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Age, origin and significance of a new middle MIS 3 tephra horizon identified within a long-core sequence from Les Echets, France

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A new tephra has been identified within a long core (EC 3) sequence recovered from Les Echets, near Lyon, France. This visible tephra was discovered as part of a high resolution multiproxy re-investigation of the Les Echets sequence. Independent chronological information suggests that the tephra is *c.* 42 000–45 000 years old, and geochemical analysis indicates that it is of basanitic composition. The latter suggests a possible origin in the Eifel; however, as yet, no other volcanic events or deposits can be correlated to the Les Echets tephra. New sedimentological and chronological data are presented indicating that the tephra falls within an interval that most likely correlates with Dansgaard–Oeschger events 12-9. Thus, this tephra could potentially be an important middle MIS 3 marker horizon in central Europe if it can be traced in other palaeorecords.

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The long-sedimentary sequence at Les Echets (45°54′N; 4°56′E) (Fig. 1) was first investigated by de Beaulieu & Reille (1984), whose work showed that Les Echets is one of the few terrestrial sequences in Europe that provided detailed insight into vegetation changes during the last glacial cycle. Alternating phases of forest and open vegetation during Marine Isotope Stage (MIS) 5 and a dominance of cold-tolerant species (MIS 4-2) are some of the key changes that have been identified (de Beaulieu & Reille 1984). Moreover, the detailed pollen stratigraphy has shown that pine pollen percentages fluctuated in a quasi-cyclic pattern throughout most of MIS 3. These fluctuations in pine pollen are of particular importance and may be responding to rapid climate oscillations – the so-called Dansgaard–Oeschger (DO) events – identified in the ice-core records during the last glacial period (Johnsen *et al.* 1992; Dansgaard *et al.* 1993). Although evidence for these millennial-scale fluctuations has been identified in a number of different palaeoarchives in Europe (e.g. Allen *et al.* 1999; Sánchez Goñi *et al.* 2002; Spötl & Mangini 2002; Genty *et al.* 2003), an understanding of the spatial variability and, in particular, of the nature of the terrestrial response to these events is still incomplete. Accordingly, the need to address these questions was the main impetus for carrying out a new multiproxy investigation of the Les Echets sequence. Not only does this site offer a high-resolution record of environmental changes during the late Quaternary (Veres *et al.* 2007), but in particular its location, in an intermediate position between central northern Europe and the Mediterranean region (Fig. 1A), could add important data determining the spatial variability and impact of these rapid climatic fluctuations in Europe.

New sediment cores were obtained from the centre (EC 1) and margin (EC 3) of the basin in 2001 (Fig. 1B). Good chronological control of the analysed sediment sequences has been a central component of this project with the employment of three different dating methods – radiocarbon dating, luminescence dating and tephrochronology. The last-mentioned, in particular, offers considerable potential for the precise correlation between different archives, particularly as recent work has demonstrated that volcanic ash from some events can be traced over areas far more distal than previously realized (e.g. Davies *et al.* 2003; Hang *et al.* 2006; Pyle *et al.* 2006; Blockley *et al.* 2007). The site of Les Echets has the potential for preserving a record of volcanic events from a number of different European sources during the last glacial period (Fig. 1A). In particular, this site is ideally located for establishing a record of intra-plate volcanism from the nearby Massif Central and the more distal Eifel volcanic field in Germany (Fig. 1A). Recent work suggests that Quaternary

