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Palaeotemperature reconstruction during the Last Glacial from $\delta^{18}O$ of earthworm calcite granules from Nussloch loess sequence, Germany

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ABSTRACT

The Nussloch loess–palaeosol sequence (Rhine Valley, Germany) is considered to be one of the most complete records of the last glacial period in Western Europe due to its very high sedimentation rate and its good chronological control. This sequence is therefore a good framework in which to develop new proxies for palaeoenvironmental reconstructions. In this study, we explore, for the first time, the potential of earthworm calcite granules as a new bio-indicator and climatic proxy of absolute air and soil temperature in the context of Last Glacial loess. These granules are composed of rhomboedric calcite crystals, organized in a radial crystalline structure. As these granules are individually generated by earthworms at a relative fast rate, they are expected to record intra-annual variations in the available sources of oxygen: percolating waters of meteoric origin. We extracted thirty earthworm calcite granules from 11 of 5 cm layers thick from tundra gley and brown soil horizons previously, dated at 45 to 23 ka. Oxygen isotope ratios were measured on each individual granule. The $\delta^{18}O$ of calcite granules and interlinked transfer functions between water cycle, air and soil temperatures allowed us to estimate air temperatures ranging from 10 to 12 ± 4 °C, which most likely reflect the warm periods of the year when earthworms were the most active.

1. Introduction

The Last Glacial period, or Weichselian in Northwest Europe, ca. 112 to 17 ka, is characterized by rapid climatic fluctuations first described in Greenland ice cores, then in North Atlantic marine sediments. These events are known as Dansgaard–Oeschger (DO) events (Dansgaard et al., 1993), and Heinrich (H) events (Bond et al., 1992). Their impacts on Earth's climate and environment are recorded in diverse continental archives in Europe such as lacustrine sediments (Bohncke et al., 2008; von Grafenstein et al., 1999), pollen assemblages (Moreno et al., 2014), speleothems (Genty et al., 2003), and loess–palaeosol sequences (Antoine et al., 2001, 2009; Rousseau et al., 2002).

The wide spatial distribution (Haase et al., 2007) and high temporal resolution (Frechen et al., 2003) of loess deposits for glacial time make loess sequences the most important terrestrial archives of palaeoenvironmental change available for the European plains during the Last Glacial. Based on stratigraphy, sedimentology (grain-size, $CaCO_3$, TOC and magnetic susceptibility data) and malacofauna, boreal brown soils (Middle Pleniglacial), and tundra gley horizons (Upper Pleniglacial) are correlated with the Dansgaard–Oeschger events recorded in Greenland ice-cores (Antoine et al., 2009; Moine et al., 2008; Rousseau et al., 2002, 2007).

Apart from terrestrial molluscs, which are the main macrofossils investigated in the loess sequences for palaeoenvironmental reconstructions (Ložek, 1990), these sequences are extremely poor in bio-indicators. However, they are rich in secondary pedogenic carbonates (mainly rhizoliths) that have been used for palaeoclimatic reconstructions because of their sensitivity to moisture availability and temperature (Barta, 2011; Becze-Deák et al., 1997). Although the analysis of rhizoliths stable isotope com-

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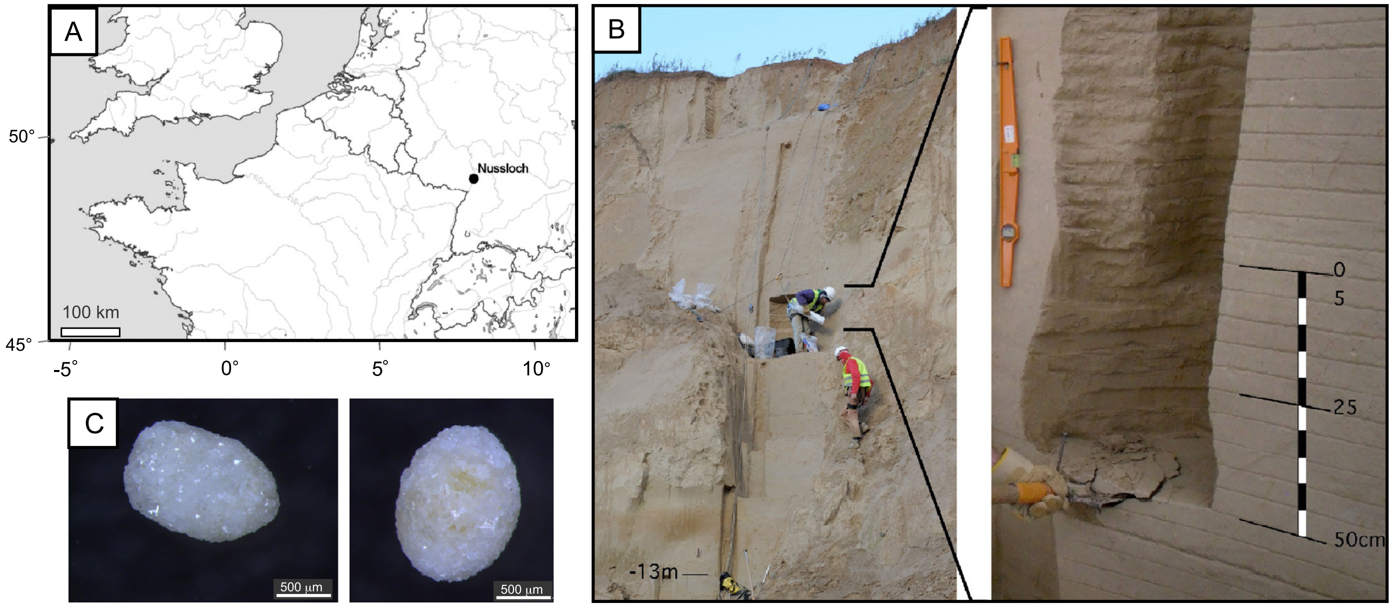

