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The lithostratigraphy of the Les Echets basin, France: tentative correlation between cores

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Two new long sediment cores (EC1 and EC3), recovered from different locations within the infilled basin at Les Echets, France, provide a new high-resolution record of terrestrial and lacustrine responses to climatic changes during Marine Isotope Stages (MIS) 3 and 2. The lithologies of the cores are described in detail and correlated with each other by stratigraphic marker horizons, fluctuations in organic matter and AMS radiocarbon ages. The tentative correlation of the new cores to those described and analysed by de Beaulieu *et al.* (1980) and de Beaulieu & Reille (1984a) provides a preliminary chronostratigraphic framework. Sedimentation during MIS3 started with accumulation of sands and silts and was followed by alternating gyttja and clayey gyttja silts. Exceptionally high sedimentation rates during MIS2 led to the infilling of the basin. Alternating organic-rich and minerogenic-rich sediments appear to coincide with changes in pollen assemblages (de Beaulieu & Reille 1984a) and suggest that millennial-scale climatic changes controlled lake productivity and catchment stability during most of MIS3.

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More than 20 years ago, de Beaulieu & Reille (1984a) presented in *Boreas* the first results of pollen stratigraphic investigations of a 56-m long lake sediment core obtained from the French site of Les Echets (Fig. 1A). This proved to be an important paper for defining the late Quaternary terrestrial stratigraphy of Europe (de Beaulieu & Reille 1984b, 1989; Guiot *et al.* 1989; Pons *et al.* 1992; van Andel & Tzedakis 1996; Lowe & Walker 1997; Cheddadi *et al.* 1998; Allen & Huntley 2000; Guiter *et al.* 2003; Klotz *et al.* 2004) and confirmed the successive vegetation communities identified by Woillard (1978) within the La Grande Pile sequence.

Sediments started to accumulate in the lake basin of Les Echets during the penultimate termination, corresponding with the uppermost part of Marine Isotope Stage (MIS) 6. The series of successive forest episodes alternating with open vegetation were assigned to the climatic substages of MIS5 (de Beaulieu & Reille 1984a, 1989). For the middle and upper part of the last glacial period, the pollen stratigraphic record indicated a dominance of cold-tolerant species but also a cyclic occurrence of intervals with high *Pinus* pollen percentages. Similar features have also been recognized in other long French sequences (Reille & de Beaulieu

1990; de Beaulieu *et al.* 2001) and in the laminated lake record from Lago Grande di Monticchio in Italy (Allen *et al.* 1999).

In addition, results from Lago Grande di Monticchio suggested that the palaeoenvironmental development during the last glacial period was closely linked with climatic changes in the North Atlantic region, where ice cores (e.g. Dansgaard *et al.* 1993; North Greenland Ice Core Project Members 2004) and marine sediments (e.g. Bond *et al.* 1993; Rasmussen *et al.* 1997) indicate a period of severe climatic fluctuations, both in timing and amplitude. Abrupt shifts between stadial conditions and conditions similar to today's climate characterized this time, while extensive ice sheets covered North America and Europe (Svendsen *et al.* 2004). These rapid shifts between cold and warm conditions have been termed Dansgaard–Oeschger (D–O) stadials and interstadials, respectively. Most of the D–O interstadials started with an abrupt increase in temperature, thought to occur within a few decades, and some seem to coincide with ice-free conditions along the coast of Norway (Raunholm *et al.* 2004) and in northern Finland (Helmens *et al.* 2000; Sarala *et al.* 2005; Mäkinen 2005). Evidence for D–O events has been inferred from

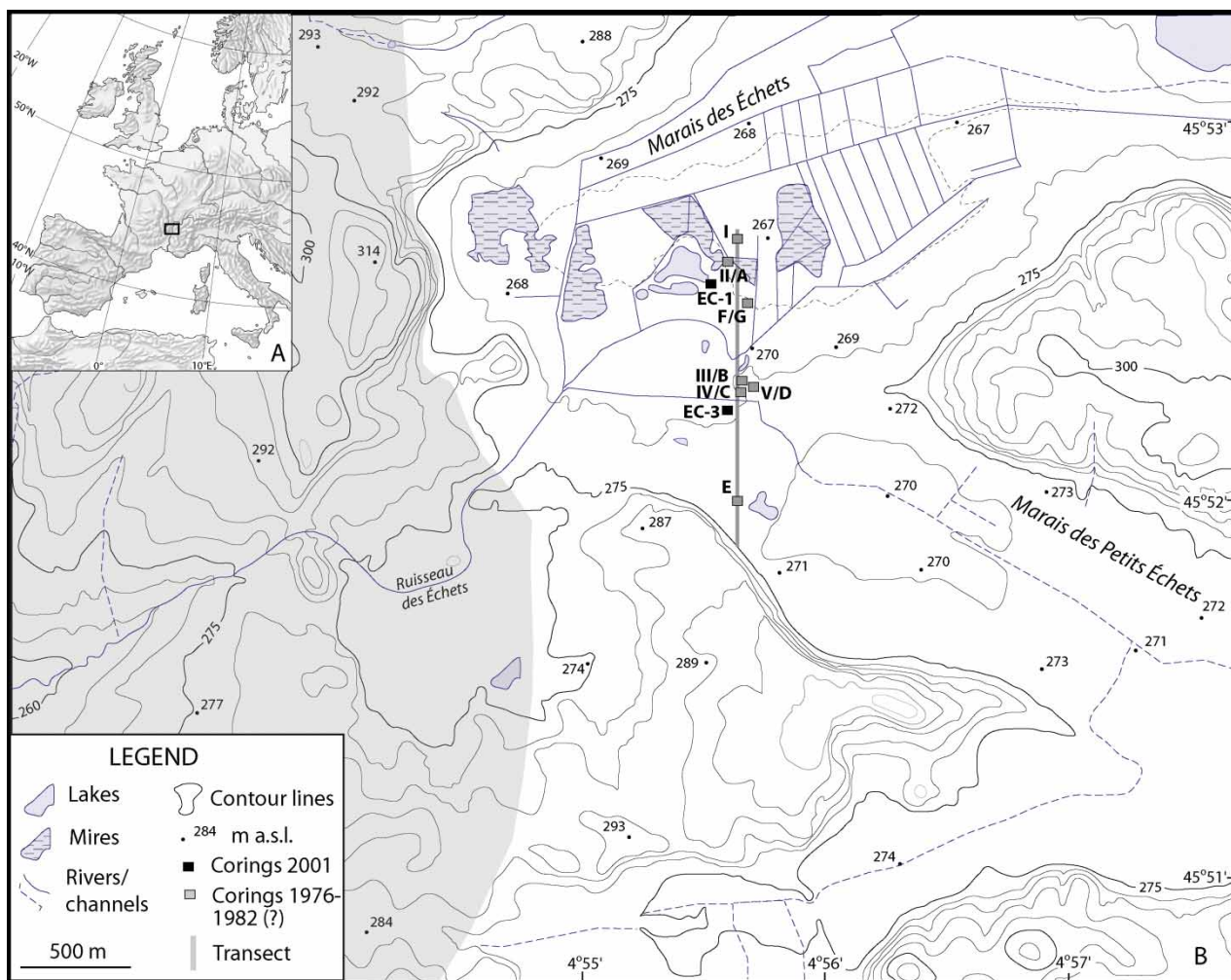


Fig. 1. A. Location of the study area in Europe. B. Topographic map of the Les Echets basin. The new cores EC1 and EC3 are shown by black squares and previous coring locations by grey squares (de Beaulieu *et al.* 1980; de Beaulieu & Reille 1984a). The extent of the mire is approximately equivalent to the 275 m a.s.l. contour line. The shaded area to the west of the mire marks the Rissian external moraine belt.

a number of different depositional environments in Europe, including marine sediments (Rasmussen *et al.* 1997; Shackleton *et al.* 2000; Sánchez-Goñi *et al.* 2002), speleothems (Spötl & Mangini 2002; Genty *et al.* 2003) and lake sediments (Allen *et al.* 1999; Tzedakis *et al.* 2004) (see also review by Voelker *et al.* 2002), suggesting a strong atmospheric teleconnection between marine and continental areas during the last glacial cycle.

