The ACER pollen and charcoal database: a global resource to document vegetation and fire response to abrupt climate changes during the last glacial period

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

The ACER pollen and charcoal database: a global resource to document vegetation and fire response to abrupt climate changes during the last glacial period

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Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

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Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
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Discussion started: 28 February 2017

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Abstract

Quaternary records provide an opportunity to examine the nature of the vegetation and fire responses to rapid past climate changes comparable in velocity and magnitude to those expected in the 21st century. The best documented examples of rapid climate change in the past are the warming events associated with the Dansgaard-Oeschger (D-O) cycles during the last glacial period, which were sufficiently large to have had a potential feedback through changes in albedo and greenhouse gas emissions on climate. Previous reconstructions of vegetation and fire changes during the D-O cycles used independently constructed age models, making it difficult to compare the changes between different sites and regions. Here we present the ACER (Abrupt Climate Changes and Environmental Responses) global database which includes 93 pollen records from the last glacial period (73-15 ka) with a temporal resolution better than 1,000 years, 32 of which also provide charcoal records. A harmonized and consistent chronology based on radiometric dating (^{14}C, $^{234}U/^{230}Th$, OSL, $^{40}Ar/^{39}Ar$ dated tephra layers) has been constructed for 86 of these records, although in some cases additional information was derived using common control points based on event stratigraphy. The ACER database compiles metadata including geospatial and dating information, pollen and charcoal counts and pollen percentages of the characteristic biomes, and is archived in *Microsoft Access*™ at https://doi.org/10.1594/PANGAEA.870867.

1. Introduction

There is considerable concern that the velocity of projected 21st century climate change is too fast to allow terrestrial organisms to migrate to climatically suitable locations for their survival (*Loarie et al., 2009; Burrows et al., 2011; Ordonez et al., 2013; Burrows et al., 2014*). The expected magnitude and velocity of 21st century climate warming is comparable to abrupt climate changes depicted in the geologic records, specifically the extremely rapid warming that occurred multiple times during the last glacial period (Marine Isotope Stages 4 through 2, MIS 4-MIS2, 73,500–14,700 calendar years, 73.5–14.7 ka). The estimated increases in Greenland atmospheric temperature were 5–16°C [*Capron et al.*, 2010] and the duration of the warming events between 10 to 200 years [*Steffensen et al.*, 2008]. These events are a component of longer-term millennial-scale climatic variability, a pervasive feature through the Pleistocene [*Weirauch et al.*, 2008] which were originally identified from Greenland ice archives [*Dansgaard et al.*, 1984] and in North Atlantic Ocean records [*Bond and Lotti*, 1995; *Heinrich*, 1988] and termed Dansgaard-Oeschger (D-O) cycles and Heinrich events (HE) respectively.

D-O events are registered worldwide, although the response to D-O warming events is diverse and regionally specific (see e.g. [*Fletcher et al.*, 2010; *Harrison and Sanchez Goñi*, 2010; *Sanchez Goñi et al.*, 2008]) and not a linear response to either the magnitude or the duration of the climate change in Greenland. Given that the magnitude, length and regional expression of the component phases of each of the D-O cycles varies [*Johnsen et al.*, 1992; *Sanchez Goñi et al.*, 2008], they provide a suite of case studies that can be used to investigate the impact of abrupt climate change on terrestrial ecosystems.

The ACER (Abrupt Climate change and Environmental Responses) project was launched in 2008 with the aim of creating a global database of pollen and charcoal records from the last glacial (73 - 15 ka, kyr cal BP) which would allow us to reconstruct the regional vegetation and fire changes in response to glacial millennial-scale variability, and evaluate the simulated regional climates

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

resulting from freshwater changes under glacial conditions. Although there are 232 pollen records covering the last glacial period worldwide, only 93 have sufficient resolution and dating control to show millennial-scale variability [*Harrison and Sanchez Goñi*, 2010]. It was necessary to re-evaluate and harmonize the chronologies of these individual records to be able to compare patterns of change from different regions. In this paper, we present the ACER pollen and charcoal database, including the methodology used for chronological harmonization and explore the potential of this dataset by comparing two harmonized pollen sequences with other palaeoclimatic records. Such a comparison illustrates the novel opportunities for the spatial analyses of global climate events using this research tool.

2. Data and methods

2.1. Compilation of the records

The ACER pollen and charcoal database includes records covering part or all of the last glacial period and with a sampling resolution better than 1,000 years. These records were collected as raw data, through direct contact with researchers or from the freely available European and African Pollen Databases. Four records were digitized from publications using the Grapher™ 12 (Golden Software, LLC) because the original data were either lost (Kalaloch: [*Heusser*, 1972] and Tagua Tagua [*Heusser*, 1990]) or are not publicly available (Lac du Bouchet [*Reille et al.*, 1998] and Les Echets [*de Beaulieu and Reille*, 1984]). These digitized records are available as pollen percentages rather than raw counts. All the records are listed and described in Table S1 (supplementary material).

2.2. Harmonization of database chronologies

The chronology of each of the records was originally built as a separate entity. In order to produce harmonized chronologies for the ACER database, decisions had to be made about the types of dates to use, the reference age for modern, the choice of calibration curve, the treatment of radiocarbon age reservoirs, and the software used for age-model construction.

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
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Discussion started: 28 February 2017

Radiometric ages (^{14}C, $^{235}U/^{230}Th$, OSL, $^{40}Ar/^{39}Ar$) and radiometrically-dated tephras are given preference in the construction of the age models. The tephra ages were obtained either through direct $^{40}Ar/^{39}Ar$ dating of the tephra or ^{14}C dating of adjacent organic material (Table 1). When a radiometric or tephra date was obtained on a unit of sediment, the depth of the mid-point of this unit was used for the date in the age modelling. Both the age estimate and the associated errors (standard deviation) are required for age-model construction. When the positive and negative standard deviations were different, the larger value was used for age-model construction. In cases where the error measurements on the radiometric dates were unknown (e.g. site F2-92-P29), no attempt was made to construct a harmonized age model.