Fig. 1. A) Location of the Nussloch loess sequence in Germany. B) Picture of the P8 profile illustrates the sampling performed using a continuous column protocol. C) Binocular microscope photographs of two earthworm calcite granules extracted from tundra gley horizons, Nussloch P8.

positions ($\delta^{13}C$ and $\delta^{18}O$) has already been performed to estimate the prevailing palaeoclimatic conditions (Gallant et al., 2014; Koeniger et al., 2014; Pustovoytov and Terhorst, 2004), in most cases the relationship between ambient temperature and the $\delta^{18}O$ value has not yet been quantified. The ages of these carbonates is not well constrained because they are generally younger than the horizons in which they formed.

During malacological sieving, small calcite granules (0.5 to 1.5 mm) have been found in various calcareous Quaternary deposits (Barta, 2011; Becze-Deák et al., 1997; Preece et al., 1995) and have been assigned to earthworm activity (Bräm, 1956; Canti, 1998; Darwin, 1881). More recently, earthworm granules have been discovered in abundance in tundra gleys and brown soil horizons of Last Glacial loess sequences from northern France, in which they have been used as a new palaeoenvironmental indicator (Prud'homme et al., 2015). These granules (Fig. 1C) are composed of rhombohedral calcite crystals (Canti, 1998; Gago-Duport et al., 2008) and are organized in a radial crystalline structure. They are secreted by several earthworm genera of which *Lumbricus* is one of the most productive (Bräm, 1956; Canti, 1998). Calcite granules are mainly released within the top few centimetres of soil (Canti and Piearce, 2003). They are produced by calciferous glands (Morren glands) located in pairs on each side of the oesophagus in segments 10, 11 and 12 (Darwin, 1881). Biomineralization is initiated in the calciferous glands through the secretion of a colloidal "milky" fluid, which contains amorphous calcium carbonate (Briones et al., 2008; Gago-Duport et al., 2008; Hodson et al., 2015). The milky fluid reaches the oesophageal pouches where the former calcium carbonate precipitate evolves into macroscopic crystals of calcium carbonate, which are finally released into the soil though the gut (Briones et al., 2008; Gago-Duport et al., 2008). The function of these calcite granules is still debated; they could serve either to excrete the Ca-excess from the earthworm organism (Darwin, 1881; Piearce, 1972; Robertson, 1936) or to regulate its CO_2 (Briones et al., 2008; Robertson, 1936) as well as to buffer the gut pH (Darwin, 1881).

These granules have three main advantages compared to many other terrestrial fossils: 1) their wide spatial and temporal abundance, 2) their chemical composition, being made of well-crystallized low Mg-calcite rather resistant to diagenetic alteration, and 3) the fact that the $\delta^{18}O$ values of their calcium carbonate are both controlled by soil temperature and water isotope composition (Versteegh et al., 2013). Consequently, we consider that the $\delta^{18}O$ values of granules record the temperatures of granule crystallization within the Morren glands, which should be very close to the surrounding soil temperature. Recently, Versteegh et al. (2013) have shown a systematic ^{18}O enrichment, by $1.51 \pm 0.12‰$, compared to the isotopic fractionation determined by Kim and O'Neil (1997) between inorganic calcite and water. Versteegh et al. (2013) established an empirical fractionation equation between the oxygen isotope composition of earthworm granules ($\delta^{18}O_{ECG}$), ambient water being ultimately meteoric in origin ($\delta^{18}O_{mw}$), and the soil temperature:

$$1000\ln(\alpha_{\text{calcite-water}}) = [20.21 \pm 0.92]\left(10^3.T^{-1}\right) - [38.58 \pm 3.18] \tag{1}$$

with

$$\alpha_{\text{calcite-water}} = [1000 + \delta^{18}O_{ECG}]/[1000 + \delta^{18}O_{mw}];$$

$$T\,(K) \quad \text{and} \quad \delta^{18}O\ (‰\text{V-SMOW}) \tag{2}$$

The aim of this study is to perform stable oxygen isotope measurements of the fossil calcite earthworm granules from loess palaeosol sequences in order to quantify soil temperature during the Last Glacial, using the equation of Versteegh et al. (2013). The studied earthworm calcite granules have been extracted from specific horizons (tundra gley, arctic and boreal brown soil horizons) of the Nussloch loess–palaeosol stratigraphic sequence (Rhine Valley, Germany; Fig. 1). Intensively studied, this sequence has become the reference for Western Europe, with more than 12 m of loess accumulated between about 45 and 23 ka BP (Antoine et al., 2001, 2009). The two main questions that are addressed in this study are:

1) Are the $\delta^{18}O$ values of calcite granules related to intra-annual changes in the interlinked $\delta^{18}O$ and temperature of the ambient air through the surface water cycle?
2) Do the $\delta^{18}O$ values of calcite granules record mean annual air temperatures or a specific period of the year?