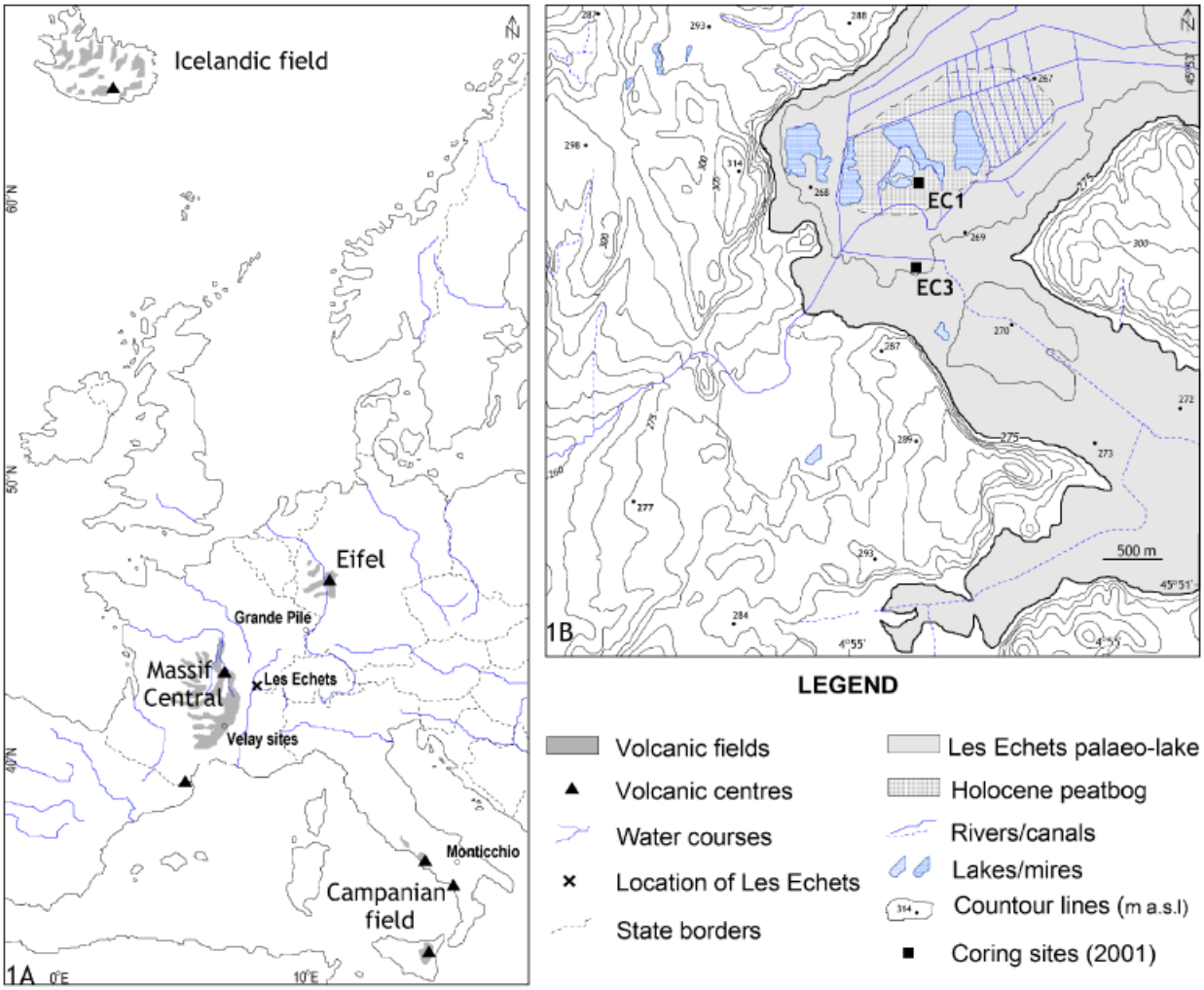

Fig. 1. A. The location of Les Echets and its geographical relation to the main late Pleistocene volcanic centres of Europe. B. Detailed topographic map over the western part of the Les Echets mire and the location of the cores recovered in 2001 (adapted from Veres *et al.* 2007).

volcanism in these regions is episodic, correlating in particular with warming at the beginning of interglacial periods (Nowell *et al.* 2006). During the last glacial period, however, a number of volcanic events are known to have occurred in these regions. Volcanism in the Massif Central occurred predominantly along the Chaîne des Puys, with at least 75 ash-fall events identified in the Clermont Ferrand basin (Vernet *et al.* 1998). In the Eifel region, on the other hand, the frequency of volcanic events is lower during the glacial period (Nowell *et al.* 2006), although some are thought to have been high magnitude eruptions, e.g. Meerfelder Maar (Zolitschka *et al.* 1995; Schmincke in press).

Here we report on the identification of the first tephra horizon in the marginal core EC 3 (<14.55 m depth) from Les Echets spanning MIS 3 and MIS 2. New luminescence and radiocarbon age determinations are used to develop a chronological model and an age estimate for the tephra horizon. New sedimentological data are also presented to provide a palaeoenvironmental and palaeoclimatic context (MIS 3 and 2) for this tephra horizon. These new data build on the data published previously in Veres *et al.* (2007).

Methods

Tephra and mineralogical analyses

Sampling for tephra was initially undertaken on 25 cm long contiguous samples which contained a number of coarse-grained layers. These samples were prepared according to the methodology outlined in Turney (1998) and Davies *et al.* (2005) for the preparation of minerogenic lake sediments. Subsequent to ashing and sieving the material, density separation (using SPT, sodium polytungstate $[Na_6(H_2W_{12}O_{40})H_2O]$) was undertaken to separate the material at 2.5 g cm^{-3}. The <2.5 g cm^{-3} material was subsequently subjected to a NaOH treatment to remove the biogenic silica (Rose *et al.* 1996). Identification of tephra shards was undertaken optically using a high-magnification light microscope. This procedure was repeated

Table 1. Electron microprobe analysis of glass shards for the tephra identified at 10.86 m in core EC 3. Operating conditions of the Cameca SX 100 electron microprobe are as follows: accelerating voltage 15 kV, beam current 10 nA, beam diameter rastered over 10 μm. Counting times on the peak of each element was restricted to 10 s. Sodium was measured in the first counting period and a series of standards (pure metals, synthetic oxides and silicates) was used for calibration. Any drift in the reading was monitored by analysing an andradite at regular intervals. A PAP correction was applied for atomic number, absorption and fluorescence effects (Pouchou & Pichoir 1991).

n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
1	44.38	3.24	15.79	10.89	0.19	4.92	11.11	5.31	2.44	1.08	99.35
2	44.52	3.31	15.67	10.85	0.20	4.98	11.16	5.17	2.36	1.10	99.31
3	44.38	3.36	15.72	10.92	0.19	4.45	11.20	5.40	2.29	1.07	98.97
4	44.00	3.18	15.69	11.06	0.18	5.52	10.57	5.40	2.31	1.04	98.95
5	43.89	3.14	15.84	11.01	0.23	4.86	11.22	5.42	2.27	1.05	98.92
6	44.09	3.28	15.73	10.96	0.24	5.12	10.97	5.09	2.24	1.04	98.77
7	44.15	3.26	15.75	10.89	0.16	4.95	10.89	5.29	2.36	1.07	98.77
8	43.95	3.35	15.48	10.85	0.16	5.10	11.26	5.15	2.31	1.02	98.63
9	44.72	3.26	15.73	10.48	0.15	4.43	10.94	5.43	2.37	1.09	98.60
10	43.85	3.31	15.85	10.63	0.20	4.74	10.99	5.44	2.32	1.03	98.37
11	43.82	3.17	15.66	10.65	0.21	5.20	10.97	5.15	2.43	1.03	98.30
12	43.50	3.24	15.43	11.08	0.23	5.08	11.03	5.28	2.35	1.02	98.25
13	43.90	3.18	15.97	10.47	0.18	4.65	11.01	5.42	2.39	1.06	98.23
14	44.19	3.19	15.42	10.61	0.22	4.97	10.98	5.31	2.25	1.07	98.21
15	44.06	3.22	15.54	10.71	0.17	4.84	11.10	5.11	2.34	1.05	98.13
16	43.61	3.21	15.69	10.82	0.17	4.99	10.96	5.22	2.39	1.07	98.11
17	44.19	3.27	15.67	10.73	0.21	4.44	10.77	5.35	2.38	1.08	98.09
18	43.52	3.14	15.57	10.83	0.19	4.98	11.03	5.41	2.37	1.02	98.05
19	44.24	2.78	15.79	9.97	0.18	4.46	10.96	5.83	2.43	0.96	97.57
20	42.25	3.18	15.49	10.69	0.23	4.31	10.88	5.29	2.38	0.99	95.68
Mean	43.96	3.21	15.67	10.75	0.19	4.85	11.00	5.32	2.35	1.05	98.36
St. dev.	0.51	0.12	0.15	0.25	0.03	0.31	0.16	0.16	0.06	0.04	0.78