In light of these findings from the North Atlantic region, a multiproxy study of the long lake sediment sequence at Les Echets seemed timely for a number of reasons. First, the site offers the potential for high-resolution studies of MIS3 and MIS2 (de Beaulieu & Reille 1984a; Voelker *et al.* 2002). Second, the landscape is open to the northwest, making it possible that the site records D–O events driven by changes in marine and atmospheric conditions in the North

Atlantic region and that the signals would not be biased by orographic effects. Third, earlier investigations focused solely on pollen stratigraphy and a multiproxy investigation and detailed chronology were lacking, which prevented correlations with other records during parts of MIS4 and MIS3 (de Beaulieu & Reille 1984a; Allen & Huntley 2000). Finally, the timing and spatial extent of the Alpine ice sheet and glacial dynamics in the region during MIS4 to MIS2 are not well constrained chronologically (Monjuvent & Winistorfer 1980; Mandier 1984; Florineth & Schlüchter 2000). Given the location of the site in between the Alpine moraine belts (de Beaulieu *et al.* 1980; Mandier 1981), crucial information can potentially be extracted from the record of Les Echets by employing a multiproxy approach together with a detailed chronological framework. This record could also form an important link between the well-defined

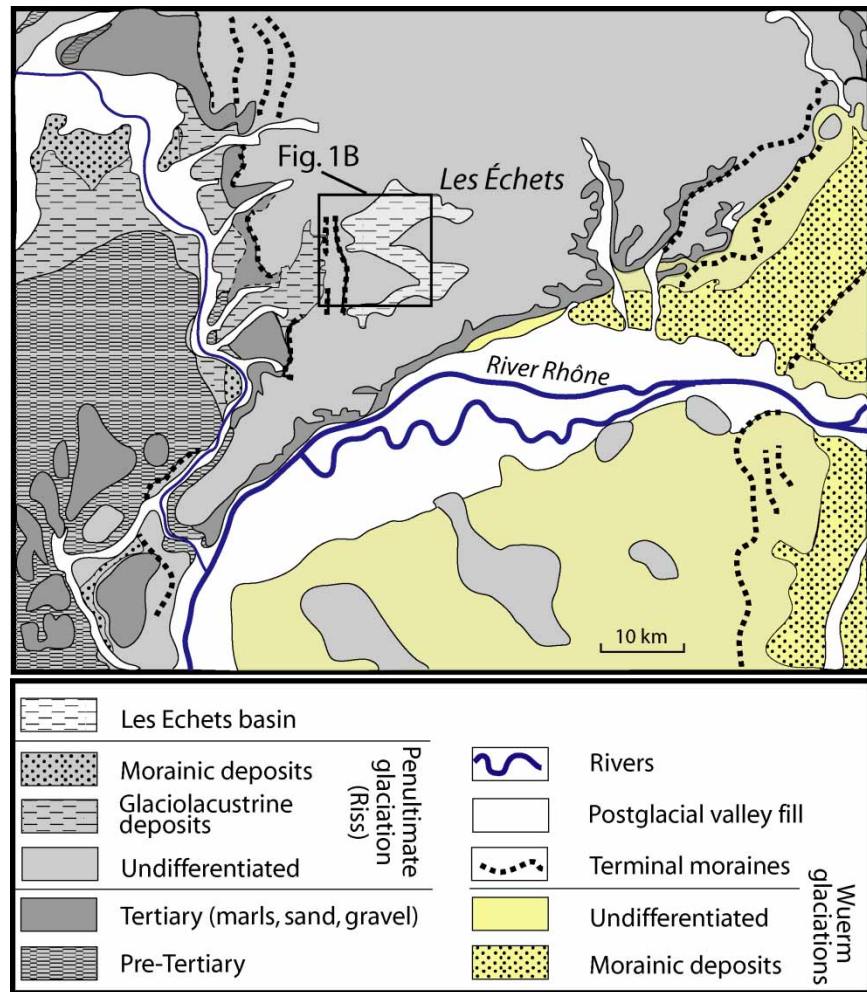


Fig. 2. Simplified geological map of Les Echets area (adapted after J. Brulhet, pers. comm. 2006).

southern European pollen records (Allen *et al.* 1999; Tzedakis *et al.* 2004) and north European pollen stratigraphies, which are still fragmentary (de Beaulieu *et al.* 2001) and thus difficult to correlate precisely (Whittington & Hall 2002).

New sediment cores were obtained at Les Echets during a coring expedition in the autumn of 2001 (Fig. 1B), with the central aim of investigating whether and how the limnic and terrestrial ecosystem responded to the rapid climate variability during the last 140 kyr. This paper is the first in a series directed at a multiproxy re-investigation of the Les Echets sequence for MIS3 and MIS2. The project aimed to constrain the ages of the different temperate periods, earlier recognized in Les Echets during MIS3 and MIS2 (de Beaulieu & Reille 1984a, b), and provide a detailed reconstruction of the response of the terrestrial ecosystem to the abrupt changes observed in North Atlantic records. Here we present detailed lithostratigraphies of the two new sediment cores, including organic matter content and AMS ^{14}C measurements for the upper 30.06 m in core EC1 and 14.55 m in core

EC3, which cover MIS3 and MIS2. We tentatively correlate these sequences with the previously recovered cores based on distinct lithological markers and radiocarbon ages. This correlation and re-investigation of the lithostratigraphy provides insight into the former depositional environment of this lake basin.

Site description

Les Echets is a mire ($45^{\circ}54'N$, $4^{\circ}56'E$) located near the town of Lyon on the south-western part of the hilly Dombes Plateau, France (Fig. 1A, B). It is situated *c.* 4 km east of the westernmost moraine ridge of the Rissian external moraine complex at an altitude of 267 m a.s.l. (de Beaulieu *et al.* 1980) (Fig. 2). The mire itself extends over 13 km² inside a large glacial basin that covers an area of about 40 km², and the basin rim reaches a maximum of just over 300 m on the moraine ridges. The glacial basin is thought to have been excavated during the penultimate glaciation by the Rhône Glacier and dammed by the Rissian frontal

moraines deposited a few kilometres to the west of the site (de Beaulieu *et al.* 1980). The hills around the basin are composed of Rissian glaciofluvial and Würmian aeolian deposits, while the basin itself is filled up with *c.* 60 m of post-Rissian sediments (Fig. 2). Upper Pliocene and pre-Rissian glaciofluvial deposits are restricted to the southern and western edges of the plateau, while limestones and intrusive rocks outcrop to the west in the Saône valley. Geomorphological evidence indicates that alpine glaciers did not override the site during the Last Glacial Maximum but formed their terminal moraines (internal moraine belt in the Alpine area) approximately 15 km to the east. Extensive glaciofluvial deposits outcrop in the plains in front of the Würmian terminal moraines. The former lake gradually filled-in at the end of the Würmian and a large peat bog developed (120–130 ha) that today covers *c.* 10% of the former lake surface. Historical records mention that systematic drainage of the mire began as early as AD 1481 (de Beaulieu & Reille 1984a) and has continued up to the present day. The area receives average annual precipitations of 830 mm and mean annual temperatures are around 9.5°C (Guiot *et al.* 1989).