Measured ^{14}C ages were transformed to calendar ages, to account for the variations in the atmospheric $^{14}C/^{12}C$ ratio through time. Radiocarbon ages from marine sequences were corrected before calibration to account for the reservoir effect whereby dates have old ages because of the delay in exchange rates between atmospheric CO_2 and ocean bicarbonate and the mixing of young surface waters with upwelled old deep waters. We used the IntCal13 and Marine13 calibration curves for terrestrial and marine ^{14}C dates, respectively [*Reimer et al.*, 2013], which are the calibration curves approved by the radiocarbon community [*Hajdas*, 2014]. Although studies have shown that the radiocarbon ages of tree rings from the Southern Hemisphere (SH) are ca 40 yr older than Northern Hemisphere (NH) trees formed at the same time [*Hogg et al.*, 2013], this difference is smaller than the laboratory errors on most of the ^{14}C dates and, since the Marine13 calibration curve does not distinguish between SH and NH sites, we use the NH IntCal13 calibration curve for all the records.

The Marine13 calibration curve includes a default 400 yr reservoir correction. We adjusted this correction factor for all the twenty six marine records included in the database using the regional marine reservoir age (ΔR) in the Marine Reservoir Correction Database (http://calib.qub.ac.uk/marine/). For twenty marine records, the correction factor was based on a maximum of the 20 closest sites within 1,000 km to a specific site; for the remaining 6 marine

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

records this factor was based on a maximum of the 20 closest sites within 3,000 km. When ΔRs were homogeneous, a value ± 100 years, over this area we used the mean of the 10 sites within 100 km to provide a reservoir correction for the site. When there was heterogeneity in ΔR values within the 3,000 km target area, we selected only the sites with homogeneous ΔR within 100-200 km. Temporal variations of ΔR were not taken into account since they are currently not well established for many locations.

For periods beyond the limit of ^{14}C dating (~45 ka) and for the few records without radiometric dating, additional chronological control points were obtained based on "event stratigraphy", specifically the identification of D-O warming events and Marine Isotope Stage (MIS) boundaries (Table 1). No assumption was made that core tops were modern for both marine and terrestrial cores. The ages of D-O warming events and those of the MIS boundaries were based on the stratigraphy of core MD95-2042, southern Iberian margin (Table 1). The similarity of the planktonic foraminifera $\delta^{18}O$ record from MD95-2042 to the $\delta^{18}O$ record from Greenland allowed to match ages of individual D-O cycles, while the benthic foraminifera $\delta^{18}O$ record from MD95-204 allowed to match ages of MIS boundaries [*Shackleton et al.*, 2000]. Both D-O and MIS ages were directly transferred to the MD95-2042 pollen record. The chronology of this pollen record was in turn transferred to the other European pollen records assuming synchronous afforestation during D-O warming. The uncertainties for the event-based ages up to D-O 17 are from data summarized in *Wolff et al.* [2010] and from AICC_2012 in NGRIP ice standard deviation [*Bazin et al.*, 2013] for older events.

Non-radiocarbon dates are presented in the same BP notation as radiocarbon determinations. The modern reference date is taken as 1950 AD, since this is the reference date for the GICC05 chronology [*Wolff et al.*, 2010]).

Bayesian age modeling (e.g. using OxCAL, Bchron or BACON) requires information about accumulation rates and other informative user-defined priors [*Blaauw and Christen*, 2011] that is difficult to obtain for the relatively long ACER records. Moreover, BACON and Bchron [*Haslett and*

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

Parnell, 2008*, Parnell et al.,* 2008] do not handle sudden shifts in accumulation rate very well, and such shifts are not uncommon across deglaciation and stadial time periods. We therefore use the classical age-modeling approach in the CLAM software [*Blaauw*, 2010], implemented in R (R version 3.3.1) [*R Development Core Team*, 2016], to construct the age model.

Several age models were built for each record using the calibrated distribution of the radiometric dates: a) linear interpolation between dated levels; b) linear or higher order polynomial regression; and c) cubic, smoothed or locally weighted splines (Table S2). Linear interpolation is generally the most parsimonious solution for records with no age reversals. However, if any of the regression or spline models provided a better fit to the calibrated age range of outliers from a linear model, we selected the model that included most of the outliers. If none of the regression or spline model provided a better fit, we used linear interpolation after excluding the outliers. The database includes information on the single 'best' age-model and the 95% confidence interval estimated from the 10,000 iterated age-depth models (weighted mean) for every sample depth.

2.3 The Structure of the Database

The ACER pollen and charcoal data set is archived in a *Microsoft Access*™ relational database. There are six main tables (Fig. 1).