at a 1 cm sampling resolution if tephra shards were identified to pinpoint precisely the position of the tephra within the 25 cm long subsample. Where low concentrations of basaltic material were identified within the $<2.5\,g\,cm^{-3}$ fraction, further investigation of the $>2.5\,g\,cm^{-3}$ fraction was also undertaken with a light microscope. Geochemical analysis of glass shards was done on a SX-100 Cameca electron microprobe at the Tephrochronology Analytical Unit, University of Edinburgh. Operating conditions are outlined in Table 1. During microprobe analysis, inclusions within the glass shards were avoided so as not to affect the geochemical composition of the glass itself.

For analysis of the minerals found in association with the tephra, two fractions (250–160 μm and 125–80 μm) were isolated and observed under a petrological microscope. Particle-size distribution of bulk tephra, as well as of the two magnetically separated fractions, was measured by hand sieving (Fig. 2). The magnetic separation was performed on a Franz Magnetic Separator model L-1 following the methodology outlined in Mackie *et al.* (2002).

Infrared stimulated luminescence dating

For infrared stimulated luminescence (IRSL) dating, the polymineral fine grain fraction (4–11 μm) of the inner part (not exposed to sunlight) of the half-cores was extracted after chemical pretreatments (HCl, H_2O_2, Na-Oxalate) by settling using Stokes' law. The silt fraction was used because this fraction dominated in the sediments of core EC 3. We did not attempt to extract the quartz fraction from the samples, because this mineral usually has poor luminescence properties in samples investigated from the Alpine region (Klasen *et al.* 2006; Preusser *et al.* 2006). Previous experience reveals that K-feldspars, which will dominate the investigated IRSL signal from polymineral fine grains, are a reliable natural dosimeter in the Alpine realm (e.g. Preusser 2003; Preusser *et al.* 2003; Preusser & Schlüchter 2004) despite the problems observed for this mineral in some other areas.

Determination of D_e was carried out using the modified single-aliquot regenerative-dose (SAR) protocol of Preusser (2003) on a Risø TL/OSL reader. The detection filter was a combination of a Schott BG-39, a Schott GG400 and a Corning 7–59 giving a peak emission at ~410 nm. IRSL was recorded during a 300 s shine-down of IR diodes. The integral 200–300 s was subtracted from the rest of the IRSL decay curves as late light, and the signal of the first 5 s was used for constructing dose–response curves. A preheat temperature of 290 °C and a cut heat of 200 °C were applied. This procedure was cross-checked by preheat and dose–recovery tests, applying a dose of the same magnitude as the natural dose. The average ratio of applied/regenerated dose for the investigated samples is 1.04±0.07. All samples showed recycling ratios close to 1.00 and low recuperation (3–4%). This proves the good performance of the applied measurement procedure. Seven aliquots were measured for each sample. The plot of D_e versus stimulation time shows a flat

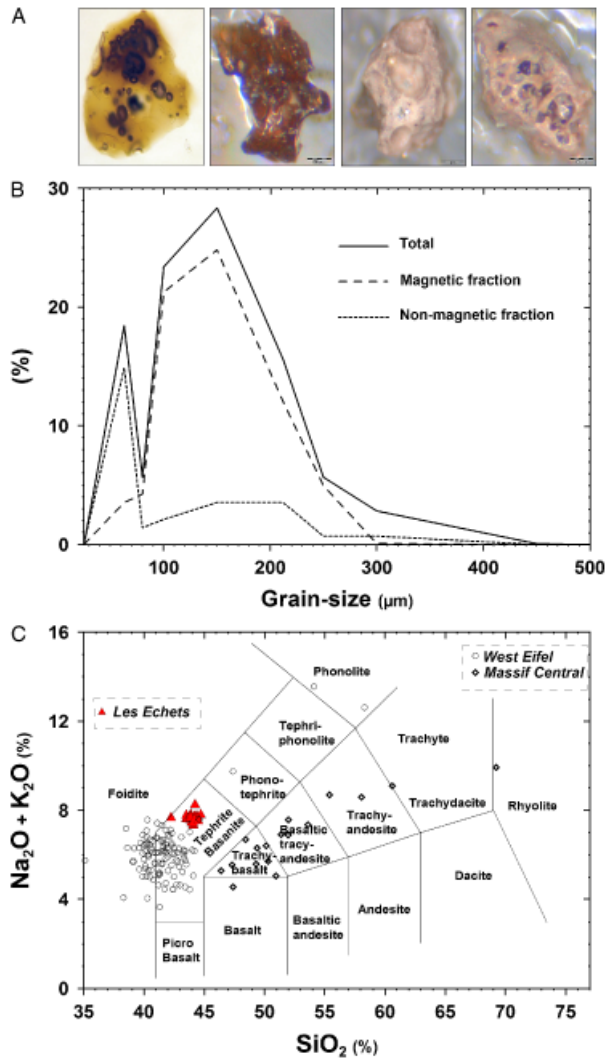

Fig. 2. A. Images of typical glass shard and pumice fragments extracted from this horizon. B. Grain-size distribution of bulk material (total) and magnetically separated fractions. C. Total alkali-silica (Le Bas *et al.* 1986) plot indicating the geochemical affinities of the glass shards from Les Echets to the basanites–tephrites field. Chemical data from Massif Central (Vernet *et al.* 1998) and West Eifel (Mertes 1983) are shown for comparison with Les Echets tephra.

plateau and this is seen as an indication for complete bleaching of IRSL prior to deposition, in accordance with most previous reports that lacustrine samples are usually well bleached (e.g. Lang & Zolitschka 2001; Preusser *et al.* 2005; Vandergoes *et al.* 2005).