Earlier investigations at Les Echets

Investigations at Les Echets started several decades ago with a geological survey summarized by de Beaulieu *et al.* (1980) and Mandier (1981). During the 1970s a series of drilling attempts resulted in the recovery of several cores (cores A–F; Fig. 1B) and the publication of the first composite pollen diagram by de Beaulieu *et al.* (1980). Mechanized coring in 1979 in the middle of the palaeolake reached the Rissian till at a depth of 56 m (core G). Above a basal unit of glaciolacustrine, organic-poor laminated clays, the sediment became an intercalation of thick organic-rich gyttjas and marls overlain by a thick succession of clays and silts in the upper 30 m.

The pollen record (upper 39 m of sediment), starting with the Late Rissian pollen zone A, shows that important changes occurred in the structure of the vegetation, with alternating long-standing periods of closed woodlands, open woodland and tundra (de Beaulieu & Reille 1984a, b, 1989). Three important periods of forest development are correlated with the Eemian (pollen zone B), Saint Germain 1 (pollen zone D) and Saint Germain 2 (pollen zone F) and mark the middle part of the sequence overlying the late Rissian sediments. The palynostratigraphic record for this part of the sequence allows a secure comparison with other long lacustrine European records (Woillard & Mook 1982; Follieri *et al.* 1988; Reille & de Beaulieu 1990; Reille *et al.* 2000; de Beaulieu *et al.* 2001; Allen & Huntley 2000). Comparisons of palaeotemperature and precipitation estimates between Les Echets and

La Grande Pile produced a highly similar trend for the two sequences (Guiot *et al.* 1989).

The pollen stratigraphic record above Saint Germain 2 (pollen zones G–P), however, is rather complex and its correlation with other sites is not as straightforward as the lower part of the sequence. The thick silty sediments yielded a pollen assemblage dominated by herbaceous taxa with sporadic peaks in *Pinus* pollen. de Beaulieu & Reille (1984a) cautiously interpreted this pollen assemblage as representing sudden and repeated changes in pollen production and delivery from a sparse vegetation cover under cold–temperate and dry climates. Levels with high *Pinus* percentages and modest rises in *Picea* and mesophilous tree pollen may point to a minor expansion of nearby regional forest stands. These assemblages were considered minor interstadials (pollen zones H, J and L) by de Beaulieu & Reille (1984a). Allen & Huntley (2000) noted that these pollen zones might correlate with pollen zones 11, 9 or 7 and 5b at Lago Grande di Monticchio, which would place them approximately between 50 and 26 kyr BP, but this correlation remained tentative given the lack of a good chronology for Les Echets.

Methods

A new coring expedition, undertaken in November 2001 by a joint Swedish–French–American team, recovered two new long sediment cores from Les Echets, EC1 and EC3 (Fig. 1B). Core EC1 (44 m long) was drilled in the presumed middle of the palaeolake, approximately 1.15 km from the palaeoshore, with the intention of replicating core G of de Beaulieu & Reille (1984a), which had been cored *c.* 0.3 km to the southeast. Core EC3 (24.2 m long) was located *c.* 0.7 km south of EC1, closer to the former margin of the palaeolake (Fig. 1B). The cores were retrieved with a semi-automatic three-walled stationary piston corer (GEOBOR S 1500 mm) equipped with an outer wall that continuously cuts the sediment during the coring operation and allows the recovery of undisturbed sediment sections in 1.5-m long plastic PVC tubes with a diameter of 11 cm (G. Seret, pers. comm. 2006). A minor disadvantage of this device is that sediments may become compacted during coring and thus may expand when the cores are opened for investigation. The length of each subcore was measured immediately after drilling and after opening, and sediment decompression was estimated to have been minimal. With the exception of two large sediment gaps in the top and middle parts of core EC3 because of the loss of loose sands, sediment recovery was 98% of the drilled length. The cores were split in half in January 2002 and their lithostratigraphy was described in detail. Colour changes were assessed using the Munsell colour chart. One subset of cores was stored

in the archive at IMEP, Aix-en-Provence (France), while the other half was transported to Stockholm University (Sweden) for further subsampling. Because of the large volume of work involved in studying such long sequences at high resolution, the work was divided between two teams within the 'Les Echets working group'. The top part of the sequences, corresponding to 30.06 m in core EC1 and 14.55 m in core EC3, which cover MIS3 and MIS2, were the object of the present study.

Volumetric samples for weight loss-on-ignition (LOI) analyses were taken in contiguous 2-cm increments, dried at 105°C for 12 h and subsequently ignited at 550°C for 4 h following the method of Heiri *et al.* (2001). The weight loss during ignition at 550°C is regarded as the sediment organic matter content and is expressed as percentage loss (%) of the original weight. Samples for AMS ¹⁴C measurements consisted of unidentified limnic and terrestrial plant material and *Phragmites* sp. These were dried at 105°C overnight in pre-cleaned glass vials before submitting them to the Poznan Radiocarbon Laboratory, Poland. Sample pre-treatment included an acid-alkali-acid treatment. Radiocarbon ages are expressed as years before present (BP). The limnic plant remains could be affected by a hard water effect; however, the extent of this has to be evaluated by dating many more samples.

Lithostratigraphy of cores EC1 and EC3

Core EC1 (0–30.06 m)

The lowermost unit H (30.06–27.48 m) is composed of dark-grey clayey gyttja silts and laminated clayey silt gyttjas, irregularly interbedded with centimetre-thick silts and sands (Fig. 3). The contact between the sandy horizons and the dominant sediment is very sharp and at times erosional. The organic matter content varies between 2% in the sandy horizons to more than 8% in the clayey silt gyttjas. Vivianite occurs mostly in the lower part of the unit.

A sharp contact between a silt layer and an olive-grey, silty algae gyttja marks the transition to unit G (27.48–22.49 m), which is composed of alternating layers of highly compacted algae gyttjas, rich in organic matter and dark grey clayey gyttja silts with low organic matter content (Fig. 3). The sediments are occasionally laminated and very thin pale olive to pale yellow silt layers are present throughout. Vivianite occurs in the silty algae gyttjas and plant macrofossils (*Phragmites* sp.) are locally present in sediments with low organic content. The contact between the different layers is gradual. In the lower part of unit G, the organic matter content increases abruptly (over c. 20 cm of sediment) to >20%, fluctuates around these values for another 50 cm and sharply declines to low values again. These cycles are repeated several

times, with each cycle covering more than 1 m of sediment. The last peak in organic matter content (c. 12%) in unit G coincides with blackish grey clayey gyttja silts and is centred around 22.70 m.

A sharp boundary separates unit G from the overlying unit F (22.49–18.55 m). This unit is composed of alternating clayey gyttja silts and faintly laminated clayey silt gyttjas and shows the same cyclic sedimentation pattern as the preceding unit (Fig. 3). However, the organic content is considerably lower, attaining around 6% in the clayey gyttja silts and around 12% in the clayey silt gyttjas. Millimetre-thick layers of clayey silt are occasionally observed. Distinct thin organic-rich layers occur in the top part of the unit, while vivianite and FeS stains occur throughout.