2. Geological context

The Nussloch loess–palaeosol section, located on the eastern bank of the Upper Rhine Graben on the Odenwald plateau, is exposed within an active quarry located at 49°18′59″N, 8°43′54″E, about ten kilometers SSE of Heidelberg (Fig. 1A). According to the classification of Köplen (Kottek et al., 2006), this area is characterized by a warm temperate climate, fully humid with a warm summer (Cfb). The warmest month is July, with a mean temperature of 18 °C, and the mean annual precipitation ranged from 700 to 900 $\text{mm}\,\text{yr}^{-1}$. The mean seasonal air temperature amplitude ranged from 1.7 ± 0.9 °C in winter (DJF) to 18.4 ± 1.9 °C in summer (JJA). The stratigraphy of newly described profiles is easily correlated, when investigated at the same resolution, with those of previously studied profiles (Antoine et al., 2001, 2009). The main lithology and pedostratigraphy of a new 17-m-thick profile (P8) has been correlated with identified units in profile P4 (Antoine et al., 2009) and have therefore been divided into two main parts (Fig. 2):

1) A lower part (ca. 5 m thick), composed of a succession of two thick boreal brown soil horizons (GBL and GBU) developed on sandy aeolian deposits, followed by loess and tundra gley horizons (units 16 to 19) and finally an arctic brown soil horizon (Lohner Boden, Unit 20). This part of the profile P8 is dated between 55 and 36 ka and correlated with the Middle Pleniglacial.

2) The upper part (ca. 12 m thick), characterized by the cyclic alternation of typical calcareous loess and tundra gley horizons, corresponding to the Upper Pleniglacial dated between 35 and 17 ka. The analyzed earthworm calcite granules were mainly extracted from profile P8 (11 samples), in addition to 3 samples collected from profile P4, and which were correlated to the P8 log (Fig. 2).

The discovery of earthworm calcite granules in tundra gley, arctic and boreal brown soil horizons from northern France and Rhine Valley loess sequences has revealed the presence and survival of earthworms during the Last Glacial, at least in these two regions. In loess sequences, variations in the abundance of earthworm calcite granules are well correlated to the stratigraphic boundaries and follow patterns in mollusc abundance (Prud'homme et al., 2015). The abundance of earthworm calcite granules is very high in tundra gley and boreal brown soil horizons whereas it is very low to null in calcareous loess horizons. The high proportion of earthworm granules and molluscs, along with a higher total organic carbon concentration in tundra gleys and boreal brown soils, reveals a period of warming during the formation of these horizons (Moine et al., 2008). These periods of warming correspond to short interstadial cycle during the Last Glacial period (Antoine et al., 2009). Therefore, earthworm calcite granules can be used as a new proxy of climatic conditions that prevailed during the formation of tundra gley horizons, arctic and boreal brown soils.

The occurrence of cryo-injection and former ice-wedges in tundra gley horizons demonstrated that they have been developed in a permafrost environment (Antoine et al., 2009). These gley horizons are formed by hydromorphic processes resulting from the active layer decay processes of a former permafrost. The presence of waterlogging is characterized by a reduction of iron and a slight decalcification with redistribution of carbonate at the base of the profile (Antoine et al., 2009; Taylor and Lagroix, 2015). There is no evidence of former active layer decay even though arctic and boreal brown soils developed during glacial time.

3. Materials and methods

3.1. Sampling procedure

High-resolution sampling of the Nussloch P8 sequence (Fig. 1B) was performed continuously, every 5 cm, throughout the 17 m