Dose rate relevant elements were determined by ICP-MS (Preusser & Kasper 2001) and the validity of the analytical procedure was cross-checked by measuring certified reference material. The samples could not be tested for radioactive equilibrium due to the limited amount of material available for high-resolution gamma spectrometry. However, according to our experience, sediments such as the silts investigated in the present study are usually not significantly affected by radioactive disequilibrium (Lang & Zolitschka 2001; Thomas *et al.* 2003; Preusser *et al.* 2005).

The contribution from cosmic rays to the total dose rate was calculated using present-day sediment depth (Prescott & Hutton 1994). Dose rates were determined using the conversion factors of Adamiec & Aitken (1998) and a mean a-value of 0.07±0.02 (Preusser 1999). Present-day moisture was used for calculating the effect of attenuation of radioactive radiation by water in the sediment pores. Owing to the consolidation of lacustrine sediments, it is likely that average moisture in the past was higher than it is today. As a consequence, we consider all IRSL ages as minimum estimates, but it is expected that the true age of a sample may not differ by more than 10% from the given calculation (e.g. Juschus *et al.* 2007).

Radiocarbon dating

The radiocarbon age estimates of core EC 3 were obtained by accelerator mass spectrometry (AMS) dating using facilities at Uppsala (Ua), Poznañ (Poz) and Lund (LuS) Radiocarbon Dating Laboratories. Measurements were performed on plant macrofossils and organic detritus, except for two samples (LuS 6351 and LuS 6350) bracketing the tephra horizon which were measured on the alkali-insoluble fraction of bulk sediment (Table 2).

Owing to the high content of clastic material in core EC 3 it was particularly difficult to find suitable material for radiocarbon dating. The distribution of radiocarbon dates shows the levels at which identifiable macro-remains (mainly limnic and riparian material) were found. No terrestrial macro-remains were identified and because the carbonate content varies throughout the core we cannot exclude the possibility that the dated material is affected by uptake of dissolved inorganic carbon.

Thirteen AMS ^{14}C age determinations are available for core EC 3 (Fig. 3). The uppermost two ^{14}C ages (on wood) yielded modern estimates, while the lowermost two dates gave infinite ages, in accordance with IRSL ages. The remaining dates fall beyond the IntCal04 calibration curve of Reimer *et al.* (2004). Since no calibration curve beyond 26 000 calendar years BP has yet been ratified (see van der Plicht *et al.* 2004), we used the paired ^{14}C/U coral data of Fairbanks *et al.* (2005) to derive tentative calendar age estimates. This approach allows for a more direct comparison of the radiocarbon-dated levels with the IRSL dates, as the latter age estimates are in calendar years (Fig. 3). All ^{14}C ages referred in the text are therefore 'corrected' ages and may be subject to changes when an approved calibration curve beyond 26 000 yr BP is published.

Sedimentological analyses

Sediment-relative moisture, organic matter and inorganic carbon contents were measured by drying each

Table 2. AMS ^{14}C measurements for core EC 3. The 'calibrated' ages were calculated according to Fairbanks *et al.* (2005) on-line calibration programme. The modern ages obtained around 1.20 m depth indicate that either the dated material (twigs) has been introduced into the sediment during coring or the sediment has been disturbed by agricultural activities.

Laboratory number	Depth (cm)	Material	^{14}C ages yr BP (±1σ)	δ^{13}C (‰ PDB)	Cal ages yr BP (±1σ)
Ua 17109	120	Wood fragments	Modern	−27.5	
Ua 17110	123	Wood fragments	Modern	−31.1	
Poz 2494	488–498	Organic detritus	23 640±150	–	28 190±180
LuS 6150	510–511.5	*Phragmites* sp.	24 140±120	–	28 718±149
LuS 6181	548	*Phragmites* sp.	24 300±140	–	28 887±166
LuS 6182	775	*Phragmites* sp.	29 470±230	–	34 634±403
LuS 6351	1082–1083	Bulk sediment	42 000±1000	–	45 686±912
LuS 6350	1088–1089	Bulk sediment	36 600±500	–	41 723±310
LuS 6183	1115	Organic detritus	37 370±550	–	42 177±336
LuS 5993	1134	Organic detritus	37 385±830	–	42 195±534
Ua 17111	1152	*Phragmites* sp.	38 480±490	−16.2	42 890±422
Ua 16751	1253–1254	*Phragmites* sp.	>41000	−13.5	
Ua 16860	1775–1776	Aquatic mosses	>41000	−27.9	