The sharp decline in organic matter content at 18.55 m coincides with a distinct change in sedimentation at the onset of unit E (18.55–16.20 m). This unit is composed of a massive, faintly laminated dark grey clayey silt gyttja, which becomes slightly calcareous in the upper part. The organic content fluctuates around 8%. Distinct thin layers of beige clayey silt occur and coarse plant macrofossils are present. AMS radiocarbon dating of *Phragmites* macrofossils at 18.295–18.29 m depth gave an age of 23 890 ± 150 ¹⁴C BP (Poz-2493).

With the onset of unit D (16.20–11.55 m), the sediment becomes more minerogenic (Fig. 3). Dark grey partly oxidized and faintly laminated calcareous clayey gyttja silts make up the bulk of this unit. Vivianite occurs frequently. The organic matter content fluctuates around 6%, with values below 4% at the lower boundary of the unit. Thin horizons of clayey silt gyttjas are present around 14 m and at the transition to the overlying clayey gyttja silts of unit C. Although the lithology of the sediments in unit C (11.55–5.91 m) is similar to unit D, the sediments appear to be more massive and are only discretely laminated and partly oxidized. This monotonous sedimentation is interrupted at 5.91 m by the appearance of sandy sediments rich in coarse organics that mark the onset of the overlying unit B (5.91–0.68 m). This unit is composed of grey clayey gyttja silts with frequent calcareous sandy layers, thin organic layers, sands and faintly laminated silty clays. This alternation of sediments produces an oscillating pattern in the organic matter content, varying between 2% and 10%. Root structures and FeS stains are visible in the upper part. Plant remains from an organic-rich layer between 5.69 m and 5.63 m depth gave an age of 17 090 ± 90 ¹⁴C BP (Poz-2492).

The sequence is capped by a 0.5-m thick black peat that is overlain by a peaty soil rich in clay lenses. The whole of this organic-rich horizon (peat and peaty soil) is distinguished as unit A (0.68–0 m). The upper peaty soil is probably disturbed by agriculture.

Core EC3 (0.3–15.80 m)

Unit H comprises the sediment between 14.55 m and 13.00 m and has sharp lower and upper boundaries (Fig. 4). It starts with a 10-cm thick silty gyttja layer overlain by a clayey silt horizon that inversely grades upwards into massive sandy gyttja silts with occasional fine sand layers (Fig. 4). The contact at 14.55 m is probably erosional, and the majority of the underlying sand layer was lost during coring because of its loose nature.

Unit H is sharply overlain by an alternation of organic-rich gyttja horizons and thick gyttja silts that make up unit G (13.00–6.45 m). This unit can be separated into three subunits (Fig. 4): 13.00–11.00 m, 11.00–9.40 m and 9.40–6.45 m. The lower subunit between 13.00 m and 11.00 m consists of two silt gyttja layers separated by faintly laminated gyttja silts. The organic matter content rises abruptly to values around 25% in the silt gyttjas and oscillates around 5% in the gyttja silts. Between 11.00 m and 9.40 m, the sediment is made up of laminated sandy clayey gyttja silts alternating with thin layers of gyttja silts. FeS staining is frequent and coarse organic matter occurs throughout but is not abundant. The organic matter content is low but rises gradually towards the top of the subunit. Three minor peaks reaching around 9% occur in the middle of the subunit. A sudden change in lithology at 9.40 m marks the transition to 3 m of alternating dark-grey silt gyttjas and light-coloured gyttja silts. The organic matter trend follows these lithological changes, with five well-developed peaks of 10% or higher, alternating with low values of around 5%. Although the change in lithology is gradual, the rise to high organic matter values and the return to low values occur abruptly.

Unit F (6.45–4.90 m) starts with the appearance of massive FeS-stained slightly calcareous clayey gyttja silts, with a coarsening upwards trend (Fig. 4). Some coarse organic material occurs in the lower part of the unit and becomes abundant upwards. A few thin silt layers are observed in the top part. The organic matter content oscillates between 2% and 6%. A radiocarbon age of $23\,640 \pm 150$ ^{14}C BP (Poz-2494) was obtained on bulk sediment between 4.98 m and 4.88 m depth.

The overlying succession of faintly laminated clayey silts and clayey silt gyttjas, alternating with silty gyttja clays, that starts at 4.90 m is defined as unit E (4.90–3.60 m). The sediment is rich in calcareous clasts, coarse organic matter and vivianite. The contact between individual horizons is sharp and the organic matter content varies between 2% and 5%.

A sudden drop in the organic matter content between 3.60 m and 3.25 m depth to values below 2% marks a change in sediment type to grey sandy clayey silt (Fig. 4). Coarse organic material and carbonate clasts occur occasionally. This horizon is capped by a package of massive silty sands with low organic content (<2%) but rich in carbonate clasts. The sediment between 2.10 m and 1.65 m was lost during coring. Above this gap, the sediment becomes coarser, massive and rich in plant macrofossils. The organic matter content fluctuates between 0% and 5%. The top 85 cm are made up of pebbly and gravelly silty gyttjas with fluctuating organic matter content (0–10%). This part of the sequence is probably disturbed by late agricultural activities. The whole of the sediment between 3.60 m and 0.3 m is grouped as unit D–B.

Correlation between cores EC1 and EC3

Cores EC1 and EC3 were drilled in different parts of the former lake basin (Fig. 1B): EC1 was drilled close to the presumed centre of the basin and EC3 closer to the former shore. The different locations of the two profiles within the basin have certainly created different depositional environments, affecting sediment composition and deposition. We might expect more continuous deposition of fine-grained organic sediments in the deeper part of the basin, while clastic and coarser grained sediments accumulated around the margin of the basin. Also, the deeper site may have been less sensitive to changes in water levels compared with the marginal core, where lake level variations may have resulted in periods of non-deposition or reworking. Figure 5 shows a tentative correlation between cores EC1 and EC3, based on lithological markers, radiocarbon ages and trends in organic matter content but also taking into account the respective location of the cores and the resulting differences in sediment lithology and sedimentation rate.

The two sequences can be well correlated for the lowermost unit, H. This is the only interval in the two cores that shows abundant detrital sandy layers, suggesting that the sediments below 27.48 m in core EC1 might be contemporaneous with the sediments below 13.00 m in EC3. The well-sorted sandy layers are intercalated in clayey gyttja silts (EC1) and sandy gyttja silts (EC3) and may indicate oscillations in water level over shorter time intervals and/or periodical delivery of coarser sediments from the lake catchment.

Unit G is characterized by alternating layers of clayey gyttja silt, algae gyttja and clayey silt gyttja (EC1) and slightly more minerogenic sediments (clayey

Fig. 3. Lithostratigraphy, radiocarbon ages and organic matter content (LOI) of Les Echets core EC1 (1.50–30.00 m) (see Fig. 5 for legend). The undulating horizontal lines mark erosional layer boundaries. The length of the individual subcores is shown by grey bars. Two intervals with contrasting lithologies are detailed in the expanded views to the right of the figure.