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

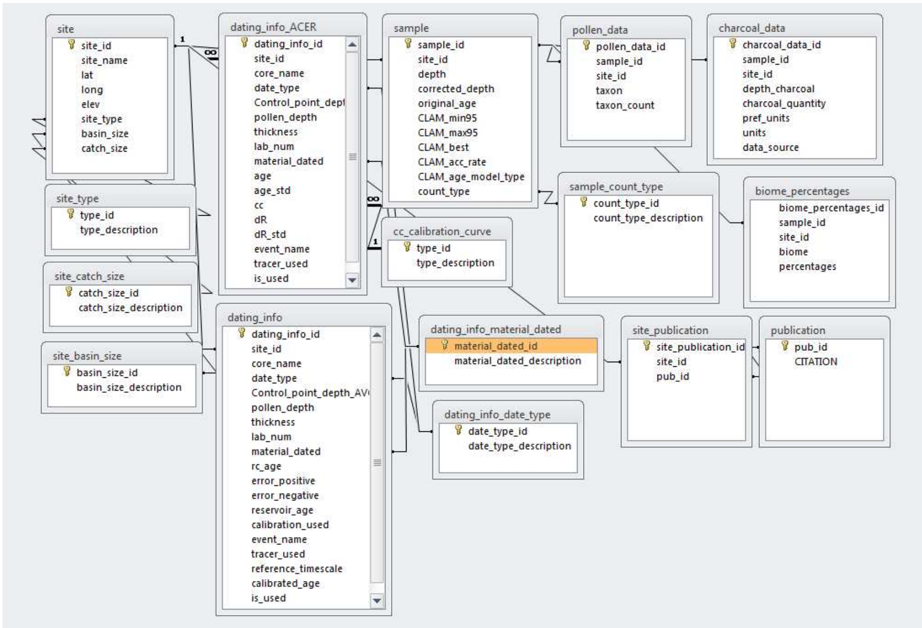


Figure 1 – ACER database structure in ACCESS format.

(1) Site Metadata. This table includes the original site name, geographical coordinates (latitude and longitude in decimal degrees, elevation in meters above or below sea level) and additional meta-data including site type (marine or terrestrial), basin size, catchment size. Basin size and catchment size determine the size of the area sampled by the record (or pollen source area: see Prentice, 1988), but are not always recorded in the original publication or known very accurately. A categorical classification (small, medium, large, very large) is recorded in the database where these categories are specified by ranges in km^2. The details of the original publication of the data are also given in this table.

(2) Sample data. The table records the identification number of each sample (sample id) at each site (site id) and provides the depth of the sample (in cm from the surface). In only one site, core MD04-2845, a corrected depth is provided on which the new age model is based. The pollen count type (raw pollen count, pollen percentages given by the authors, or digitized percentage) is also given. The original age of the sample according to the published age model when available and the

age determined from the best CLAM model (the min and the max at 95%, the accumulation rate and the type of model used to obtain this age) are given.

(3) Pollen data. The pollen data are recorded as raw counts or as the pollen percentage of each pollen and spore morphotype identified. The table records the identification number of each sample (sample id), the taxon name and count/percentage. Although the taxon names were standardized with respect to the use of terms such as type and to remove obvious spelling mistakes, no attempt was made to ensure that the names are taxonomically correct.

(4) Charcoal data. The table records the identification number of each sample (sample id). The charcoal data are recorded by depth (in cm from the surface), and information is given on the quantity and unit of measurement, and data source. Charcoal abundance is quantified using a number of different metrics, given for the majority in concentrations and for few of them in percentages.

(5) Original dating information. This table contains information on dating for each core at each site. The core name from the original publication is given, and the table provides information on date type (conventional ^{14}C, AMS ^{14}C, $^{234}U/^{230}Th$, OSL, $^{40}Ar/^{39}Ar$, annual laminations, event stratigraphy, TL), the average depth assigned to the data in the age-model construction, the dating sample thickness, laboratory identification number, material dated (bulk, charcoal, foraminifera, pollen, tephra, wood), measured radiometric age and associated errors. The marine reservoir age (and associated error) and the radiocarbon calibration curve used in the construction of the original age model, and the original calibrated age, are also given. Dates that are based on recognized events are also listed, and identified by the name of the event (event name) and the type of record in which it is detected (tracer used). The column “is_used” corresponds to the dates used by the authors for building the original age models.

(6) ACER dating information. The ACER dating information table duplicates the original dating information file, except that it provides information about the explicit corrections and the harmonized control points used to produce the ACER age models (Table 1). Specifically, it gives the

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

calibration curve used (no calibration, INTCAL13, MARINE13), and the local reservoir age (and uncertainty) for marine cores.

Table 1. Harmonized control points used for age models when radiometric ages (^{14}C, OSL, ^{40}Ar/^{39}Ar, ^{234}U/^{230}Th) were not available.

Event stratigraphy[1,2,3,4,5,6]		GICC05[8] b1950 Age ka	Tephra layers[8-19]	ACER chronology Age ^{14}C[a]	ACER Age ka	Uncertainties[8,24] Years
			K-Ah[9]	6.28		130
			Mazama Ash[10]	6.84		50
			Rotoma[11]	8.53		10
			U-Oki[12]		10[b]	300
Onset Holocene		11.65			11.65	50
			Rotorua[11]	13.08		50
MIS 1/2	D-O 1	14.6			14.6	93
			Rerewhakaaitu[13]	14.7		95
			NYT[14]		14.9[b]	400
			Sakate[15]	16.74		160
			Y-2[16]	18.88		230
LGM					21	
			Kawakawa/Oruanui[17]	21.30		120
	D-O 2	23.29			23.29	298
MIS 2/3	D-O 3	27.73			27.73	416
			AT[9]	24.83		90
	D-O 4	28.85			28.85	449
			TM-15		31[b22]	8000
	D-O 5	32.45			32.45	566
	D-O 6	33.69			33.69	606
	D-O 7	35.43			35.43	661
			TM-18		37[b22]	3000
	D-O 8	38.17			38.17	725
			Y-5[16]		39.28[b]	110
			Akasuko[18]	40.73		1096
	D-O 9	40.11			40.11	790
	D-O 10	41.41			41.41	817
	D-O 11	43.29			43.29	868
			Breccia zone[18]	43.29		955
	D-O 12	46.81			46.81	956
	D-O 13	49.23			49.23	1015
	D-O 14	54.17			54.17	1150
			TM-19		55[b22]	2000
	D-O 15	55.75			55.75	1196
	D-O 16	58.23			58.23	1256
MIS 3/4	D-O 17	59.39			59.39	1287

	onset HS 6	64.6[6]		64.6	*1479*
	D-O 18	65[6]		65	*1518*
MIS 4/5	D-O 19 (onset Ognon II)	72.28		72.28	*1478*
	D-O 20 (onset Ognon I)	76.4		76.4	*1449*
	C 20 (stadial I)	77[6]		77	*1476*
	MS-insolation 15°S*	81		81	*1504*
MIS 5.1	D-O 21 (onset St Germain II)	82.9[5]		82.9	*1458*
	C 21	85[7]		85	*1448*
			Vico[19]	87[b]	7000
			Aso-4[20]	89[b]	7000
			Ash-10[21]	100[b]	1540
MIS 5/6				135[23]	*2500*