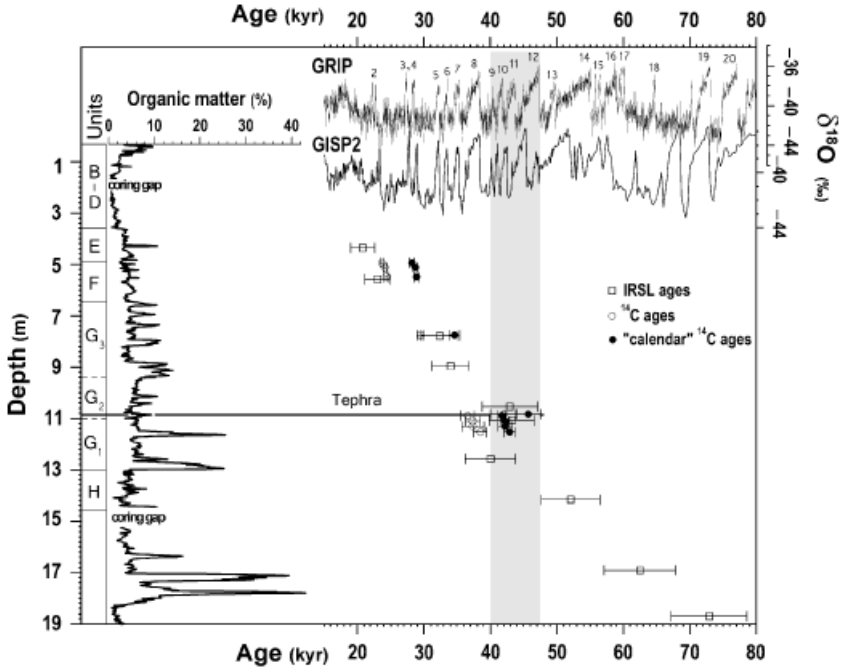

Fig. 3. IRSL, AMS ^{14}C and 'calibrated' AMS ^{14}C dates plotted versus depth for core EC 3. The ^{14}C ages are plotted with two sigma error and the IRSL ages with one sigma error. Lithostratigraphic units are also shown and the horizontal line indicates the position of the tephra layer discussed in the text. The vertical grey bar suggests the most likely time interval when the tephra was deposited. The organic matter contents of core EC 3 and the $\delta^{18}O_{ice}$ records from the GRIP (Johnsen *et al.* 2001) and GISP2 (Meese *et al.* 1997) ice-cores are shown for comparison. Numbers 2–20 refer to Dansgaard–Oeschger (DO) interstadials.

sample (2 cm increments) at 105 °C for 24 h, followed by combustion for 4 h at 550 °C and 925 °C, respectively. The minerogenic content represents the ignition residue after combusting the samples at 925 °C (Fig. 4). All parameters are given as percentage (%) loss of the original weight (Heiri *et al.* 2001). Dry density was calculated as the dry mass of the sample divided by its wet volume and is expressed as g cm^{-3}.

Particle-size distribution was determined by laser diffraction using a Fritsch A22 Laser Particle Sizer. Sample preparation and measurement details are given in Konert & Vandenberghe (1997). The cumulative particle-size distribution is reported as total sand fraction (63 μm – 2 mm), total silt fraction (5.5–63 μm) and total clay fraction (< 5.5 μm).

Whole core magnetic susceptibility was measured on split half-cores with a Bartington MS2EI point sensor core logger at 0.5 cm resolution. The susceptibility meter operated at 0.565 kHz, with a low field intensity of 80 A/m.

Results and discussion

Geochemical and mineralogical characterization of the tephra

A high concentration of dark brown glass shards was identified within the > 2.5 g cm^{-3} fraction at 10.86 m in core EC 3, relating to a visible coarse-grained layer *c.* 5 mm thick. A peak in magnetic susceptibility also