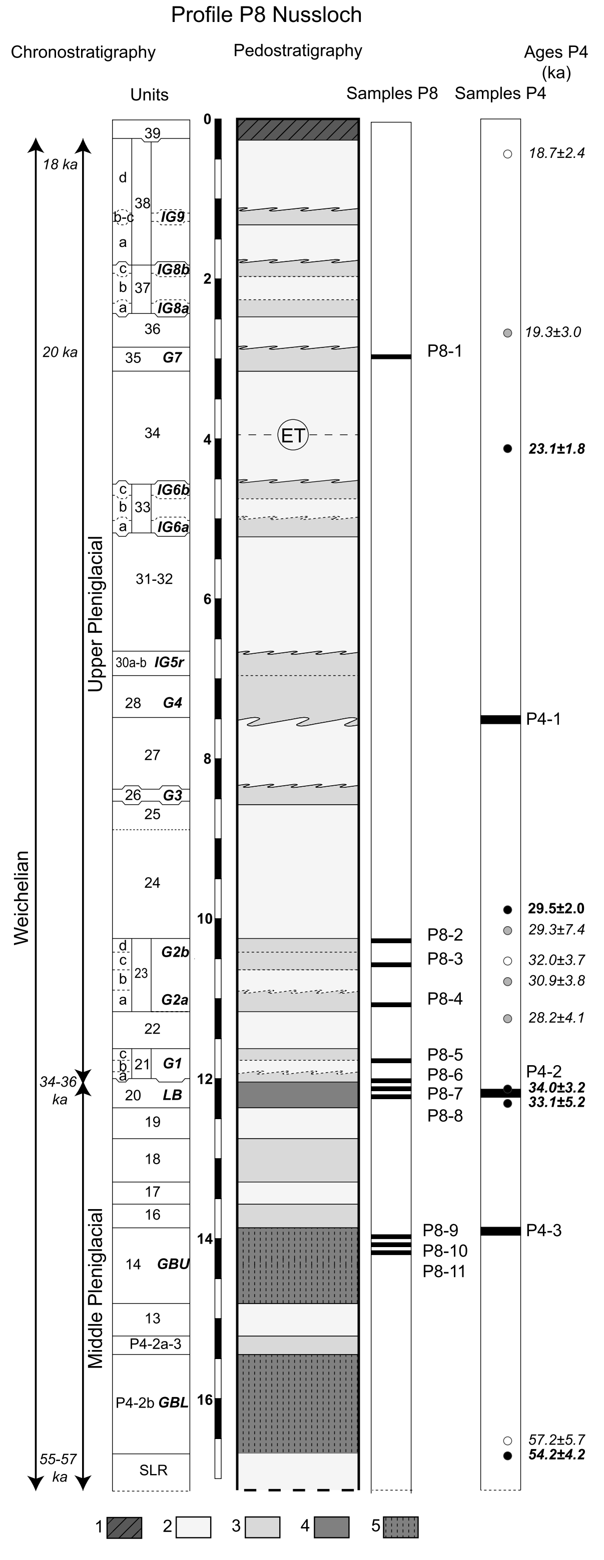

Fig. 2. Stratigraphic sequence of Nussloch profile P8 with the location of the eleven samples from P8 (5 cm) and the three samples from P4 (profile P4 see: Antoine et al., 2009). A detailed description of the stratigraphy and lithology of profile P4 is available in Antoine et al. (2001, 2009). 1: Holocene topsoil, 2: loess horizons, 3: tundra gley horizons, 4: arctic brown soil horizon, 5: boreal brown soil horizons. GBL = Gräselberger Boden Lower (boreal brown soil, Bw horizon), GBU = Gräselberger Boden Upper (boreal brown soil, Bw horizon), LB = Lohner Boden (arctic brown soil, Bw horizon), G = major tundra gley (gelic gleysol horizon), IG = incipient tundra gley and r = reworked, ET = Eltviller Tuff. P4 dating: Open circle represents dating by IRSL (Rousseau et al., 2007), the grey circle represents dating by IRSL made by Bibus et al. (2007) and the black grey represents dating by OSL on quartz done by Tissoux et al. (2010).

thick outcrop. This profile is located at 50 m southeast of the reference profile Nussloch P4. After wet sieving (>0.425 mm) of 10 l of sediment per sample, earthworm calcite granules with a diameter higher than 0.8 mm were extracted to focus mainly on *Lumbricus* material (Canti, 1998; Canti and Piearce, 2003). From profile P4, three samples of 10 cm in thickness were selected: one at the base of the tundra gley G4 (P4-1) and two others from brown soil horizons (Lohner Boden, P4-2 and Gräselberg P4-3). For profile P8, we chose eleven layers of 5 cm (Fig. 2), numbered P8-1 to P8-5 in tundra gley horizons (G7, G2b, G2a and G1), P8-6 to P8-8 in the arctic brown soil (Lohner Boden) and P8-9 to P8-11 in the boreal brown soil (Gräselberger Boden) (see Fig. 2). Among available granules larger than 0.8 mm, we selected the largest ones (using a binocular microscope) characterized well-preserved surface crystals and absence of impurities. These granules were cleaned in deionized water using an ultrasonic bath to remove any remaining sediment matrix, then washed again with deionized water and dried at room temperature.

3.2. Analytical techniques

For profile P4, we analyzed 28 granules from P4-1, 27 granules from P4-2 and 12 granules from P4-3. From the P8 profile 30 granules from each of the eleven chosen layers were analyzed.

Stable oxygen ($\delta^{18}O$) isotope ratios were measured on individual granules by using an auto sampler MultiPrep^{TM} system coupled to a dual-inlet GV Isoprime^{TM} isotope ratio mass spectrometer (IRMS) at the Laboratoire de Géologie, University of Lyon. For each granule, an aliquot of about 200 to 300 µg of calcium carbonate was reacted with anhydrous oversaturated phosphoric acid at 90 °C for 20 min, according to the method developed by Swart et al. (1991). Data are reported as $\delta^{18}O$ values vs. V-PDB (in ‰δ units) after calibration against the internal reference 'Carrara Marble', itself regularly calibrated against NBS18 and NBS19 according to the protocol given by Werner and Brand (2001). External reproducibility is ±0.1‰ for $\delta^{18}O$ values (1σ). In total, for both profiles (P4 and P8), we measured 795 aliquots of calcite (135 for P4 and 660 for P8).

4. Results

4.1. Oxygen isotope compositions of earthworm calcite granules

4.1.1. Nussloch profile P8

$\delta^{18}O$ values of earthworm granules obtained from the eleven layers of profile P8 at Nussloch are compiled in Table 1 along with mean values and standard deviations (SD). Among the 330 analyzed earthworm calcite granules, the oxygen isotope ratios range from −14.8‰ to −0.3‰ (V-PDB) with a mean value of -5.2 ± 1.9‰ (Table 1). The mean granule $\delta^{18}O$ values from tundra gleys and brown soils are -5.4 ± 2.1‰ and -5.0 ± 1.8‰ (V-PDB), respectively (Fig. 3).

