be applied according to the Marine Calibration dataset (http://www.calib.qub.ac.uk/marine). Some marine studies in the LAPD implemented a fixed reservoir effect of 400 yr (according to Bard, 1988) for marine dates, while others only mentioned the used version of the CALIB program.

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A handful of marine cores in Chile (MD07-3104; MD07-3107; MD07-3088) estimate different local reservoir ages on calibrated ages from the IntCal calibration curve.

While Stuiver and Polach (1977) were the first to establish the conventions for reporting radiocarbon data, Reimer et al. (2004b) dealt with the growing use of postbomb ^{14}C and a corresponding new symbol in ^{14}C reporting. Correct postbomb ^{14}C reporting is problematic in the LAPD. Negative ^{14}C ages are treated highly variably, from being totally discharged, titled "modern" or "too young" without specified ^{14}C value, or considered valid as the subtracted age from 1950 AD (resulting in any age estimate between 2014 and 1950). Also postbomb dates as percentage modern carbon values (% pMC, normalized to 100 %) or "fraction of modern" (F14C, normalized to 1) sometimes mislead uninformed authors to be acceptable ^{14}C. At this moment, only one pollen record is known to report the F14C value with the corresponding post-bomb curve as proposed by Reimer et al. (2004b), namely Quistococha in Peru (Roucoux et al., 2013). Laboratory sample or identification number (ID), which are given to the samples by the radiocarbon dating laboratory, enable the laboratory to be identified and should always be published alongside the ^{14}C measurements. This is the case for most recent chronologies although the lack of laboratory ID sometimes seems to depend more on the authors than on the year of publication.

3.3 Calibration curves and software

The relatively recent development of freely available computing packages has a consequence that there is a large bulk in the LAPD-ChronDB without any age model ($n = 457$), where most radiocarbon dates are simply plotted along the pollen record. The most common age model ($n = 298$) is based on the simplest design, namely the linear interpolation between the dated levels even though this is hardly a realistic reflection of the occurred sedimentation history (Bennett, 1994; Blaauw and Heegaard, 2012). Polynomial regression methods ($n = 31$) and the smooth spline ($n = 12$) are becoming increasingly popular but mostly in international peer-reviewed journals compared to national publications. In the latter linear interpolation is more persistent. In 6 cases, age models and calibrated ages were created by the authors without further explanation. In a significant number of cases, age-depth modelling was performed with uncalibrated ^{14}C ages, which does not produce valid results due to the non-linear relationship between radiocarbon years and calendar years.

Statistical approaches to chronological modelling have expanded dramatically over the last two decades. Advances in computer processing power and methodology have now enabled Bayesian age models which require millions of data calculations – a method which would not have been possible before. The development of such freely available Bayesian statistical computing packages as “OxCal” (Bronk Ramsey, 1995), “BCal” (Buck et al., 1999), “BPeat” (Blaauw and Christen, 2005) and “Bacon” (Blaauw and Christen, 2011) has greatly advanced the science. To our knowledge, however, so far there has been only a single application of Bayesian methods for age modelling in South America, namely at Papallacta 1-08 (Ledru et al., 2013). The authors included a priori information on sedimentation rates and tephra-layers to construct the age model and consequently derive the best age for an uncertain tephra deposition.

The previous situation of complementing calibration curves has led to finding pollen records from the same region using curves from either side of the hemisphere. This is seen in the highland of Peru and Bolivia where the boundary between the IntCal13 (NH-curve) and SHCal13 (SH-curve) realms is still unclear and even causing the use of different calibration curves for the same lake. Several Bolivian lowland studies explain the influence of the southern range of the ITZC migration and therefore justify the use of the northern calibration curve (Mayle et al., 2000; Maezumi et al., 2015, this issue). Nevertheless, this is a temporal uncertainty that has to be taken into account and the choice of calibration curve should be addressed in the publications.

3.4 Age model evaluation of northwest South America (NW–SA)

From a total of 292 pollen records revised, 242 preliminary age models were regenerated based on the provided radiocarbon dates. The other 50 pollen records either presented a lack of multiple geochronological dates or too many chronological problems.