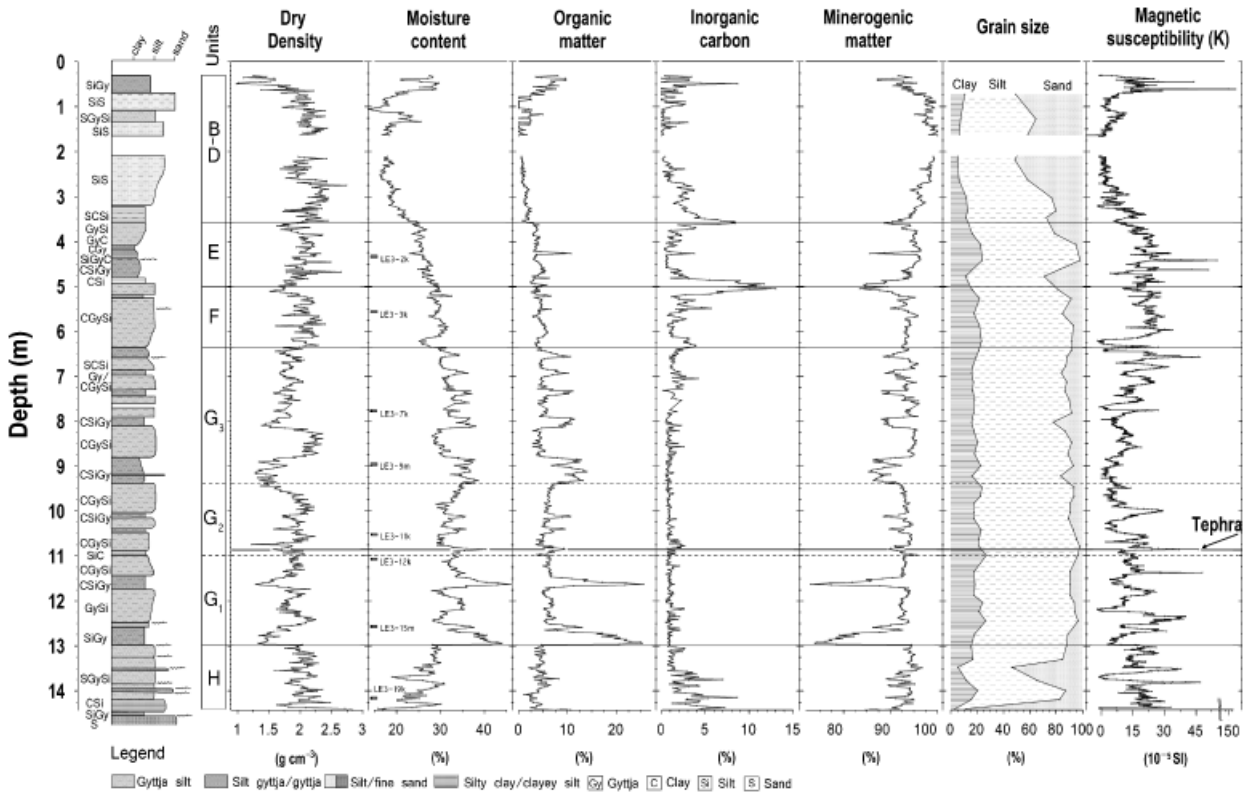

Fig. 4. Lithostratigraphy and vertical profiles of dry density, moisture, organic matter content, inorganic carbon, minerogenic content, grain-size variations and magnetic susceptibility (K) between 14.55 and 0.30 m depth in core EC 3. A thin (0.5 cm) tephra layer discussed in the text is indicated by the horizontal line and by an arrow in the magnetic susceptibility graph. Horizontal dashed lines represent boundaries of lithostratigraphic units. In the lithological description, C stands for clay, Si for silt, S for sand and Gy for gyttja. Undulating horizontal lines mark sharp/erosional lithological contacts. Also shown is the position of the IRSL samples for comparison with sediment moisture.

pinpoints the presence of the tephra, but this (magnetic) signal is not indicative, as investigation of several of these coarse-grained layers with high susceptibility values did not yield any tephra finds.

The tephra itself is composed of about 80% vitreous material, which is angular to subrounded in morphology and contains a number of vesicles and inclusions. Microscoriae and micropumices are also found within the sample (Fig. 2A). Grain-size analysis on the bulk tephra shows a two-modal distribution, with a peak around 63 μm and a broader peak centred on 100–150 μm (Fig. 2B). However, optical investigation of the magnetically separated fractions indicated that the peak at 63 μm relates exclusively to rounded particles of quartz and feldspar. We interpret this fraction as aeolian fine sands–silts in accordance with de Beaulieu & Reille (1984), who concluded that wind-transported material might represent most of the sediment accumulated in Les Echets. On the other hand, the magnetic fraction consists only of glass fragments, pumice and biotite flakes, and the grain size of shards ranges from 60 μm to 250 μm, with a peak around 100–150 μm (Fig. 2). Other magmatic minerals found in association with the tephra include rare olivines, clinopyroxenes and brown amphiboles (hornblende type) partially or completely enclosed in glass.

Twenty shards from the horizon at 10.86 m in EC 3 were analysed by electron microprobe and the major element results place this tephra among the basanites/tephrites field, very close to the foidites, as indicated by the SiO_2 concentrations of *c*. 43.9% and a total alkali concentration of 7.8% (Fig. 2C). Some other distinctive geochemical characteristics of this tephra include relatively high concentrations of MgO (4.85%), CaO concentrations of *c*. 11%, relatively high K_2O values in excess of 2.4% (Fig. 2C, Table 1) and high P_2O_5 (*c*. 1%) values.

Several other potential tephra horizons have also been identified within the Les Echets sequences, but obtaining geochemical data has proved difficult because of the low concentration of shards present. Further work is currently ongoing to characterize these horizons and will be reported at a later stage.

Age and possible origin of the tephra

Despite the large standard deviations, the IRSL age estimates provide some chronological age control and suggest that the sediment sequence presented here is of MIS 3 age (Fig. 3). The two IRSL dates near the bottom of the sequence gave ages of late MIS 5–MIS 4, in

Table 3. Summary of luminescence data including sampled core depth, concentration of dose rate relevant elements (K, Th, U), measured sediment moisture (W), dose rate (D), equivalent dose (D_e) and resulting IRSL ages.

Sample (kyr)	Depth (cm)	K (%)	Th (ppm)	U (ppm)	W (%)	D (Gy kyr^{-1})	ED_{IRSL}BL (Gy)	Age_{IRSL}BL (kyr)
LE3-2k	431–437	1.48±0.13	14.94±0.31	3.27±0.14	35.2	3.53±0.29	73.4±1.1	20.8±1.8
LE3-3k	554–558	1.44±0.13	13.07±0.27	3.28±0.14	41.6	3.15±0.26	72.6±1.0	23.0±1.9
LE3-7k	775–780	1.53±0.14	11.27±0.24	3.40±0.15	52.1	2.85±0.23	92.1±2.3	32.4±2.8
LE3-9m	893–898	1.36±0.12	9.08±0.21	2.57±0.11	58.0	2.24±0.18	76.2±1.4	34.0±2.8
LE3-11k	1050–1055	1.57±0.14	11.66±0.24	2.96±0.13	42.4	2.97±0.24	127.2±7.2	42.9±4.2
LE3-12k	1104–1109	1.71±0.15	11.29±0.24	3.02±0.13	48.1	2.92±0.23	125.9±1.0	43.2±3.4
LE3-15m	1254–1259	1.44±0.13	11.06±0.24	3.37±0.15	57.8	2.63±0.22	104.2±5.1	40.0±3.8
LE3-19k	1413–1418	1.45±0.13	11.24±0.24	2.89±0.13	30.9	3.0±0.25	161.2±2.6	52.1±4.4
LE3-22k	1688–1693	1.65±0.15	10.63±0.22	3.11±0.13	44.5	2.91±0.24	181.7±4.4	62.5±5.4
LE3-25k	1867–1872	1.05±0.09	6.82±0.14	1.70±0.07	24.1	2.12±0.17	154.4±1.9	72.9±5.7

good agreement with the ages expected for these sediments based on pollen stratigraphy (Andrieu-Ponel *et al.* 2006; Veres *et al.* 2007) (Fig. 3, Table 3). The uppermost available dates would indicate that sediments around 4 m depth are of MIS 2 age.