We used the T-student test to check whether or not the mean values of the two populations are statistically different at a significance threshold of 5%. A p-value higher than 0.05 validates the null hypothesis, i.e. the two populations are not statistically different and so that environmental conditions should have been similar. Conversely, a p-value lower than 0.05 rejects this hypothesis. Indeed, t-tests indicate that the $\delta^{18}O$ values are statistically different (p-value = 0.068) between the tundra gley horizons and brown (arctic and boreal) soils (Fig. 3), which implies some differences between these two types of pedological units.

4.1.2. Nussloch profile P4

In the Nussloch P4 profile, 67 granules were extracted from three different layers, each 10 cm thick (tundra gleys and brown soils). $\delta^{18}O$ values range from −9.9‰ to −0.9‰ (V-PDB) with a mean value of -5.3 ± 1.9‰. The tundra gley calcite granules have a mean $\delta^{18}O$ value of -4.4 ± 2.1‰ (V-PDB). In the case of brown soils, the mean $\delta^{18}O$ values are comparable (p-value = 0.658) being -5.9 ± 1.8‰ and -5.6 ± 1.9‰ for Lohner Boden and Gräselberger Boden, respectively.

Table 1

Mean and standard deviations of $\delta^{18}O$ (‰ V-PDB) values of earthworm calcite granules recovered from several gley horizons (G7, G2b, G2a, and G1), arctic brown soil (Lohner Boden, LB) and boreal brown soil (Gräselberger Boden, GBU) of the Nussloch loess sequence (P8 and P4) in Germany. Samples are located along the stratigraphic sequence (cm) in Fig. 2 and n represents the number of analyzed samples.

Profile	Level (cm)	Sample	Horizon	n	Mean $\delta^{18}O$ (‰V-PDB)
P8	295–300	P8-1	G7	30	-4.4 ± 1.8
	1025–1030	P8-2	G2a	30	-7.0 ± 2.8
	1055–1060	P8-3	G2b	30	-5.3 ± 1.4
	1105–1110	P8-4	G2d	30	-5.2 ± 1.7
	1175–1180	P8-5	G1	30	-4.9 ± 1.3
	1200–1205	P8-6	LB	30	-4.9 ± 1.3
	1210–1215	P8-7	LB	30	-5.7 ± 1.9
	1220–1225	P8-8	LB	30	-5.3 ± 1.6
	1395–1400	P8-9	GBU	30	-5.1 ± 1.9
	1405–1410	P8-10	GBU	30	-4.6 ± 1.4
	1415–1420	P8-11	GBU	30	-4.4 ± 2.3
P4	1000–1010	P4-1	G4	27	-4.4 ± 2.1
	510–520	P4-2	LB	28	-5.9 ± 1.8
	340–350	P4-3	GBU	12	-5.6 ± 1.9

4.2. Processing raw data

As previously shown by Versteegh et al. (2013), the oxygen isotope composition of granule calcite is related to both soil temperature and isotopic composition of soil water (Eq. (1)). The $\delta^{18}O$ value of soil water mainly reflects that of rainfall (Łacka et al., 2009), which is itself linearly dependents on the mean air temperature at mid and high latitudes (Dansgaard, 1964; Rozanski, 1985). Therefore, to a first approximation, we have established a linear equation relating the $\delta^{18}O_{mw}$ to the mean annual air temperature (T_a) by compiling IAEA (International Atomic Energy Agency) data from the available 72 mid- to high-latitude stations located in North America and Europe. European stations under the influence of a Mediterranean climatic regime were not used for establishing the following linear relationship:

$$\delta^{18}O_{mw} = [0.72 \pm 0.03]T_a + [15.97 \pm 0.28] \tag{3}$$

Zhang et al. (1997) and Zhang (2005) established a linear equation relating the daily ground temperature (T_{soil}) to the daily air temperature (T_a) under snow-free conditions at West Dock and Franklin Bluffs in Alaska, for the time period spanning from 1987 to 1992 as follows:

$$T_{soil} = 0.89T_a + 3.40 \tag{4}$$

Consequently, by combining Eqs. (1), (3) and (4), we were able to calculate air temperatures for periods of the year when earthworms were active and produced the granules.

5. Discussion

Present-day earthworm activity is seasonally-dependent, with peaks during spring and autumn (Satchell, 1967). In the Last Glacial period, we assume that production activity of earthworms occurred during the active layer thawing season, probably from May to September, the five warmest months of the year