Les Echets Core EC 1

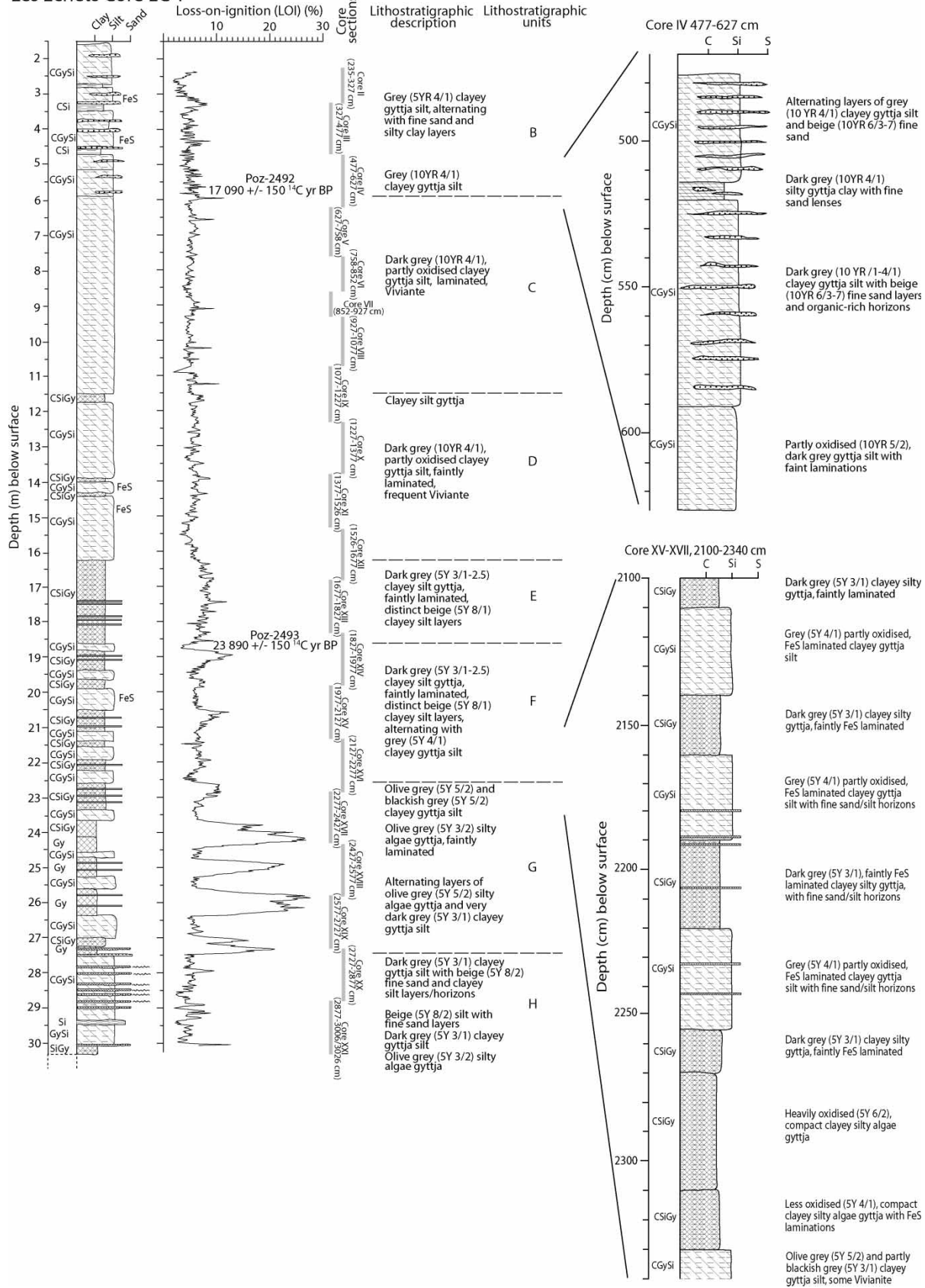


Fig. 3 (Continued)

Les Echets core EC 3

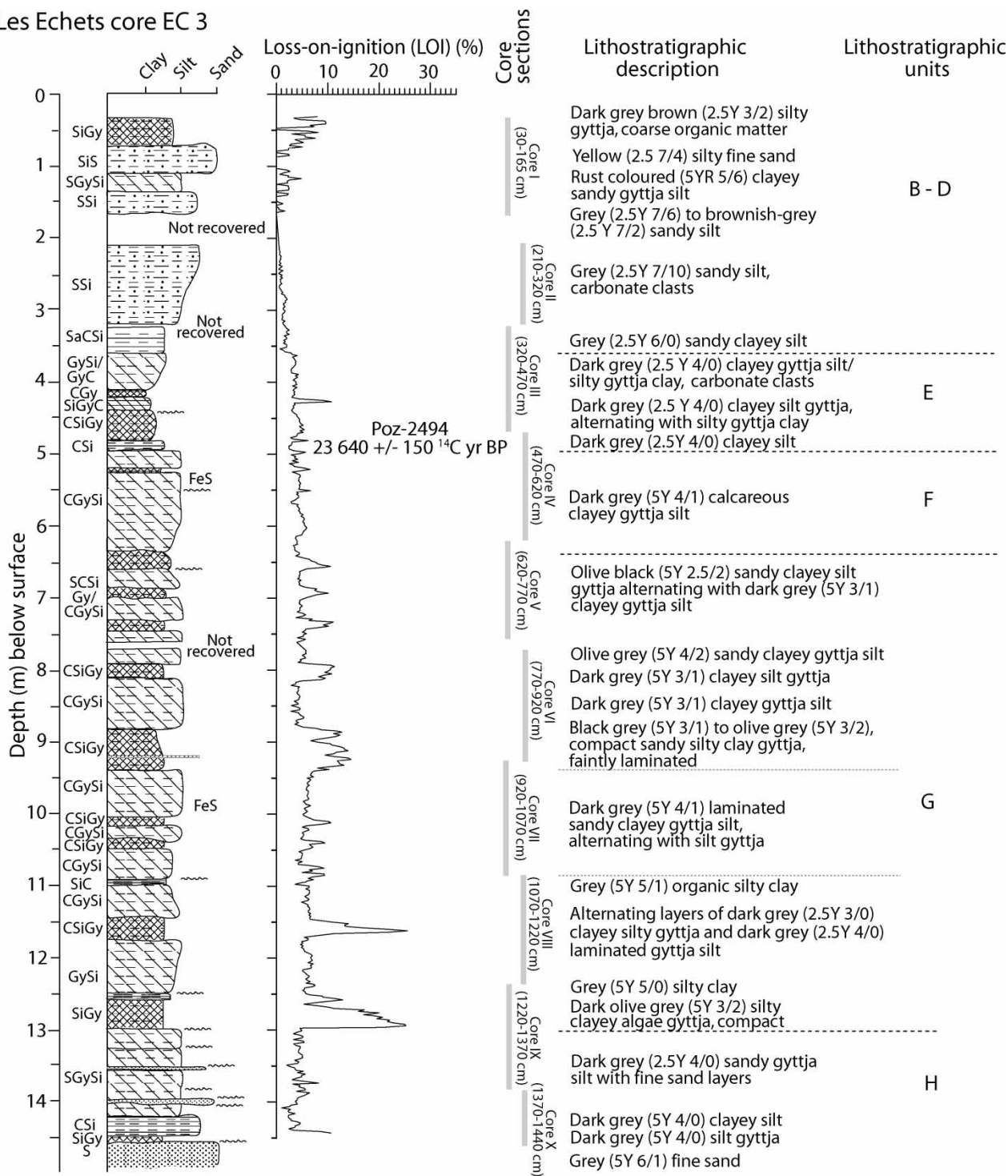


Fig. 4. Lithostratigraphy, radiocarbon ages and organic matter content (LOI) of Les Echets core EC3 (0.30–14.55 m) (see Fig. 5 for legend). The undulating horizontal lines mark erosional layer boundaries. The length of the individual subcores is shown by grey bars.