Two IRSL samples bracket the tephra horizon at 11.09–11.04 m and 10.55–10.50 m and gave overlapping ages of 43 200±3400 yr BP (LE3-12) and 42 900±4200 yr BP (LE3-11). Considering a potential change in water content with time, the minimum IRSL age of the tephra could be about 45 000 yr BP (Fig. 3). Two ^{14}C ages (LuS 6350 and LuS 6351) also closely bracket the tephra layer and fall within the errors of the IRSL dates. The date of 36 600±500 ^{14}C yr BP at 10.89–10.88 m is consistent with the other ^{14}C age determinations on macrofossils and provides a tentative 'calibrated' age of *c.* 41 720±310 yr BP below the tephra layer (Fig. 3, Table 2). However, sample LuS 6351 dated to 42 000±1000 ^{14}C yr BP at 10.83–10.82 m appears to produce aberrant ages and is treated here as unreliable until supported by more age determinations. Nonetheless, we believe that the age of the tephra falls in the range 42 000–45 000 yr BP.

The high concentration of glass shards, the size of the shards and the visible nature of the tephra at 10.86 m suggested initially that this tephra originates from a proximal source in the Massif Central, *c.* 150 km to the west (Fig. 1A). The general aspect of the vitreous and other magmatic grains indicates that the mineral associations identified within this tephra might be linked to a highly explosive phreatomagmatic eruption. A number of eruptions are known to have occurred during this time in the Massif Central region (e.g. Nowell *et al.* 2006) and were associated with the initial formation of the Chaîne des Puys (Vernet *et al.* 1998). One of the phreatomagmatic phases associated with the Chaîne des Puys activity was the Puy de la Toupe eruption at *c.* 45 500 yr BP (thermoluminescence age estimate from Guérin 1983). This fits well with the age estimate for the Les Echets tephra (*c.* 42 000–45 000 yr BP); however, the basanite composition of the tephra identified at Les Echets (Fig. 2C) suggests that the origin of this tephra lies outside the Massif Central region, and may lie instead in the Eifel region (*c.* 500 km to the northeast) (Fig. 1A).

A large phreatomagmatic eruption is known to have occurred in the Eifel region around 45 000 yr BP (Schmincke in press; or estimated to >35 000 yr BP in Zolitschka *et al.* 1995), resulting in the formation of Meerfelder Maar. However, chemical analysis of glass material from this eruption is still unavailable and so we are unable to provide a detailed geochemical comparison in this article. Nevertheless, a comparison of Les Echets tephra with averaged chemical data (XRF analyses) from 112 tuff ring, pyroclastic material and lava-flow samples from Quaternary eruptive centres from the West Eifel (Mertes 1983) indicate that this volcanic field is the most likely source for our tephra (Fig. 2C). Most of the samples from the Eifel cluster at the border between basanites and foidites – compositions that are similar to the Les Echets tephra. In contrast, chemical data from 17 glass-pyroclastic samples from the Chaîne des Puys, Massif Central (Vernet *et al.* 1998), show that materials from this volcanic field, ranging from trachybasalts to trachytes, are of a different composition to the Les Echets tephra. Consequently, we believe that the West Eifel volcanic field is the most likely origin of the Les Echets tephra. Up until now, however, no other tephra of similar composition and age to the Les Echets tephra has been reported in other sequences spanning the last glacial period. If this tephra originates from the Eifel region, its presence at Les Echets may indicate that it was widely distributed in western and central Europe and highlights the possibility of this event being traced within other long-core or loess sequences (Fig. 1A). Indeed, there would be great potential in tracing this event within some of the maar sequences in the Eifel region itself (Sirocko *et al.* 2005) as well as within the French sequences, e.g. Grande Pile (Woillard & Mook 1982) or the Velay sites (de Beaulieu & Reille 1992), and even in some of the key laminated sequences in Italy (e.g. Allen *et al.* 1999). Thus, it may be possible to utilize this tephra as a tie-point for palaeorecords spanning the last glacial period in Europe.

The potential of using this tephra as a marker horizon, however, depends entirely on whether it can be

identified in other palaeoarchives. Indeed, one peculiarity of this work is that the entire EC 1 sequence spanning MIS 3 and MIS 2 (*c.* 40 m) has been screened for the presence of tephra shards, and no similar shards were identified. This may be a reflection of the operation of complex sedimentary processes in the basin resulting in an uneven distribution of tephra, which has been observed within other lacustrine environments (e.g. Mangerud *et al.* 1984; Davies *et al.* 2001; Pyne O'Donnell 2007). If so, there is a possibility that this tephra is present in cryptotephra from within EC 1, but the extensive nature of the mineral material precludes the isolation and extraction of volcanic particles. On the other hand, core EC 1 has been dated at high resolution and the results indicate that sediments >36 700 yr BP have been seriously disturbed by erosive processes (Wohlfarth *et al.* in press). The age estimates available for core EC 3 and the identification of this visible tephra layer validate the inter-core correlation suggested in Veres *et al.* (2007), where only subunit G_3 from core EC 3 could be related to core EC 1 (the whole of unit G). It is therefore likely that subunits G_1–G_2 are not recorded in core EC 1, and that core EC 3 although recovered from a more littoral area is more complete, highlighting the complex nature of sedimentation and sediment preservation in this large, glacially formed lacustrine basin (Fig. 1B).