*Middle of "high" magnetic susceptibility record zone (consistently <50 SI units) tied to low in insolation for January 15°S [*Gosling et al.*, 2008].
[a] Ages in ^{14}C that were calibrated for the construction of the age model.
[b] Ages in $^{40}Ar/^{39}Ar$ or $^{40}K/^{40}Ar$
K-Ah: Kikai-Akahoya; U-Oki: Ulleungdo-U4; NYT: Neapolitan Yellow Tuff ; AT: Aira Tephra; K-Tz: Kikai-Tozurahara
[1][*Shackleton et al.*, 2000], [2][*Shackleton et al.*, 2004], [3][*Svensson et al.*, 2006], [4][*Svensson et al.*, 2008], [5][*Sánchez Goñi*, 2007], [6][*Sanchez Goñi et al.*, 2013], [7][*McManus et al.*, 1994], [8][*Wolff et al.*, 2010], [9][*Smith et al.*, 2013], [10][*Grigg and Whitlock*, 1998], [11][*Newnham et al.*, 2003], [12][*Smith et al.*, 2011], [13][*Shane et al.*, 2003]; [14][*Deino et al.*, 2004], [15][*Katoh et al.*, 2007], [16][*Margari et al.*, 2009]; [17][*Vandergoes et al.*, 2013]; [18][*Sawada et al.*, 1992], [19][*Magri and Sadori*, 1999],[20][*Nakagawa et al.*, 2012], [21][*Whitlock et al.*, 2000], [22][*Wulf et al.*, 2004],; [23][*Henderson and Slowey*, 2000], [24][*Bazin et al.*, 2013] (italics: uncertainties of the closest age in AICC_2012 in NGRIP ice standard deviation).

Additional tables document the codes used in the main tables for e.g. basin type, basin size, date type, material dated, calibration curve and biome percentage table that includes selected biomes provided by the authors (Table 1). The taxa defining the pollen percentages of the main forest biomes are those originally published by the authors in the Quaternary Science Reviews special issue [*Fletcher et al.*, 2010; *Hessler et al.*, 2010; *Jimenez-Moreno et al.*, 2010; *Takahara et al.*, 2010]. The taxa defining the pollen percentages of the main biomes from Africa (Mfabeni, Rumuiku) Australia (Caledonia Fen, Wangoom) and New Zealand (Kohuora) not included in this issue are described in the supplementary information.

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

Open Access Earth System Science Data Discussions

Each table of the ACCESS database is also available as .csv file: a) Site, b) Sample (original depth-age model and ACER depth-age model), c) Dating info (original dating information), d) dating info ACER (harmonized dating information from this work), e) pollen data (raw data or digitized pollen percentages; pollen percentages of different biomes) (Table 2), f) unique taxa in database (list of all the identified taxa), g) charcoal data (raw or digitized).

Table 2 – Biomes for which the pollen percentages data are included in the ACER database. Bo forest: Boreal forest; Te mountain forest: Temperate mountain forest; Te forest: Temperate forest; WTe forest: Warm-Temperate forest; Tr forest: Tropical forest; Subtr forest: Subtropical forest; SE Pine forest: Southeastern Pine forest; Gr: Grasslands; Sav: Savanah. In Europe, Te forest includes Mediterranean and Atlantic forests.

Europe	North America	Tropics		East Asia	New Zealand	Australia
		American	African			
Te forest	Bo forest Te forest WTe forest SE Pine Forest	Te mountain forest WTe forest Tr forest Gr		Bo forest Te forest WTe forest Subtr forest Gr	Te forest WTe forest	WTe forest Te mountain forest Sav

3 Results

3.1 The ACER pollen and charcoal database

ACER database comprises all available pollen and charcoal records covering all or part of the last glacial (73 to 15 ka) as of July 2015. It contains 93 well-resolved pollen records (< 1,000 years

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

between samples), 32 of which include charcoal data, from all the major potential present-day biomes (Fig. 2). There are 2486 unique pollen and spore taxa in the database.

Harmonized age models were constructed for 86 out of the 93 records (Table S2 in the supplementary information). The seven sites without harmonized age models are: F2-92-P29 (no radiocarbon age errors available); Bear Lake (pollen was counted on one core but sample depths could not be correlated with the cores used for dating); EW-9504 and ODP 1234 (original age models based on correlation with another core, but tie point information was not available); Okarito Pakihi (no dating information available) and Wonderkrater borehole 3 (multiple age reversals). The well-known site of La Grande Pile [*de Beaulieu and Reille*, 1992] is not included in the ACER database because the high-resolution data are not publicly available. Other sequences, such as Sokli in Finland, were fragmented and could not be used (Table S1). These sites are shown at the bottom of the supplementary Table S1.