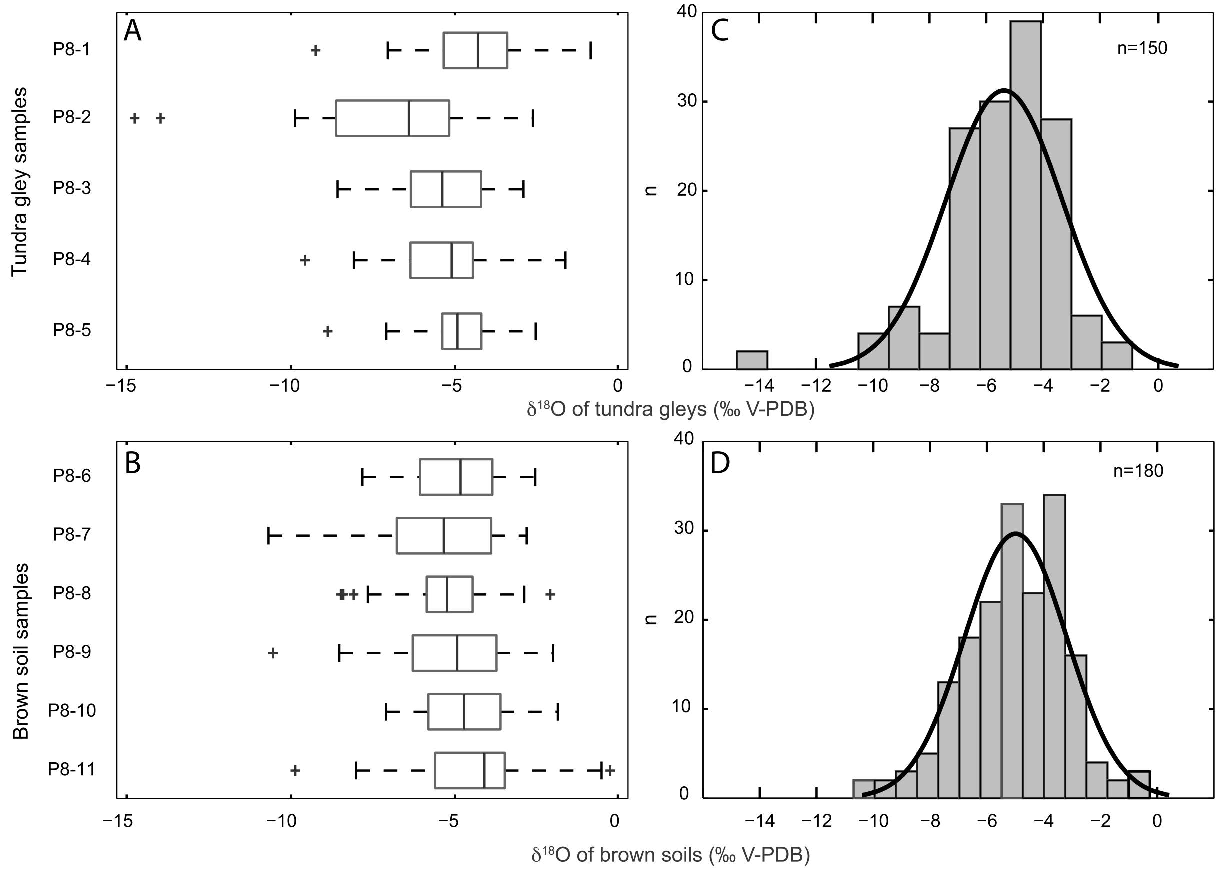

Fig. 3. Left panel: Boxplot illustrating the oxygen isotope compositions of earthworm calcite granules as a function of the stratigraphic succession of profile P8 at Nussloch, Germany. Granules were extracted from A) four tundra gley horizons (G1, G2a, G2b and G7; sample from P8-1 to P8-5) and from B) two brown soils (Lohner Boden (LB) (from P8-6 to P8-8) and Gräselberger Boden (GBU) (from P8-9 to P8-11)). Right panel: Frequency histograms of δ^{18}O of earthworm calcite granules for C) tundra gley horizons and D) arctic and boreal brown horizons from the profile P8. The curve illustrates the fit to a normal distribution.

(Zhang et al., 1997, data from Global Terrestrial Network for Permafrost http://gtnpdatabase.org). Consequently, the oxygen isotope composition of earthworm calcite granule has the potential to record the warmest period of the year rather than the mean annual temperature. The present-day T_{air}–$\delta^{18}O_{mw}$ relationship, established from North American and European stations, must be corrected for the varying δ^{18}O value of the global ocean, reflecting the volume of continental ice, which operates as the ultimate source of meteoric waters. Moreover, those linear relationships may vary through time depending on both the origin and the trajectories of humid air masses. We assume that westerly winds were most likely prevailing over Europe during the Last Glacial as suggested by the source of the loess sediments, which indicates that the dominant winds responsible for deflation and transportation was blowing from North to Northwest (Antoine et al., 2009), and recent modeling experiments performed by Sima et al. (2013). Moreover, the δD values of European groundwaters older than 35,000 years decrease with increasing longitude in a similar way to present-day meteoric waters (Rozanski, 1985). The correlation between the rapid variation of the loess sequence in Nussloch and the Greenland ice core suggests a global connection between North Atlantic and Western Europe atmospheric circulation (Antoine et al., 2009; Rousseau et al., 2007). The polar front shifted southward, with a slowdown of the Gulf Stream and reduced deep-water production (Boyle and Keigwin, 1987; Duplessy et al., 1988). Moreover, a sea level drop led to a major reshaping of the palaeogeography of northwest Europe, with both the North Sea and the Channel being totally dried out. During MIS3 and MIS2, sea level varied from 60 to 120 m below the modern value (b.s.l.), respectively (Lambeck and Chappell, 2001). Glacio-eustatic sea level fluctuations reflect changes in the budget of continental ice volume and can therefore be used to estimate past global δ^{18}O values of seawater. During the Last Glacial Maximum, the δ^{18}O of seawater was 1.0 ± 0.1‰ (Schrag et al., 2002), whilst during MIS3 we assumed that the δ^{18}O of seawater was close to 0.5‰ instead of the 0‰ (SMOW reference) of the Holocene (Lambeck and Chappell, 2001; Shackleton, 2000). In our study, we assume that the source zone of precipitation as well as the main wind trajectories prevailing during the Last Glacial were comparable to the modern ones. Hence the Last Glacial precipitation δ^{18}O values only differed by the ice-volume effect.