gyttja silt and clayey silt gyttja) in EC3 (Fig. 5). The alternation between more minerogenic and more organic sediments is clearly reflected in the organic matter content, which in this unit displays the most

distinct variations in both sequences. We therefore assume that sediments between 27.48 m and 22.49 m in EC1 and between 13.00 m and 6.45 m in EC3 belong to the same sedimentary facies. Increased catchment

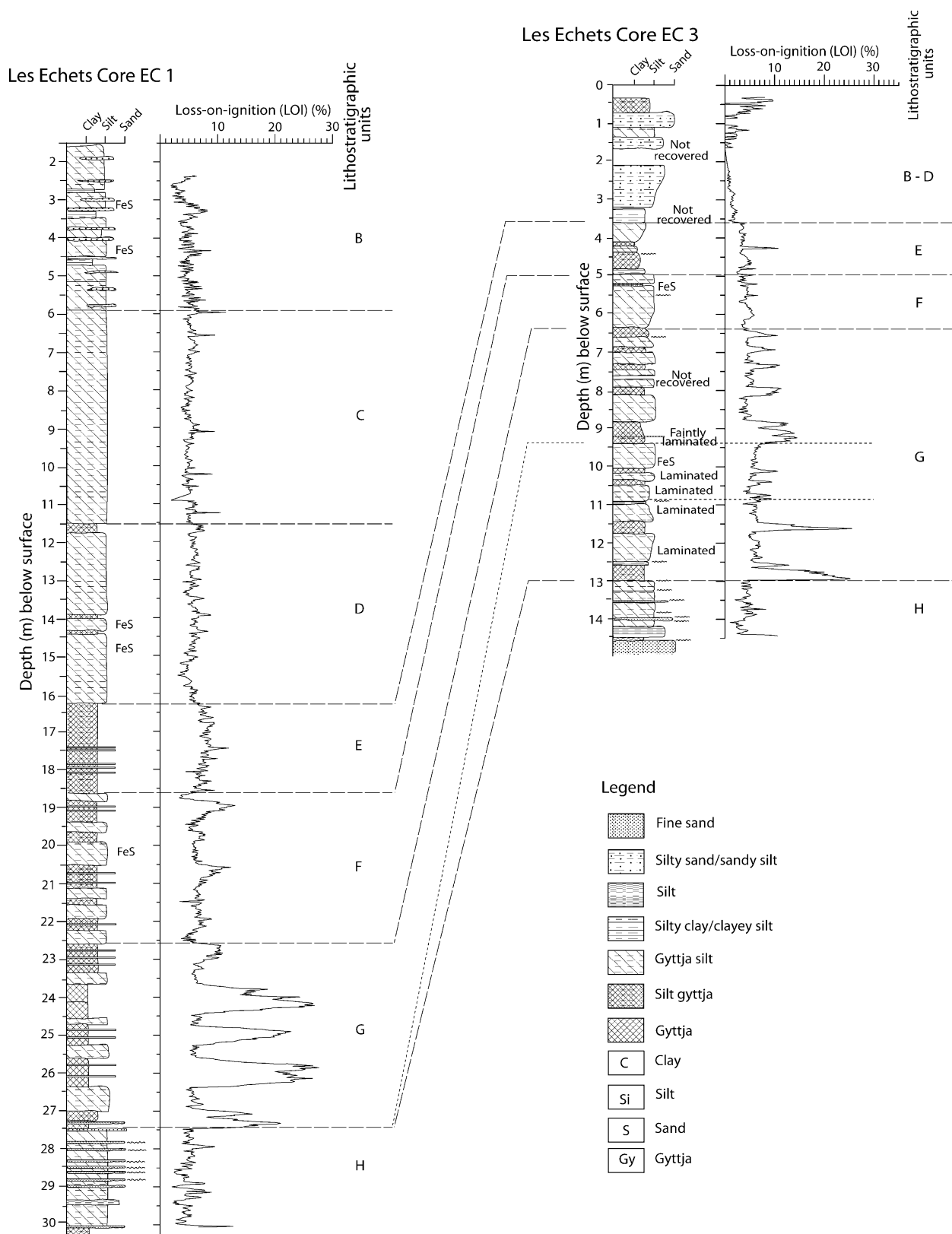


Fig. 5. Lithostratigraphic correlation (dashed lines) between Les Echets cores EC1 and EC3 based on lithological markers and the organic matter content (LOI). The dotted line indicates where the correlation is uncertain. The undulating horizontal lines mark erosional layer boundaries.

erosion as a result of decreased vegetation cover during colder periods might have delivered more minerogenic sediments to the lake basin, while the algae gyttjas reflect higher aquatic productivity during more temperate intervals. Moreover, *Phragmites* macrofossils in layers with low organic matter content could indicate lower lake levels, while the algae gyttjas were probably deposited during periods with higher water levels. Sediments between 13.00 m and 9.50 m in core EC3 cannot be directly correlated with core EC1. The shape and amplitude of the organic matter peaks between 13.00 m and 11.00 m, as well as the interval with stable medium to high organic content between 11.00 m and 9.40 m, are features that are not recognizable in core EC1. Consequently, this would imply that either more sediment accumulated in the marginal part compared with the deeper part of the basin or the sediments in EC1, which are equivalent to the lower part of unit G in EC3, were eroded after their deposition. If dramatic lake-level changes took place, these could indeed have led to a partial erosion of older layers and could explain why the bottom part of unit G (between 13.00 m and 9.40 m) in core EC3 is missing in core EC1 (Fig. 5). However, as sediments are lacking in the deeper EC1 site, it would require erosion from bottom currents, perhaps as countercurrents to the dominating wind direction and focused on the deeper parts of the basin.

Based on the sediment lithology and organic matter curve, we assume that the clayey gyttja silt between 6.45 m and 4.90 m (unit F) in core EC3 could possibly correlate with the clayey silt gyttjas and gyttja silts encountered in core EC1 between 22.49 m and 18.55 m (Fig. 5). The sediments in unit E are made up of clayey silt gyttja, which in EC3 are overlain by gyttja silt/gyttja clay, indicating slightly more minerogenic deposition in marginal areas. The age of $23\,890 \pm 150$ ^{14}C BP at 18.29 m in EC1 is close to the age of $23\,640 \pm 150$ ^{14}C BP obtained at 4.88–4.98 m in EC3, which supports the correlation. Additionally, the marked decline in organic matter content at the transition to unit D is a feature recognizable in both cores and may represent a synchronous event.

At 16.20 m the sediments in EC1 change to massive, faintly laminated clayey gyttja silts with no indications of hiatuses or erosional boundaries between the different layers that make up units D and C (Fig. 5). The low organic matter content may be a consequence of low aquatic productivity under cold climatic conditions and/or dilution of the organic fraction by high input of minerogenic particles (Meyers & Lallier-Vergès 1999). High sedimentation rates for units D and C are indeed indicated by the radiocarbon ages of $23\,890 \pm 150$ ^{14}C BP and $17\,090 \pm 90$ ^{14}C BP obtained at 18.29 m and 5.69–5.63 m, respectively. The presence of vivianite coatings on macrofossils may also indicate that the organic matter was buried rapidly, probably under anaerobic conditions (Fagel *et al.* 2005).

Anaerobic conditions would have prevented bioturbation of the sediment, which in turned would have favoured the preservation of sediment laminations in this part of the sequence.