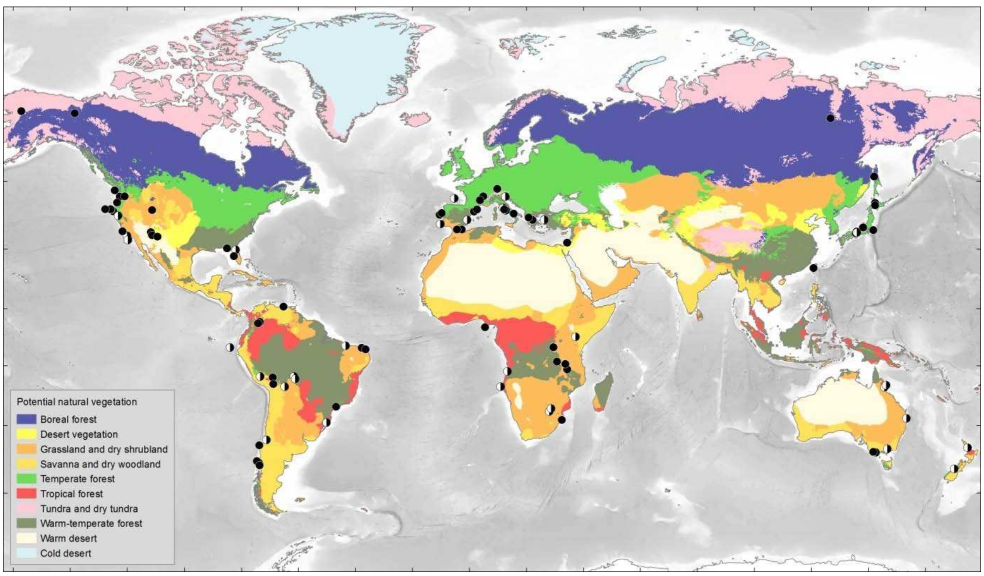


Figure 2 - Map with location of the 93 marine and terrestrial sites (pollen: black circles, charcoal: white circles) having resolution higher than 1 sample per 1000 years covering part or all the last glacial (MIS 4, 3 and 2). Present-day potential natural vegetation after [*Levavasseur et al.*, 2012].

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

3.2 Harmonized *versus* original age models

We generated a total of 774 different age models. The age models of 45 records are based on linear interpolation (Table S2 in the supplementary information). The age models of the other records are derived from smooth or locally weighted splines (e.g. Lake Caço, Brazil; Fargher Lake, North America; ODP1078C, southeastern Atlantic margin) or polynomial regression (e.g. Hanging Lake and Carp Lake, North America; Lake Fuquene, Colombia; Valle di Castiglione, Europe) to include as many as possible of the available radiometric dates. Since the focus for age modeling was the last glacial period, age models for the Holocene (11.65ka - present) and Last Interglacial *sensu lato* intervals (135ka -72.28 ka) are not necessarily well constrained.

Selected examples of the original and harmonized age models are illustrated in Figures 3 and 4. The original age model of marine core MD95-2043, western Mediterranean Sea (Figure 3a, red curve) was based on tuning the mid-points of the cold to warm D-O transitions with the equivalent mid-points in the alkenone-based sea-surface temperature (SST) record [*Cacho et al.*, 1999]. The harmonized age model (black) is based on 21 ^{14}C ages and two isotopic stratigraphic events (D-O 12 and D-O 14). The two age models are similar, with a mismatch of less than 1,000 years for periods older than 35 ka and narrow uncertainties (Fig. 3a). In contrast, the original age model of the terrestrial sequence of Valle di Castiglione, central Italy, published in Fletcher et al. (2010) differs substantially, by several millennia, from the harmonized model in the interval between 50 and 30 ka and has large uncertainties (Fig. 3b). This age model was based on two calibrated ^{14}C dates, one $^{40}Ar/^{39}Ar$ tephra age (Neapolitan Yellow Tuff, Table 2) and the identification of D-O 8, 12 and 14 while the new age model takes into account the entire number of ^{14}C dates (eight), one $^{40}Ar/^{39}Ar$ tephra age and one GICC05-event stratigraphic age (identification of D-O 21). It derives from a 3rd order polynomial regression model to take into account as many as possible of the radiometric ages available (Table S2 in the supplementary information).

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

a. b.

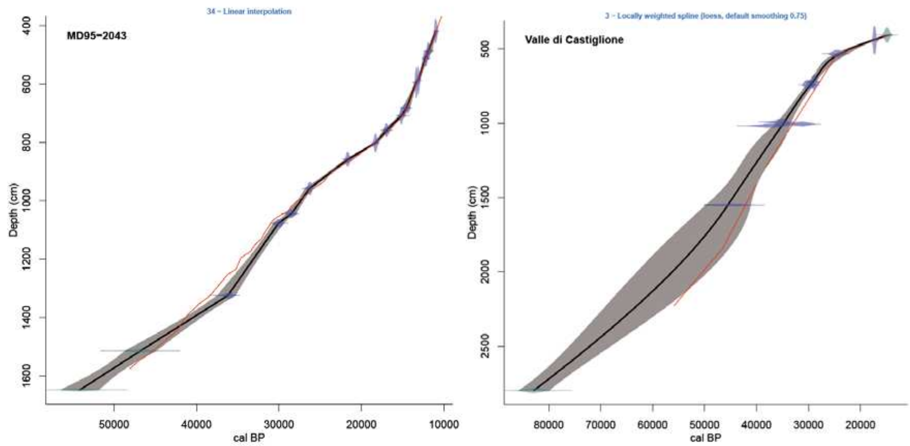


Figure 3- a) Linear age model of the marine core MD95-2043, and b) 3rd order polynomial age model of the terrestrial sequence Valle di Castiglione. Red line: original age model with the control points, Black line: harmonized age model based on radiometric dating and event stratigraphy. Blue: calibrated ^{14}C distribution. Green: non-^{14}C age distribution ($^{40}Ar/^{39}Ar$, $^{234}U/^{230}Th$, OSL, event stratigraphy). Grey shadow: age uncertainties.