During the process of adjustments of the age models for hiatus, outliers, and slumps, another 9 pollen records were rejected as no reliable models could be produced. In 125 cases both linear interpolation and spline could be implemented, requiring at least 4 valid geochronological dates for the latter. The star system classification did not assign stars to 4 chronologies, when the calibrated ages overlapped over a very short time range creating conflicts within the star calculation function. The median number of stars for recalibrated chronologies of NW–SA is 3, which we consider surprisingly high.

3.5 Temporal resolution of NW–SA

Based on the 233 checked and recalibrated age models from NW–SA (see Table S1 in the Supplement), the sample resolution (maximum, minimum, median and mean value) was estimated per pollen site and for the entire NW–SA. The resolution was calculated as the time between two consecutive depths with proxy information (sample depths). Minimum values range from 10 yr to 1 kyr, compared to the maximum value between 5 and 36 kyr (mostly due to extrapolations). The overall sample resolution estimates indicate that the temporal resolution of this multi-site synthesis is ca. 240 yr, a resolution that allows analyses of ecological responses to sub-millennial-scale climate change. From a synoptic perspective, the NW–SA pollen records do not show spatial clustering based on the assigned stars (Fig. 2a). In other words, good and poor point density chronologies can be found along all the different elevational and latitudinal ranges. The best context to the star classification system can be given in conjunction with the sample resolution estimates as chronologies might present high sample resolution but poor chronological backup, and vice versa. What is evident as a result of the recalibrated age models is the high number of pollen records within the 0–500 yr resolution with relatively high temporal quality (Fig. 2b).

3.6 Time window evaluation

MIS 5 (130–70 kyr BP): Within this study, this time window is represented by only 5 pollen records, namely from lake Titicaca LT01-2B and LT01-3A (Hanselman et al., 2005, 2011; Fritz et al., 2007; Gosling et al., 2008, 2009), Fúquene 3 and 7 (Mommersteeg, 1998; Van der Hammen and Hooghiemstra, 2003; Vélez et al., 2003; Bogotá-A et al., 2011), and El Abra (Schreve-Brinkman, 1978). As previously mentioned, there are additional longer cores but with different chronology techniques we did not consider. Research into millennial-scale climate variability is very difficult during this time window, as sample resolution varies greatly from a few centuries to several thousands of years. For periods older than 65 kyr BP, mean resolution shifts around 2000 yr per sample with a star classification of mostly 0–1. Temporal uncertainty is high due to extrapolation of age models through limited number of control points and additional hiatus difficulties.

MIS 3 (60–27 kyr BP): MIS 3 is better represented in samples (Fig. 3a) and sites (Fig. 3b), and shows a wider variation in the star classification. The median number of 1 star still indicates a relatively poor control point density in the chronologies and therefore high temporal uncertainty. This time window is characterized by relatively older sites with reduced chronological quality even though overall resolution is at centennial timescale (430 yr).

LGM, H1 and YD/Holocene transition: The vast majority of chronologies cover the Holocene and Lateglacial time intervals because they have been established from lakes formed after the last glaciation. Consistent with the large number of pollen records that fall within the Holocene (Flantua et al., 2015), the highest density of palynological sampling covers the last 10 kyr (Fig. 3c). Most samples fall within the category of presenting “good” control point density, namely either 3 or 4, just as the individual sites evaluated (Fig. 3d). There is an overall good point density in the NW–SA sites that cover the YD/Holocene transition but the Last Glacial Maximum (LGM) and H1 are represented by far fewer records with varying temporal quality.

The integration of the recalibrated chronologies and the estimated sample resolutions indicate the essential value of the existing radiocarbon calibration curves: there is a clear threshold at ca. 55 kyr BP (beyond – the extent of the current ^{14}C calibration curves) from where the control point density and resolution currently do not support millennial timescale research, as sample resolutions are on average 1300 yr and temporal uncertainty high (Fig. 4).