The mean soil temperature during the formation of tundra gley horizons (warm season) was therefore 13 ± 4 °C, whilst it was 15 ± 3 °C during the formation of arctic and boreal brown soils (Table 2, Fig. 4). The recorded soil temperatures of 15 ± 4 °C, which were inferred from the two boreal brown soils (samples from P8-6 to P8-11), do not vary over 15 cm depth (Table 2, Fig. 4). This is coherent with the soil temperature profile in the arctic environment recorded at different stations (Christiansen et al., 2010). Concerning the soil temperature of tundra gley G2b horizon, the upper sample (P8-2) recorded a mean temperature of 11 ± 5 °C, lower than the mean temperature of 14 ± 3 °C recorded by sample P8-3 (Table 2). The G2b horizon is one of the thickest tundra gley in the Nussloch sequence, being developed during a long interstadial event (Fig. 9 in Antoine et al., 2009). Variations in the δ^{18}O values of Greenland ice cores indicate an abrupt warming event at the beginning of the interstadial and a gradual cooling at the end of this event. Hence, we suggest that sample P8-3 recorded the beginning

Table 2
Mean soil and air temperatures calculated from the δ^{18}O values of earthworm calcite granules at Nussloch, Germany (profiles P8 and P4), for tundra gley horizons (G7, G2b, G2a, and G1), arctic brown soil (Lohner Boden, LB) and boreal brown soil (Gräselberger Boden, GBU). n represents the number of analyzed samples.

Profile	Level (cm)	Sample	Horizon	n	Mean T_{air} (°C)	Mean (°C)	Mean T_{soil} (°C)	Mean (°C)
P8	295–300	P8-1	G7	30	12 ± 4	**10 ± 4**	15 ± 3	**14 ± 4**
	1025–1030	P8-2	G2a	30	7 ± 6		11 ± 5	
	1055–1060	P8-3	G2b	30	11 ± 3		14 ± 3	
	1105–1110	P8-4	G2d	30	11 ± 4		14 ± 3	
	1175–1180	P8-5	G1	30	11 ± 3		14 ± 2	
	1200–1205	P8-6	LB	30	12 ± 3	**12 ± 4**	15 ± 2	**15 ± 3**
	1210–1215	P8-7	LB	30	11 ± 4		14 ± 3	
	1220–1225	P8-8	LB	30	12 ± 3		15 ± 3	
	1395–1400	P8-9	GBU	30	12 ± 4		15 ± 3	
	1405–1410	P8-10	GBU	30	13 ± 3		16 ± 2	
	1415–1420	P8-11	GBU	30	14 ± 5		16 ± 4	
P4	1000–1010	P4-1	G4	27	12 ± 4		15 ± 3	
	510–520	P4-2	LB	28	10 ± 4		13 ± 3	
	340–350	P4-3	GBU	12	11 ± 4		14 ± 3	