The original age model for marine core ODP 1233 C from the southern Pacific Ocean off southern Chile was based on 19 AMS ^{14}C dates calibrated using Calpal 2004 [*Heusser et al.*, 2006] and is very similar to the harmonized age model (Figure 4a). The use of the new INTCAL13 calibration curve is sufficient to explain the small differences between the original and harmonized age models. In contrast, there are major differences between the original and harmonized age models for the terrestrial pollen record of Toushe, Taiwan (Figure 4b). The original age model [*Liew et al.*, 2006] was based on 24 uncalibrated radiometric dates for the 0-24 ka interval , and two dated isotopic events, MIS 3/4 and MIS 4/5, which were dated following *Martinson et al.* [1987] to 58.96 ka and 73.91 ka respectively. The harmonized age model is based on calibrated ages from 3 AMS ^{14}C and 28

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

conventional ^{14}C dates and dating of the MIS 3/4 and MIS 4/5 boundaries. In the ACER chronology, these two events are dated to 59.39 ka and 72.28, respectively. In combination, these differences produce substantially younger ages (by up to 5,000 years) for the interval between 50-26 ka than in the original age model.

a. b.

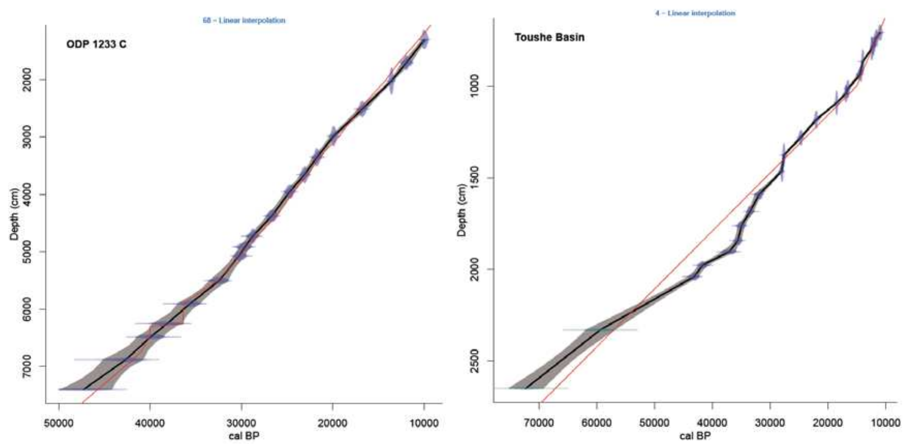
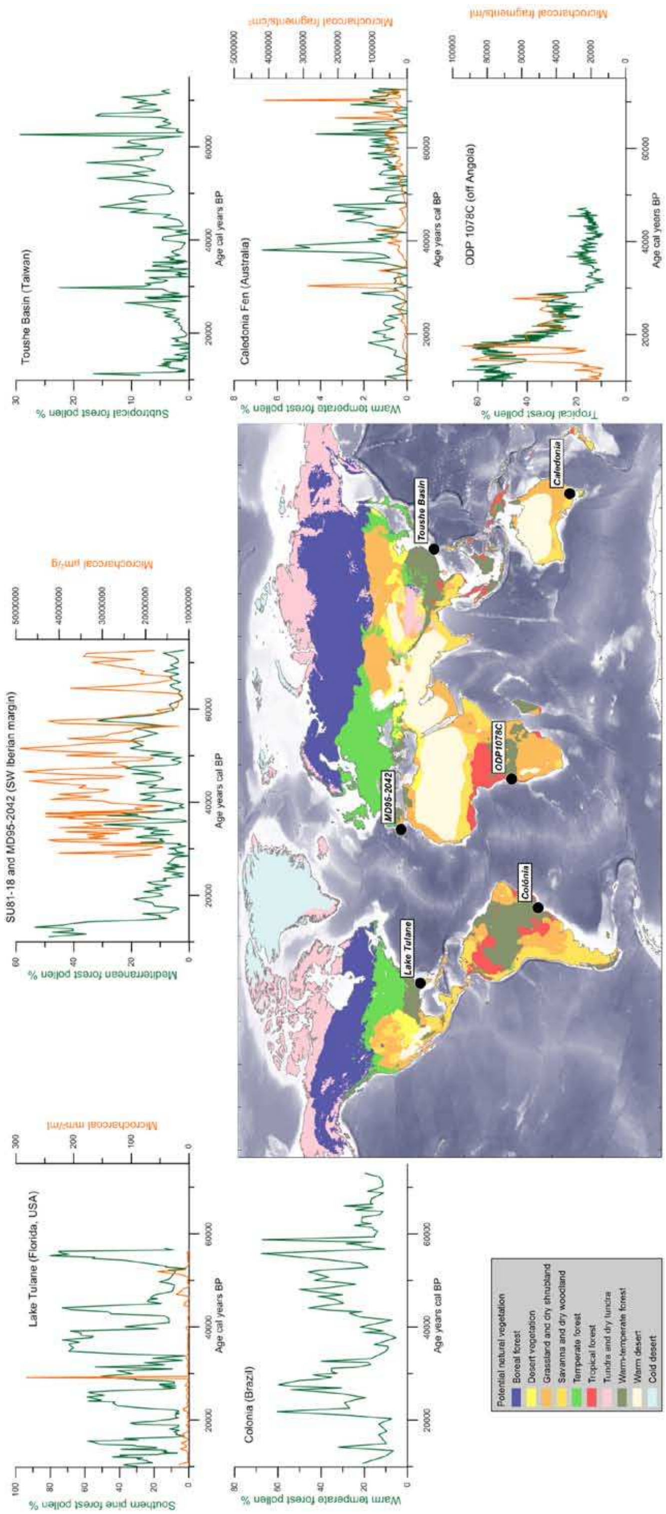


Figure 4- a) Linear age model of the marine core ODP 1233 C, and b) Linear age model of the terrestrial sequence Toushe (Taiwan). Red line: original age model with the control points, Black line: harmonized age model based on radiometric dating. Blue: calibrated ^{14}C distribution. Green: non-^{14}C age distribution ($^{40}Ar/^{39}Ar$, $^{234}U/^{230}Th$, OSL, event stratigraphy). Grey shadow: age uncertainties.