4 Discussion

4.1 Chronological data reporting in Central and South America

The relevance of publishing details on the sample, laboratory and reference numbers, provenance and reservoir correction details seems heavily underestimated by authors in many cases. Studies with insufficient chronology reporting undermine the consistency and credibility of the results presented, let alone weaken the value of the radiocarbon dates. Furthermore, considering the expanding palynological research in Central and South America (Flantua et al., 2015), papers with deviations in chronology reporting will most likely not be used within the context of multi-proxy comparisons or more expanded regional synthesis efforts. Additionally, paleo-vegetation records with proper chronology details are frequently scanned by the archaeological community to correlate human and environmental dynamics (Aceituno et al., 2013; Delgado et al., 2015). Equally relevant are paleoecological records with solid chronologies for late Pleistocene understanding of megafaunal extinctions (Barnosky et al., 2004). Missing out on the chronology description is without a doubt an unnecessary way to affect the credibility and citation rate of any study. A top-down approach to improve radiocarbon reporting initiates at the journals demanding complete and correct chronology information. Not less important are the reviewers in evaluating critically the presented age models. Sources to remain updated on the requirements of dating reporting are numerous (e.g. see Millard, 2014), but specific details can be online accessed through http://www.c14dating.com/publication.html. Additional recommendations can be found in Blaauw and Heegaard (2012) and from the "Neotoma Age models, chronologies, and databases workshop" in Grimm et al. (2014).

4.2 Temporal uncertainty assessment of chronologies

The importance of high-resolution records but especially temporal quality has been illustrated through the development of updated age models and control point density assessment. Compared to the implementation of the method in the EPD (Giesecke et al., 2012), there is a higher portion of samples and sites in the last 5 kyr in NW–SA. The normal range of sample resolution in the EPD is between 50 and 250 years, while the NW–SA has a mean resolution of 235 years. This resolution is actually higher than we expected and could be due to several reasons. First of all, during the age models procedure, chronologies with too many disturbing features were not used, implementing a first selection towards the best possible age models. Secondly, to assign 10 cm sample intervals for older pollen to unknown sample depths could be an overestimation for sample resolution. Thirdly, there are several very high resolution sites that cover significant time periods overpassing greatly in sample numbers the sites with relatively low temporal resolution. Nonetheless, the general tendency is that pollen records in NW–SA are improving chronological settings with high sample resolution on centennial timescale.

Combining prior information from the sequences with the geochronological data is the basis of a Bayesian approach to construct an age-depth model (Blaauw and Heegaard, 2012). The current lack of Bayesian based age models in Central and South America could be due to classic age-depth models (based on linear interpolation, smooth splines or polynomial regressions) being regarded as the most realistic models, or to the usefulness of Bayesian methods not yet having been explored. Each model comes inherent with errors and uncertainties, and each method consists of different approaches to address them. Linear interpolation for example provides reasonable estimates for ages and the gradients between adjacent pairs of points, but only includes the errors at the individual age-determinations and does not consider uncertainties and additional measurements (Blaauw and Heegaard, 2012). A wider range of possible errors can be included in “mixed-effect models”, while Bayesian age-depth modelling produces more realistic estimates of ages and uncertainties. The latter approach additionally supports the decision making process in labelling outliers through “outlier probability” and corresponding “age-model fit” measurements (Blaauw and Christen, 2005). Researchers should make use of the freely available character of the Bayesian software packages to test multiple age-depth models, compare models that best approximate their knowledge of the sediment conditions, and address these comparisons in their studies.

Until now, differences in resolution and chronological quality between older and newer sites have hampered the ongoing discussion on the rapid climatic shifts such as the YD. A synchronous similar climate reversal at the YD is not evident throughout South-America. Differences in magnitude has been observed between Venezuela and Colombia (Rull et al., 2010), while pollen records at relatively close distances in Peru/Bolivia are considered both different in timing and expression (Hansen, 1995; Paduano et al., 2003; Bush et al., 2005). This points again to the danger of using assumed synchronous events to align archives across a region, e.g., Israde-Alcántara et al. (2012a) who align several poorly dated sites in Latin America to circularly argue for a YD comet impact (Blaauw et al., 2012; Israde-Alcántara et al., 2012b). New studies on correlating biostratigraphic patterns with improved chronology are important as they can identify possible long-distance synchronicity of climate signals, but at the same time display their own local signature when supported by high resolution data. Therefore, additional well-dated records have a high potential of contributing to this current discussion (e.g. Rull et al., 2010; Montoya et al., 2011). However, advanced tools to assess leads, lags and synchronicities in palaeorecords are still urgently needed (Blockley et al., 2012; Seddon et al., 2014) while only few case studies have yet explored the available tools (Blaauw et al., 2007, 2010). So long the discussion consists of correlating poorly dated events, new hypotheses based on assumed synchronous events fail to provide additional insights to current questions.