Evidence for DO climate variability in relation to the Les Echets tephra horizon

The Les Echets tephra horizon falls in the interval of recurrent variations in organic matter content in unit G, which according to our chronology is coeval with MIS 3 (Figs 3, 4). These fluctuations in organic matter are similar in appearance to the temperature variations (DO events) identified in the Greenland ice-core records (Meese *et al.* 1997; Johnsen *et al.* 2001) (Fig. 3). Indeed, the multiproxy investigation of the parallel sequence EC 1 (Veres 2007; Wohlfarth *et al.* in press) interpreted similar quasi-cyclic lithological variations between organic-rich silty gyttja layers and inorganic layers to represent the response of the lake system to DO climate variability. Intervals with higher organic matter content identified in core EC 1, similar to the ones described here (see Veres *et al.* 2007), are interpreted as periods of higher lake organic primary productivity and interstadial conditions. Stadial conditions, on the other hand, are marked by an increase in mineral content, high magnetic susceptibilities and bulk densities. Hence, it is reasonable to assume that the marked lithological fluctuations seen in core EC 3 are responses to the same millennial-scale climatic events (Figs 3, 4).

The two most distinct organic horizons are present within unit G_1, prior to the deposition of the tephra horizon, and according to our chronological model this unit was deposited in early MIS 3 (Fig. 3). Although the timing of the two large organic matter peaks cannot be constrained with the available chronological data, it is possible that they relate to DO 12 and 14 (Fig. 3). These early MIS 3 (>40 000 yr BP) interstadial events are of considerable length in the Greenland ice-cores (Meese *et al.* 1997; Johnsen *et al.* 2001), and the distinct organic-rich layers may indicate that they relate either to environmental conditions which favoured high organic matter production or to long periods of organic accumulation in the basin.

If the large organic matter peak at 11.70–11.24 m depth relates to DO 12, as suggested in Fig. 5, then it is possible that the three minor increases in organic matter content in subunit G_2 could represent the sequence of shorter interstadial events subsequent to DO 12 in the ice-cores (Fig. 3). By taking account of the IRSL ages that bracket the tephra horizon, it appears that the tephra layer could have been deposited some time during the interval between DO 12 and DO 8 (Figs 3, 5). More specifically, the tephra layer falls in association with the peak in organic matter (the first of the three minor peaks) from subunit G_2, which could, if our assumptions are correct, relate to DO 11 (Fig. 5), which is dated to *c.* 43 500–42 500 yr BP on the GRIP ss09sea time scale (Johnsen *et al.* 2001). Although the correlations above should be regarded as tentative, the ages obtained for the tephra layer and the onset of subunit G_2

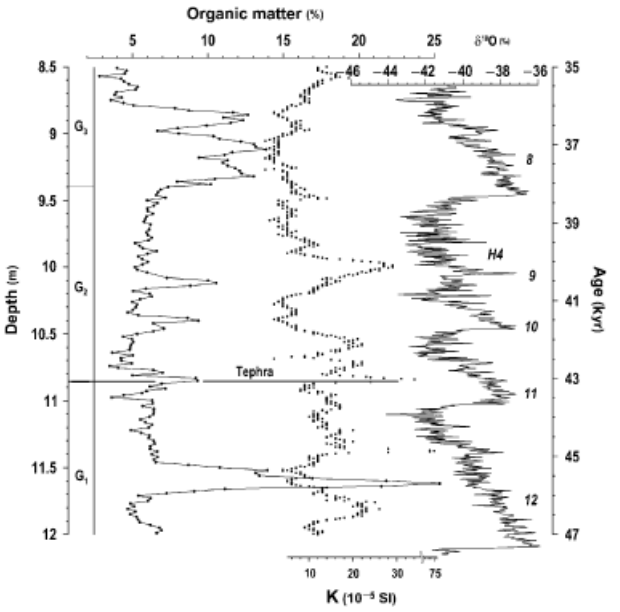

Fig. 5. Comparison of the sediment organic matter content and magnetic susceptibility data between 12.00 and 8.50 m depth in core EC 3 and the GRIP isotopic record spanning the time interval between 47 and 35 kyr BP (Johnsen *et al.* 2001). Numbers 9–12 refer to DO events, and H4 stands for Heinrich event 4. The suggested correlations are only tentative due to the chronological limitations, but it is possible that the tephra layer shown by the vertical line was deposited during DO interstadial 11. Note the scale difference between graphs.

are in good agreement with the ice-core data (Fig. 3). Our correlations raise the possibility of narrowing the search for a corresponding ash-fall event in other records for the period within and immediately around this event (Fig. 5). Moreover, the significant rise in susceptibility values after the uppermost organic layer within subunit G_2 corresponding to high dry densities and a coarsening of the grain size point towards an erosional event in the catchment area (Fig. 4). This interval may relate to the long stadial between DO 9 and DO 8, a time-interval also characterized by the deposition of Heinrich layer 4 in the nearby Atlantic Ocean (Hemming 2004) (Fig. 5).

Above this interval (<9.46 m depth), several more clearly delimited intervals with increasing organic matter contents contrast markedly with intervening intervals with increasing susceptibilities and dry densities (Figs 3, 4). It is likely that these rapid quasi-cyclic lithological changes represent the response of the lake system to the short interstadials/stadials that characterized late MIS 3 (i.e. subsequent to Heinrich event 4).

Conclusions

The Les Echets tephra (*c.* 42 000–45 000 yr BP) provides new evidence of a past volcanic event in central Europe. We propose that the Eifel region is the most likely source of this tephra, which falls within MIS 3 and was deposited during a small interstadial event, possibly relating to DO 11 in the North Atlantic. As such, this tephra may potentially act as a time-synchronous marker horizon for deposits of middle MIS 3 age to better assess the regional development and environmental response of DO events in the terrestrial environments of central-western Europe. Further work is required to identify this tephra in other terrestrial deposits, to explore its full distribution pattern and to determine the potential for using this horizon as a time-parallel marker for precise correlation of different palaeoarchives.

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