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

Figure 5 additionally illustrates pollen and microcharcoal data plotted against the harmonized age models for few sites from different biomes. This figure highlights the regional response of the vegetation and fire regime to the D-O events.

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017



Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

Figure 5 – Pollen (black) and charcoal (orange) curves from six sites plotted against the harmonized age model.

3.3 Vegetation and climate response to the contrasting D-O 8 and D-O 19 warming events.

Comparison of the vegetation and climate response to warming events in two different regions provides an example of the importance of developing harmonized chronologies. D-O 19 and D-O 8 are iconic D-O events, characterized by strong warming in Greenland followed by long temperate interstadials of 1,600 (GI 19) and 2,000 (GI 8) years respectively [*Wolff et al.*, 2010]. D-O 8 occurred ca 38.17 ka b1950 AD and was marked by an initial short-lived warming of ca 11°C, whereas D-O 19 (ca 72.28 ka b1950 AD) was characterised by a maximum warming of ca 16°C. The difference in the magnitude of warming suggests that the Northern Hemisphere monsoons would be stronger during D-O 19 than D-O 8, but this is not consistent with speleothem evidence from Hulu Cave (China) indicating that monsoon expansion was more marked during D-O 8 than during D-O 19 [*Wang et al.*, 2001] (Fig. 6). *Sanchez Goñi et al.* [2008] argued that the smaller increase in CH_4 during D-O 19, by ca 100 ppbv, than during D-O 8, by ca 200 ppbv, was because the expansion of the East Asian monsoon (and hence of regional wetlands) was weaker during D-O 19 due to the differences in precession during the two events (Fig. 6). Differences in the strength of the monsoons between GI 8 (precession minima, high seasonality) and GI 19 (precession maxima, low seasonality) can also be tested using evidence from the pollen record of Toushe Basin, which lies under the influence of the East Asian monsoon. This record shows a similar development of moisture-demanding subtropical forest, during the two interstadials (Fig. 6), and thus does not support the argument that the East Asian monsoon was weaker/less expanded during GI 19 than during GI 8. However, Toushe Basin lies in the tropical belt (23°N) and is likely to be less sensitive to changes in monsoon extent than more marginal sites such as Hulu Cave (32°N).

Previous works have also hypothesized that the Mediterranean forest and climate were tightly linked to the Asian and African monsoon through the Rodwell and Hoskins zonal mechanism

[*Marzin and Braconnot*, 2009; *Sanchez Goñi et al.*, 2008] or through shifts in the mean latitudinal position of the ITCZ [*Tzedakis et al.*, 2009]. Data from Hulu cave [*Wang et al.*, 2001] and the western Mediterranean region (MD95-2042 and SU81-18 twin pollen sequences) show that during warming events occurring at minima in precession, such as D-O 8, monsoon intensification is stronger and associated with a marked seasonality in the Mediterranean region (strong summer dryness) and, therefore, a strong expansion of the Mediterranean forest and decrease in the summer dry-intolerant Ericaceae (Fig. 6) [*Sánchez Goñi et al.*, 1999; *Sánchez Goñi et al.*, 2000]. Actually, we observe parallel strong and weak increases in East Asian monsoon and Mediterranean forest during GI 8 and GI 19, respectively. However, here again there is a discrepancy between the harmonized Toushe pollen sequence and that from the Hulu cave and the western Mediterranean region: the Mediterranean forest and monsoon during D-O 8 strongly increased while the subtropical forest cover weakly expanded. The different latitudinal position of the Toushe Basin (23°N) in tropical region and that of the Hulu Cave (32°N) and the southern Iberian margin sequence (37°N) both in the subtropical region could explain such a discrepancy. A comprehensive analysis of differences in the magnitude of monsoon expansion between D-O 8 and D-O 19 is now possible because of the creation of robust and standardised age models for the ACER records.