5 Conclusions and recommendations

This paper presents an overview on chronological dating and reporting in Central and South America based on a new LAPD-Geochronological Database consisting of 5116 dates from 1097 pollen records. To support centennial-millennial timescale climate research, the temporal resolution and quality of chronologies from 292 pollen records in the northwest South America were assessed based on the method proposed by Giesecke et al. (2012). This method includes associated evaluations of uncertainties for the inferred sample ages and age models, and is suitable for a wide range of paleoproxies. Over 300 publications were evaluated and new age models were constructed based on new calibration curves implementing either linear interpolation or (preferentially) smoothing splines. Using the R-code CLAM these newly derived chronologies formed the basis to estimate the sample error from the uncertainties of control points density in the age model. These sample-age confidences are assigned so-called “stars” and this semi-quantitative star classification system is discussed for different time windows such as MIS7, MIS5, the LGM and the YD. Based on these classifications, uncertainties and age control requirement are discussed for millennium-scale climate variability research. This provides a general-purpose chronology fit for most continental-scale questions and multi-proxy comparisons of temporal uncertainties. Finally we address specific fields of improvements for chronological reporting in Central and South America pollen records.

Recommendations in practice, approaches or techniques

It is important for authors to report at the necessary detail the chronology of their sediment core because it is the spinal core of the interpretation. Furthermore, due to the spatial coverage of the LAPD, for the increasing number of questions requiring multi-proxy comparison, sites can be selected based on their considered usefulness for models. There is a lose-lose situation by not including potentially important sites just because the chronology is insufficiently presented in the paper. The number of recent sites that present incomplete descriptions of their presumed age model is striking, leaving out information such as depths, calibration method, and even only presenting calibrated dates without further explanation.

The discussion on detecting synchronicity of rapid climate change events should pass from correlating chronologies with incompatible resolution and temporal quality, to understanding the causes of leads and lags between geographically different localities with high chronological settings. Future studies on detecting rapid climate changes in a multi-site and multi-proxy context can be supported in their site selection procedure by the method in Giesecke et al. (2012). The method here implemented is fully suitable for other regions and proxies that deal with geochronological dating. As the LAPD-ChronDB currently covers a much larger area of the continent, similar exercises can be done for other regions for comparison purposes.

The vast number of sites reflecting the last 10 kyr with high samples densities and well-presented chronologies offer great opportunities for current running working groups, like *International Biosphere Geosphere Programme/Past Global Change – 6k* (IGBP-Pages 6k, www.pages-igbp.org/workinggroups/landcover6k/intro) and *Long-Term climate REconstruction and Dynamics of South America – 2k* (LOTRED-SA-2k; www.pages-igbp.org/workinggroups/lotred-sa/intro). Both multi-proxy working groups address human–environmental interactions in which pollen records in Central and South America are a vital source of information (Flantua et al., 2015).

The produced chronologies in this paper do not substitute the validity and interpretation of the authors' original chronology, but serve the purpose to present an overview of the current potential temporal resolution and quality, and contribute to the discussion on age model assessments. Users should always check the original papers and address questions on the chronologies to the main authors. At the same time, calibration curves as well as age-modelling methods will continue to be updated, so age models should rather be considered as inherent to a dynamic process of continuous improvement, rather than a static side component of a paleoecological record. For that purpose, we would like to emphasize that there are increasingly more resources available for providing Digital Object Identification (DOI) to stand-along datasets, figures and variable media to obtain the rights to be cited as any other literature reference (e.g. Fig. Share: http://figshare.com; Data Dryad: http://datadryad.org/). Authors considering an updated version of an age model could evaluate these resources, as well as for unpublished pollen datasets.

The LAPD database and corresponding metadata of the pollen records will soon come available through the Neotoma Paleoecology Database (http://neotomadb.org) as well as the LAPD literature database.

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Table 1. Classification of sample age uncertainty.