Unit B (5.91–0.68 m) in core EC1 is composed of calcareous sediments with sand lenses, which may indicate sediment starvation and a low-energy sedimentary environment in this late stage of basin infilling. As a whole, units D–B may be interpreted as reflecting the gradual infilling of the basin. The package of sediments above unit E in both cores suggests that high and variable sedimentation rates for the distal units were associated with shoreward thinning and upward coarsening for the littoral areas (Figs 5, 6). The coarse minerogenic sediments overlying unit E in EC3 cannot be further subdivided but probably indicate deposition in shallow water and may be synchronous with units D–B in EC1. The slopes adjacent to the mire are made up of unconsolidated and unsorted glaciofluvial deposits. During times of little vegetation cover (e.g. MIS2) and increased slope instability, these deposits could have provided the sediment for rapid infilling of the basin, which was probably achieved shortly after $17\,090 \pm 90$ ^{14}C BP (Poz-2492). Moreover, reworking of sediments from the littoral zone, as a result of changes in water level, might have been an important supplier of sediment to the middle of the lake. In addition, the occurrence of nearby aeolian sediments points to the fact that airborne particles may account for a large part of the sediments corresponding to MIS2 (de Beaulieu & Reille 1984a).

The uppermost unit A in core EC1 has no counterpart in EC3 and indicates that the marginal areas of the lake had already been filled in at the time of deposition of unit A in EC1.

Correlation of cores EC1 and EC3 to the earlier investigated sequences

Based on detailed pollen stratigraphy, de Beaulieu & Reille (1984a) attempted to correlate the littoral cores IV–C, III–B and V–D of de Beaulieu *et al.* (1980) and the centre core G (Figs 1B, 6, Table 1). Their correlation showed that a number of hiatuses are evident in both sequences and that only parts of the pollen zones recognized in the central core G are present in the marginal cores III–V/B–D.

The sequence between 30 m and 36 m in core G is composed of alternating layers of gyttja and clayey silt (pollen zones B–F) and correlates with the interval between 17 m and 23 m in marginal cores III–V/B–D (Table 1) (de Beaulieu *et al.* 1980; de Beaulieu & Reille 1984a). This succession has a pollen signal typical of vegetation development during the Eemian, Melisey 1, Saint Germain 1, Melisey 2 and Saint Germain 2

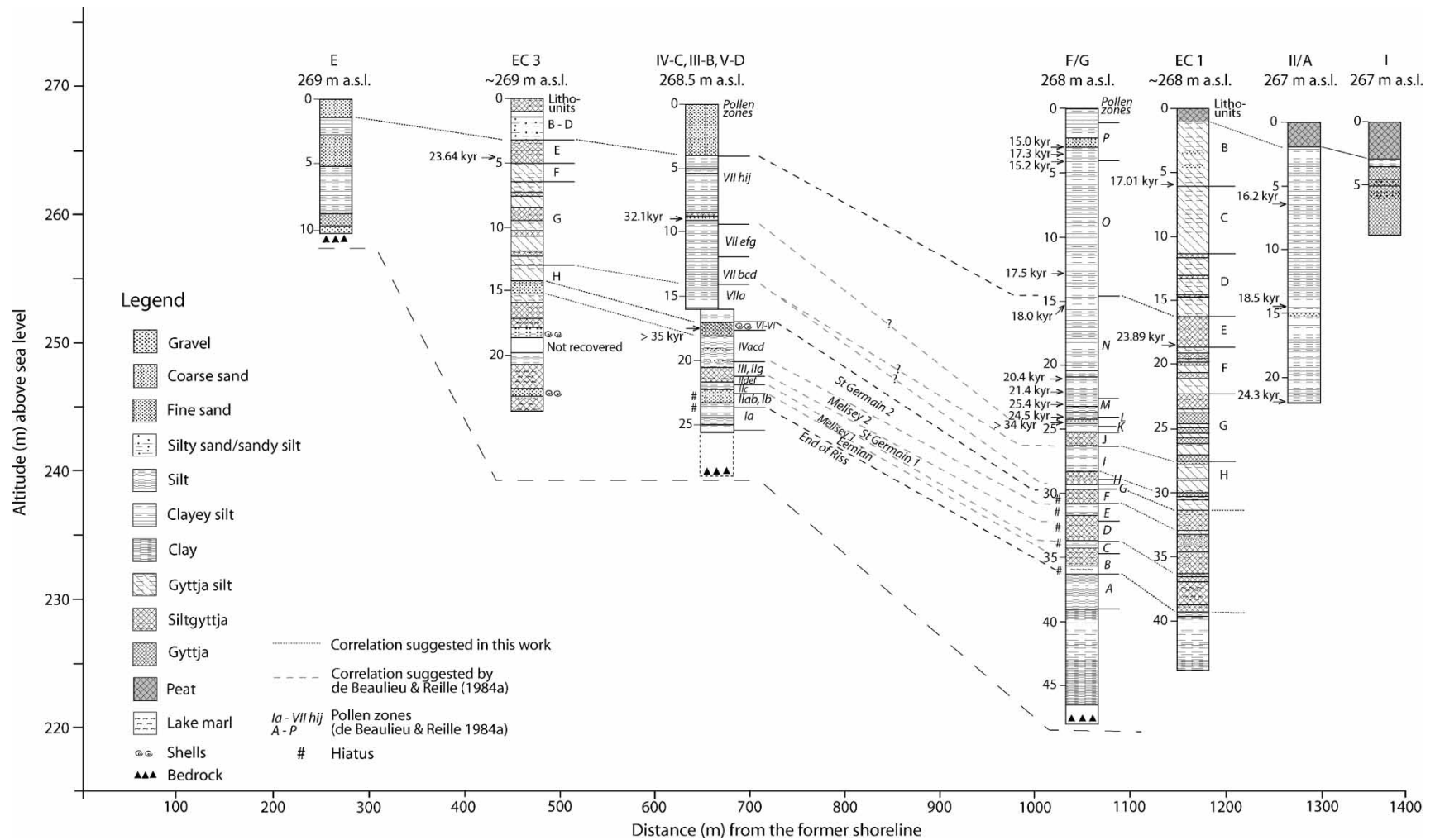


Fig. 6. Stratigraphic transect (south to north) through the Les Echets basin (adapted from Mandier 1981) combining data from previous drillings (see Fig. 1B and Table 1) and the new cores EC1 and EC3. Details on the lithology and palaeoenvironmental interpretation of cores I, II-A, III-B, IV-C, V-D, E and F/G are given in de Beaulieu *et al.* (1980) and de Beaulieu & Reille (1984a, b, 1989) and are summarized in Table 1.

Table 1. Pollen stratigraphic correlation between core G and the littoral cores (III–V/B–D) and summary of the main climatic events identified by de Beaulieu *et al.* (1980) and de Beaulieu & Reille (1984a, b, 1989) at Les Echets.