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

Open Access Earth System Science Data Discussions

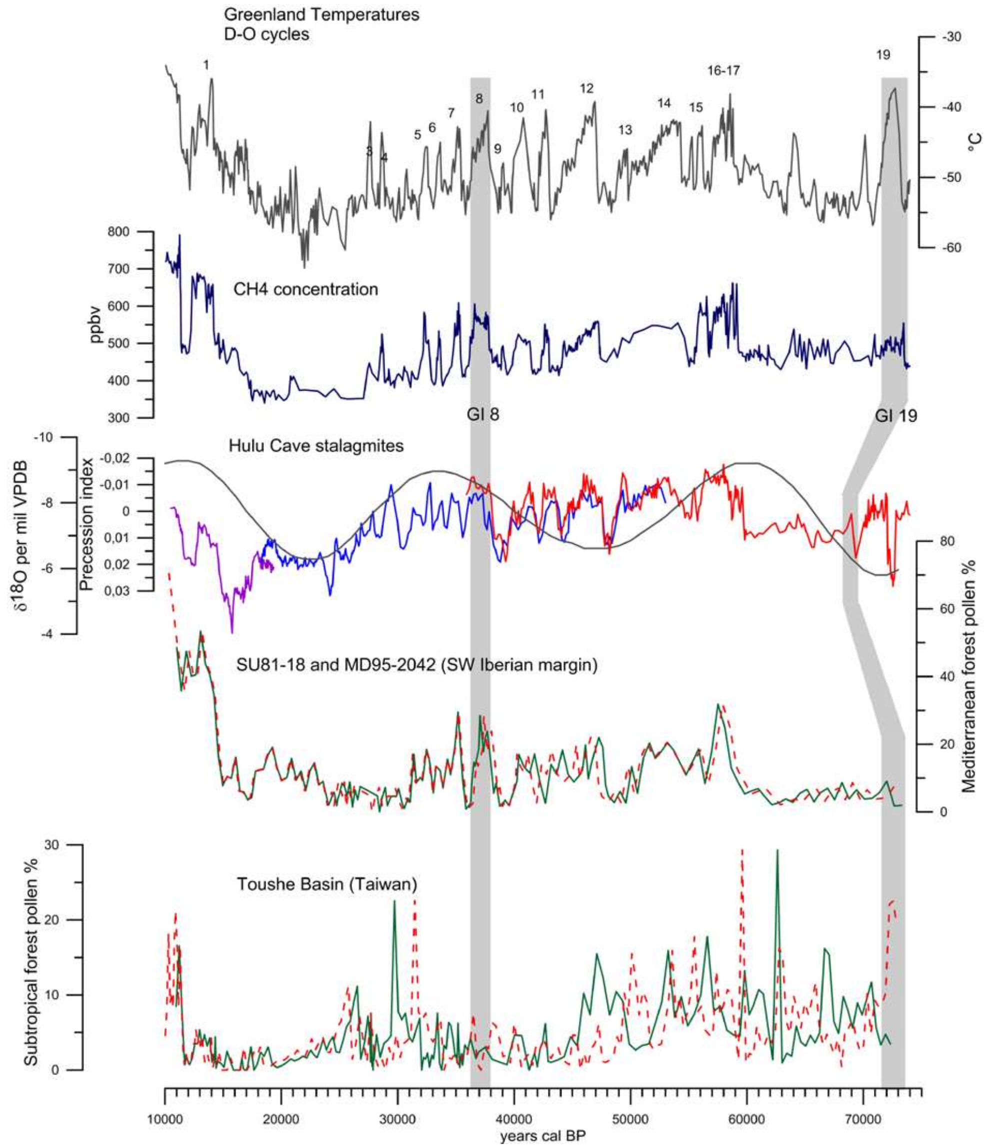


Figure 6 - Comparison of pollen sequences from the Toushe Basin (Taiwan) and the SW Iberian margin (cores MD95-2042 [Desprat et al., 2015; Sanchez Goñi et al., 2008] and SU 81-18 (23500-10000 cal years BP) [Lézine and Denèfle, 1997]) for the interval 73-23.5 ka. Green line: new harmonized age model, red dashed line: original age model. Grey vertical bands indicate the duration of GI 8, GI 16-17 and GI 19. Also shown the comparison with the Greenland temperature record (black) [Huber et al., 2006; Landais et al., 2005; Sanchez Goñi et al., 2008], atmospheric CH_4 concentration (blue) record

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

[Chappellaz et al., 1997; Flückiger et al., 2004], compiled Hulu Cave $\delta^{18}O$ speleothem records (PD in purple, MSD in green, and MSL in blue) [Wang et al., 2001], and precession index [Laskar et al., 2004]. Note the mismatch in the timing of GI 19 between the Greenland and pollen harmonized age models and the chronology of Hulu Cave.

4. Conclusions

The ACER pollen and charcoal database (ACER 1.0) comprises all available pollen and charcoal records covering part or all of the last glacial, as of July 2015. We foresee future updates of the ACER database by the research community with newly published pollen and charcoal records. For consistency age models for new sites should be constructed using the strategy described here.

The harmonization of the ACER age models in the ACER 1.0 database increases the consistency between records by (a) calibrating all the radiocarbon dates using the recommended INTCAL13 and MARINE13 calibration curves, (b) using the same ages for non-radiometric control points and basing these on the most recent Greenland ice core chronology (GICC05), and (c) using the CLAM software to build the age models and taking account of dating uncertainties. While these harmonized age models may not be better than the original models, they have the great advantage of ensuring comparability between pollen and charcoal records from different regions of the world. As we have shown in the preliminary analyses of monsoon-related vegetation changes during D-O 8 and D-O 19, this will facilitate regional comparisons of the response to rapid climate changes.

The same strategy for age-model harmonization is now being applied to the sea-surface temperature records from the last glacial that have been compiled by the ACER-INTIMATE group (http://www.ephe-paleoclimat.com/acer/ACER%20INTIMATE.htm). This will ensure that the terrestrial and marine databases share a common chronological framework, a considerable step towards improving our knowledge of the interactions between oceans and land that underlie the nature and timing of abrupt climatic changes.

Data availability

Supplementary data are available at https://doi.org/10.1594/PANGAEA.870867

Author contributions. MFSG, SD and ALD, developed the harmonized age models, ALD developed the ACER database in ACCESS, FB participated in the construction of age models, JMPM extracted the pollen percentage of the dominant biomes from the European sequences compiled in the ACER database. MFSG and SPH write the manuscript. The remaining authors are listed alphabetically and are data contributors (see their respective dataset on Table S1 in the Supplement link). All data contributors (listed on Table S1) were contacted for authorisation of data publishing and offered co-authorship. All the authors have critically reviewed the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Acknowledgements

We wish to thank the QUEST-DESIRE (UK-France) bilateral project, the INQUA International Focus Group ACER and the INTIMATE-COST action for funding a suite of workshops to compile the ACER pollen and charcoal database and the workshop on ACER Chronology that allow setting the basis for harmonizing the chronologies. We thank Maarten Blaauw for constructive discussions leading to the construction of age models. JMPM was funded by a Basque Government post-doctoral fellowship (POS_2015_1_0006) and SPH by the ERC Advanced Grant GC2.0 : Unlocking the past for a clearer future. We thank V. Hanquiez for drawing Figure 2.

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

Figures & Tables

Figure 1 – ACER database structure in ACCESS format.

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Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 28 February 2017

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Table 1. Harmonized control points used for age models when radiometric ages (^{14}C, OSL, $^{40}Ar/^{39}Ar$, $^{234}U/^{230}Th$) were not available.

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Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-4, 2017
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