Maximum distance to the nearest data (yrs)	Stars
2000	1
1000	2
500	3
Straight segment	+1

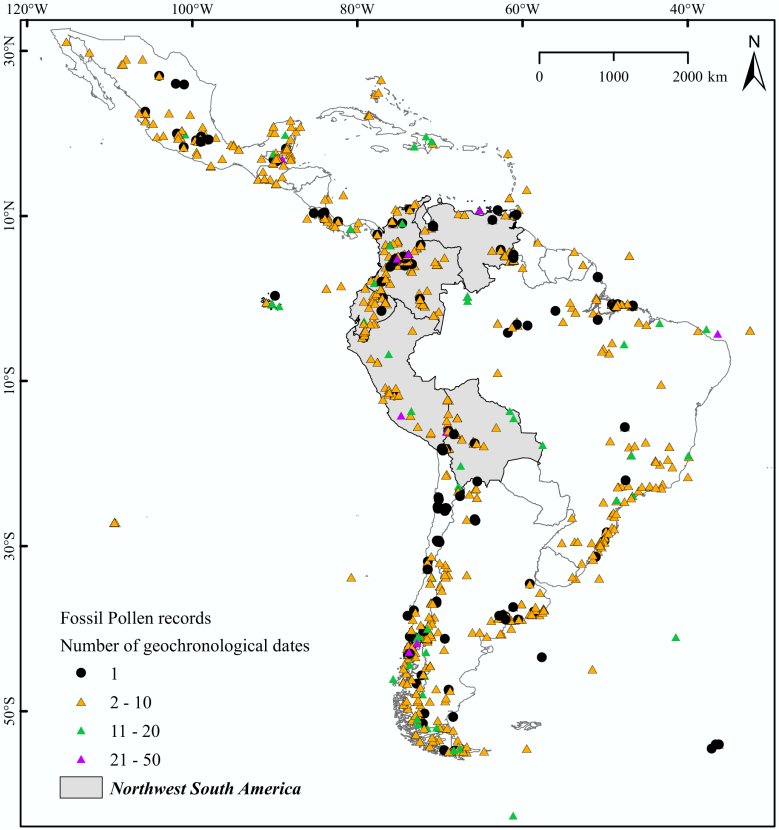

Figure 1. Pollen records currently present in the LAPD Geochronological database: all records contain at least one geochronological date.

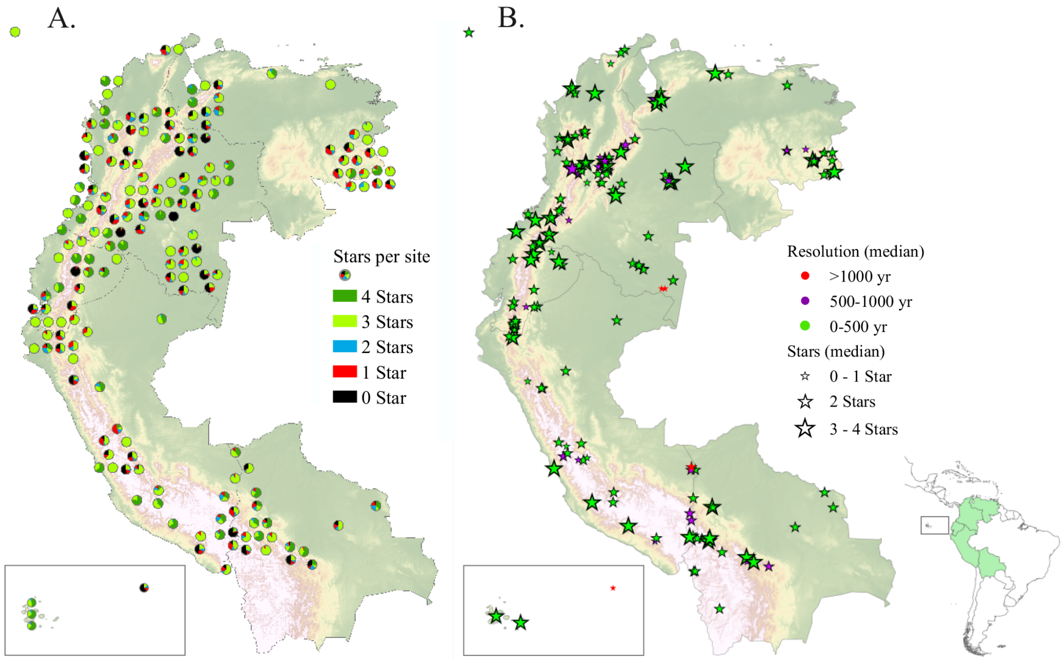

Figure 2. Temporal uncertainty assessment on recalibrated control points and age models in the NW–SA. **(a)** Number of stars assigned to samples of recalibrated chronologies (normalized to 100 %). **(b)** Median value of stars and resolution of the recalibrated chronologies. The small window displays the region of the Galapagos Islands and the marine core ODP677.