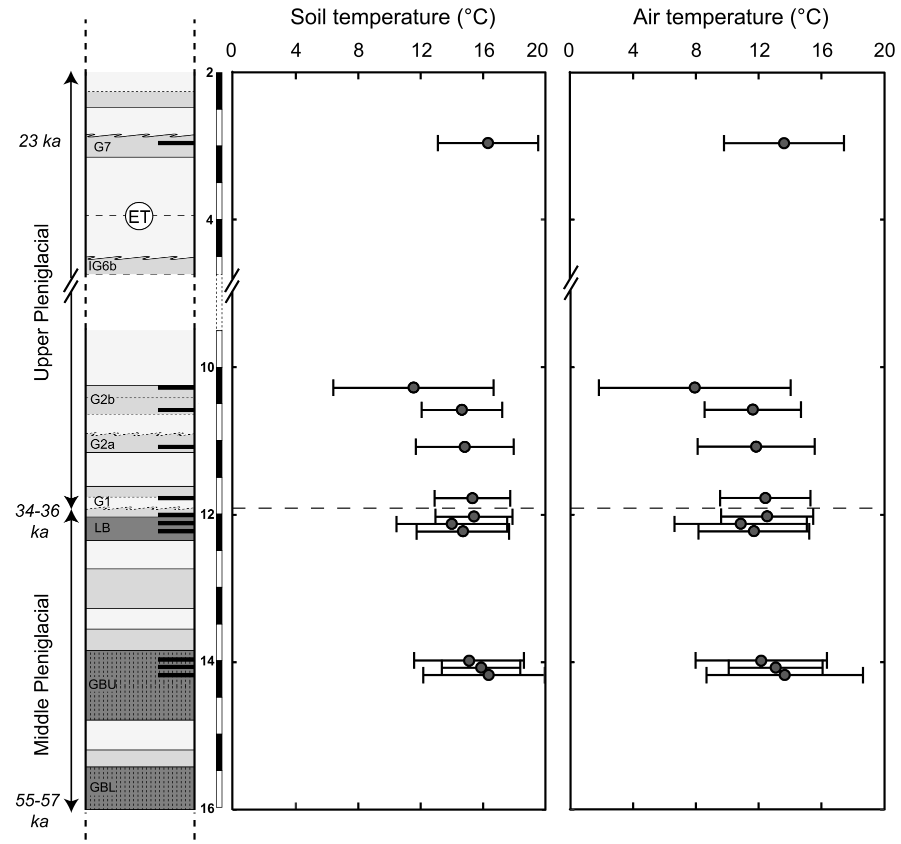

Fig. 4. Soil and air temperatures inferred from the δ^{18}O values of earthworm calcite granules for profile P8 at Nussloch, Germany. The upper part of the section represents the temperatures corresponding to the five selected tundra gleys horizons while the lower part represents the temperatures corresponding to the six selected boreal brown soils. The bars illustrate the standard deviations (1σ) associated with the mean oxygen isotope ratios.

of the interstadial whereas the surface sample P8-2 recorded the end of this event.

By using equation (4), we were able to estimate the mean air temperature during the warm season, which was 10 ± 4 °C during the Upper Pleniglacial and 12 ± 4 °C during the Middle Pleniglacial (Table 2, Fig. 4). The three samples from profile Nussolch P4 yielded mean air temperatures of 11 ± 4 °C and 10 ± 4 °C for Gräselberger and Lohen Boden, respectively. Air temperature contemporaneous with tundra gley genesis was relatively comparable, with a value of 12 ± 4 °C. We are aware that uncertainties associated with the quantitative estimates of past air temperatures may be sizeable. Indeed, it is worth noting that earthworms produced calcite granules every day when they were active, thus the δ^{18}O value of a calcite granule records daily temperatures during the warmest period of the year in the permafrost environment. Consequently, these air temperature estimates could be at variance with other methods and need to be discussed.

Temperature estimations during the Last Glacial have been performed using different methods. August temperatures reconstructed (for MIS3 and MIS2) from mollusc assemblages from the Achenheim loess sequence using the best analogue method range from 13 to 16 °C (Rousseau, 1991). Those from the Mutual Climatic Range method range from 10 to 14 °C (Moine et al., 2002). The reconstruction of palaeotemperatures from periglacial landforms, coleopteran and botanical associations yielded temperatures of 8 °C and 10 °C for the warmest month during MIS2 and MIS3, respectively (Huijzer and Vandenberghe, 1998). July temperature has been estimated at 12 to 14 °C from botanical data in thermokarst lake sediments from Germany (Bohncke et al., 2008), and 9 to 10 °C from fossil diatom assemblages from the palaeolake Les Echets, France (Ampel et al., 2010). Consequently, on the basis of these examples, our estimates of air temperatures are in agreement with previous ones. Moreover, the presence of granules demonstrated that the earthworms were active during the warmest season of the Upper Pleniglacial, which means that air temperatures were higher than 5 °C (Satchell, 1967). Schatz et al. (2015) calculated mean annual temperatures inferred from loess–palaeosol sequences located in the Hungarian part of the Carpathian Basin (Tokaj). This study was based on different transfer functions involving major and trace element contents (XRF), magnetic susceptibility and stable carbon isotope ratios. The combination of these three methods yielded a mean annual temperature ranging from 8.5 °C to 10 °C during formation of palaeosols (45–27 ka), whereas a temperature of 6.7 °C was inferred from magnetic susceptibility data during dust deposition dated from 27 to 21 ka. The presence of deciduous and coniferous trees during the Last Glacial (Willis and van Andel, 2004) in the Tokaj area suggests distinct climatic conditions prevailing at Nussloch. In areas of loess deposits, episodes of permafrost formation imply that the mean annual air temperature was between −8 °C and −4 °C (Renssen and Vandenberghe, 2003, Vandenberghe et al., 2014). As tundra gley horizons represent the active layer of the permafrost during the summer thaw (Antoine et al., 2009), and keeping in mind that our calculated air temperatures ranged from 10 °C to 12 °C, the winter air temperatures should have been in the range −20 °C to −14 °C to match the mean annual air temperature value. This result is in agreement with Rousseau (1991), who estimated the winter palaeotemperature from terrestrial molluscs of the Achenheim loess sequence at −13 °C to −4 °C during Pleniglacial times, in addition to documenting periglacial structures such as ice-wedges.

6. Concluding remarks

Oxygen isotope compositions of earthworm calcite granules from Nussloch, Rhine Valley, Germany, have been used to reconstruct soil and air temperatures during the formation of Last Glacial tundra gleys and palaeosols in loess environments. Our air palaeotemperature reconstructions for the warm season, spanning from May to September (10.0 ± 4.5 °C for tundra gleys and 12.1 ± 3.9 °C for palaeosols), suggest milder climate conditions during the formation of these horizons during interstadial events. Our results suggest that the climate at Nussloch during the formation of Last Glacial palaeosols and tundra gleys was most likely subarctic with a cool summer, and a very cold winter. These temperature reconstructions for the Weichselian period are of importance in helping to understand the responses of both flora and fauna to global climatic changes. Indeed, the availability of food resources was strongly seasonally-dependent during the Last Glacial, with contrasted seasons that most likely triggered human and vertebrate migrations.

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