Pollen zones cores III–V/B–D (de Beaulieu <i>et al.</i> 1980)	Pollen zones core G (de Beaulieu & Reille 1984a)	Pollen stratigraphy/inferred vegetation
Diagramme II	P	<i>Pinus</i> values decrease to <i>c.</i> 10%, <i>Artemisia</i> increases: steppe
VIIIhij	O	Start of Oldest Dryas
End of Würmian pleniglacial, cold and dry steppe	N*	<i>Pinus</i> values of 15–20%: steppe <i>Pinus</i> values <i>c.</i> 30% with abrupt and short peaks
VIIefg	M*	<i>Pinus</i> values <10%
VIIbcd	L*	Very weak interstadial
	K*	Woodless, very dry phase
	J*	Interstadial, minor tree expansion
	I*	Woodless immediate surroundings, sparse regional woodstands
	H*	Interstadial, locally sparse woodland
Plant species during H, J and L require >10°C mean July temperature		
Pollen zones G–L indicate cold and dry climate		
VIIa	G	Cold period
VI	F7	Ognon 1
V	F6	
IVd	F5	
IVc	F4	
IVa reworked	Missing	Saint Germain 2
	F3	
	F2	
	F1	
?	E4	Melisey 2
?	E3	Reworked sediments/pollen
III	E2	Reworked sediments/pollen
IIg	E1	
IIf	D11*	
Missing	D10	
	D9	
	D8	
	D7	
IIe	D6	Saint Germain 1
IID	D5	
Missing	D4	
	D3	
	Hiatus?	
	D2	
	D1	Lower part possibly reworked
IIc2	C/reworked	Melisey 1
IIc1 reworked		Reworked older sediments
Missing	B9	
Missing	B8	
Missing	B7	
Missing	B6a, b	Eemian
IIb	B5*	
	Short hiatus	
IIa	B4	
Missing	B3	Reworking of older sediments or persistent aridity?
Missing	B2	
Ib	B1	
Missing	A2a, b, c	End of Riss
Ia	A1a, b*	

*Correlation uncertain.

in France (de Beaulieu & Reille 1989; Reille & de Beaulieu 1990; Reille *et al.* 2000; Pons *et al.* 1992) and in the Mediterranean region (Allen & Huntley 2000; Tzedakis *et al.* 2004). The sediment succession

between 38 m and 31 m in core EC1 that overlays the glacial clays/silts can be correlated lithologically to core G and therefore attributed to the Eemian, Melisey 1, Saint Germain 1, Melisey 2 and Saint Germain 2.

Similarly, the sequence of layers between 24 m and 14 m in EC3 seems to be equivalent to the interval between 23 m and 18 m in cores III–V/B–D (Fig. 6).

The pollen stratigraphies for the Middle and Upper Würmian (<30 m in core G and <14 m in cores III–V/B–D) were difficult to correlate (de Beaulieu *et al.* 1980; de Beaulieu & Reille 1984a, b). It was tentatively suggested that pollen zones G–L in core G may be equivalent to zones VIIa–VIIefg in the marginal core and that pollen zones M–O may correspond to pollen zones VIIIhij (Fig. 6, Table 1). Frequent hiatuses in the marginal sequence indicate periods of lake-level changes, which complicate a precise correlation with core G (de Beaulieu & Reille 1984a). Moreover, rapid infilling of the basin (pollen zones M–P) and/or low lake levels may have led to non-deposition in marginal areas. The sediments corresponding to pollen zones G–L in core G are composed of alternating layers of gyttja, gyttja silts and clayey silt and show an alternation between cold and dry woodless periods (pollen zones G, I and K) and periods with locally sparse wood stands (pollen zones H, J and L), with mainly *Pinus* but also some *Picea* (de Beaulieu & Reille 1984a). The pollen stratigraphic correlation between core G and cores III–V/B–D suggests hiatuses in the sediment record of the marginal cores corresponding to pollen zones H, I and K (Table 1). Although pollen zones M–P are mainly characterized by steppe elements, *Pinus* pollen values reach nearly 30% in zone N and show a number of abrupt and short peaks (de Beaulieu & Reille 1984a) that could indicate either long-distance transport of pollen or the presence of some pine trees in the region. Radiocarbon dates for pollen zones L–N obtained between 14.50 m and 24 m in core G give ages of between 18 000 and 24 500 ¹⁴C BP and infinite ages at around 24.50 m (Fig. 6).

Assuming that cold–dry periods in our sequence are represented by more minerogenic sediments and low aquatic productivity, and warmer intervals by higher organic matter and higher aquatic productivity, the changes in lithology in cores EC1 and EC3 may be correlated with the vegetation succession and climatic inferences (cold–dry vs. warm) suggested by de Beaulieu & Reille (1984a). Based on the lithology and organic matter values, we therefore tentatively correlate the sediment succession between 31.00 m and 27.48 m in EC1 and between 14.00 m and 13.00 m in EC3 with the interval comprising pollen zones G–I in core G and pollen zone VIIa in cores III–V/B–D, respectively (Fig. 6). Lithological units G–E in core EC1 (27.48–18.55 m) and EC3 (13.00–3.60 m), which display marked variations in organic matter content and as such distinct changes in lake productivity, lake levels or erosion, very probably have a counterpart in pollen zones J–N in core G and pollen zones VIIbcd–VIIIhij in cores III–V/B–D, where minor interstadials alternate with colder intervals. The predominantly clastic sediments with low organic matter in lithological

units D–B document rapid infilling of the lake basin, possibly under cold and dry climatic conditions. These units may correspond with pollen zones O–P, for which steppe vegetation and extreme cold–dry climates have been inferred (de Beaulieu & Reille 1984a). Moreover, radiocarbon dates of between 17 500 and 15 000 ¹⁴C BP in pollen zones O–P in core G indicate rapid sedimentation and compare well with the age of 17 010 ¹⁴C BP obtained for EC1 at 5.69–5.63 m.

The tentative correlation of cores EC1 and EC3 with the pollen stratigraphic record of cores G and III–V/B–D shows that the sediments above 31 m in EC1 and above 14 m in EC3 were deposited during the middle and upper part of the last glacial, i.e. correspond with MIS3–2. However, only the combination of pollen stratigraphy with other environmental proxy data and an independent chronology will allow a precise characterization of the different warm–cold intervals that occurred during this time and their correlation with other archives. Still, our preliminary data show that the new sequence obtained at Les Echets will form an important contribution for a better understanding of the rapid climatic shifts that prevailed during the last glacial period and their impact on the terrestrial environment.

Conclusions

Two long sediment cores (EC1 and EC3) recently recovered from the Les Echets basin have been investigated and correlated based on detailed lithostratigraphy and fluctuations in organic matter content. A chronostratigraphic framework for the two sequences is based on AMS radiocarbon dates and an intrabasin correlation is proposed for the two new sediment cores and the lithostratigraphic data summarized by de Beaulieu *et al.* (1980) and de Beaulieu & Reille (1984a). Based on these correlations, we conclude that the two new cores span MIS3 and MIS2, with three distinct periods of lake development evident during this time interval. Coarse sands and silts poor in organic matter accumulated at the onset of MIS3, while cyclic deposition of relatively organic-rich and organic-poor sediments characterize a large part of MIS3. Massive and rapid sedimentation of highly minerogenic sediments occurred during most of MIS2. The lake ultimately filled in during MIS2 and an extensive Holocene peat bog developed. We also note that there are substantial sedimentological differences between the proximal and distal areas of the former lake. The littoral areas support a more discontinuous, clastic sedimentation while the centre of the lake is more complete, rich in finer sediment and organic matter. Based on the intrabasin transect, we show that the sediment supply to the lake increased significantly during MIS3 and in the later stages of in-filling, providing an exceptional high-resolution

terrestrial climatic record over MIS3 and MIS2. However, the most intriguing feature of the sequence is the cyclic alternation of relatively organic-rich and organic-poor sediments corresponding with the lithostratigraphic units G and E (MIS3). The organic-rich intervals are easily identifiable and the transitions to and from the minerogenic horizons are sharp but not erosional, indicating that important hydrological and geochemical changes occurred in the lake's regime at the time of their deposition. A close comparison with core G (de Beaulieu & Reille 1984a) indicates that the cyclic changes in the organic matter content coincide with recurring changes in pollen assemblages, suggesting that millennial-scale climatic changes controlled the lake's productivity and catchment stability during most of MIS3. A high-resolution dating effort as well as a multiproxy analytical investigation is currently in progress that will clarify the nature of these fluctuations and determine their relationship to D–O cycles.

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