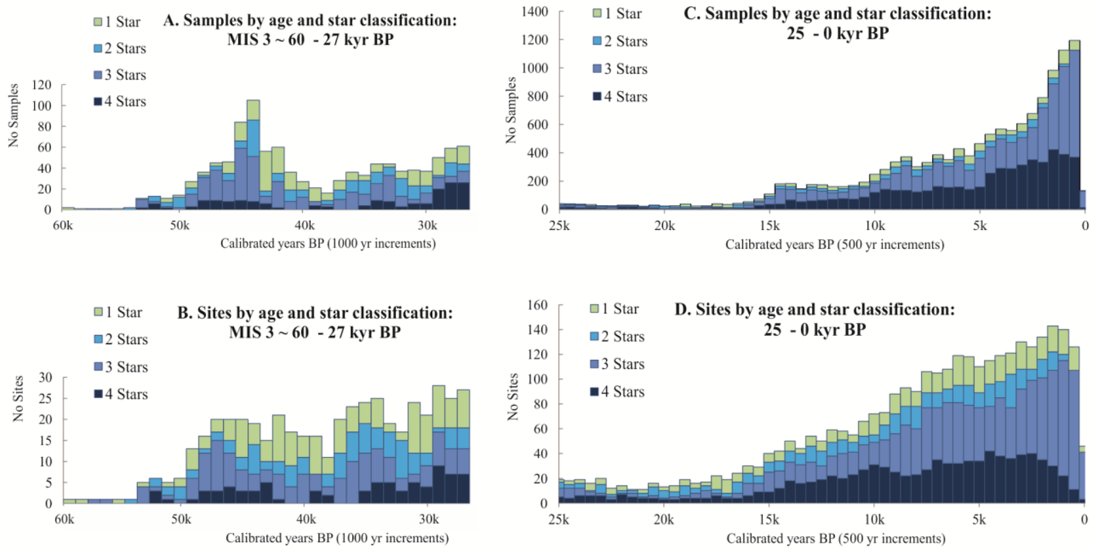

Figure 3. Histograms depicting during the MIS 3 and in 1000 year increments the distribution of samples **(a)** and sites **(b)** with their corresponding star classification. Similarly, the histograms **(c, d)** depict the samples and sites and their corresponding star classification over the last 25 kyr in 500 year increments. The different colours illustrate the number of samples or samples in core segments that were classified with 3 and 4 stars and that indicate good control-point density for most samples.

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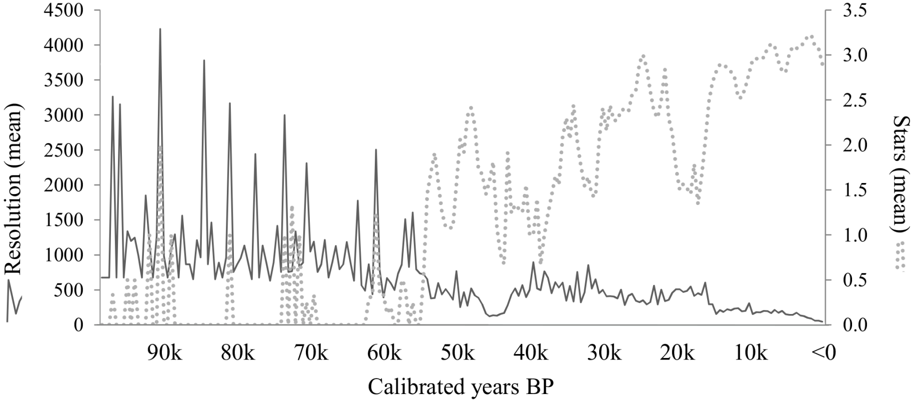

Figure 4. Changing mean sample resolution (left) and mean number of stars (right) of the pollen database of northwest South America during the period 100 kyr to −50 yr BP.