Rapid ecosystem response to abrupt climate changes during the last glacial period in western Europe, 40–16 ka

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ABSTRACT

We present a high-resolution and independently dated multiproxy lake sediment record from the paleolake at Les Échets in southeastern France that displays synchronous changes in independent limnic and terrestrial ecosystem proxies, in concert with millennial-scale climate oscillations during the last glacial period. Distinct lake-level fluctuations, low lake organic productivity, and open, treeless vegetation indicate cold and dry conditions in response to Heinrich events. Alternating phases of higher and low lake organic productivity, stratified surface waters and long-lasting lake ice cover, decreased or increased catchment erosion, and tree-dominated or herb-dominated vegetation resemble Dansgaard-Oeschger interstadial-stadial variability. Transitions between different ecological states occurred in as little as 40–230 yr and seem to have been controlled by the position of the Polar Front. Ecosystem response after 30 ka suggests that local climate conditions became more important. Our results demonstrate that all parts of the terrestrial system responded to the abrupt and dramatic climatic changes associated with Dansgaard-Oeschger and Heinrich events, and that regional factors modulated ecosystem response.

Keywords: lake sediments, paleoenvironmental reconstruction, multiproxy records, Dansgaard-Oeschger cycles, Heinrich events.

INTRODUCTION

The impact of abrupt climate change on terrestrial ecosystems and their response times are key issues in the ongoing debate on current and future climate change. Paleoenvironmental science can make an important contribution to this debate by providing detailed reconstructions of the nature and speed of ecosystem response to rapid climate change in the past (Maslin, 2004; Tzedakis et al., 2004).

The large-amplitude temperature fluctuations during the last glacial period, inferred from $\delta^{18}O$ variations in ice cores (Dansgaard et al., 1993), are ideal for testing the ecological impact of rapid climate change on land and for evaluating the importance of local and regional factors in modulating ecosystem response. These millennial-scale Dansgaard-Oeschger events, which caused rapid shifts in sea surface and air temperatures, are most pronounced around the North Atlantic (Sánchez Goñi et al., 2002; Voelker et al., 2002; Roucoux et al., 2005) and are generally explained by major shifts in meridional overturning circulation (Knutti et al., 2004; EPICA Community Members, 2006). Longer lasting Dansgaard-Oeschger (DO) events were preceded by massive iceberg surges from Northern Hemisphere ice sheets (Bond et al., 1993), the so-called Heinrich events (H), which had regional and possibly global impacts (Hemming, 2004). However, the paucity of well-dated multiproxy continental records (Voelker et al., 2002) that document past ecosystem response to DO and H events in great detail has hampered high-resolution terrestrial reconstructions of the large-scale climate changes recorded in North Atlantic marine sediments (Bond et al., 1993; Chapman et al., 2000; de Abreu et al., 2003; Hemming, 2004; Vautravers and Shackleton, 2006) and ice cores (Dansgaard et al., 1993; Johnsen et al., 2001). The nature and, in particular, the speed of the response of terrestrial ecosystems (Tzedakis et al., 2004) to these rapid climatic shifts remain inconclusive, despite the fact that the large-amplitude temperature fluctuations of 8–16 °C reconstructed for Greenland (Huber et al., 2006) must have had a major impact on continental sites around the North Atlantic.

To test this hypothesis and to evaluate the contribution of local and regional factors in modulating ecosystem response, we focused on a region in southwestern Europe, where pollen records from marine sediments (Sánchez Goñi et al., 2002; de Abreu et al., 2003; Roucoux et al.,

2005) show distinct variability in concert with DO fluctuations and H events. Our independently dated multiproxy lake sediment sequence is derived from the paleolake that existed at Les Échets (45°54′N, 4°56′E, 267 m above sea level) in southeastern France. It provides a long-sought link between North Atlantic marine and ice core archives and terrestrial sequences from Europe, where information on submillennial-scale climate variability is scarce or fragmentary (Voelker et al., 2002). High sedimentation rates, in particular between 36.3 and 16.0 ka, permitted the high-resolution multiproxy analyses necessary to determine ecosystem changes associated with the abrupt millennial-scale climate oscillations that occurred during the last glacial period.

METHODS

Core EC 1 was drilled to 44 m in the central part of the Les Échets paleolake. As the alternating organic and inorganic sediments between 30.06 and 6.00 m depth were ideally suited for accelerator mass spectrometry (AMS) radiocarbon (^{14}C) and infrared stimulated luminescence (IRSL) dating, we focused high-resolution multiproxy analyses on this section of the core (see the GSA Data Repository[1]). We used mineral magnetic susceptibility (χ), dry density, and grain-size variations to assess relative changes in catchment erosion. Lake status changes were reconstructed based on loss on ignition (LOI), total organic carbon (TOC), total nitrogen (TN), $\delta^{13}C_{org}$, hydrogen index (HI), oxygen index (OI), biogenic silica (BSi), and diatom assemblages. Changes in terrestrial vegetation were determined through pollen analysis. Age assignment is based on 48 AMS ^{14}C measurements obtained on unidentified plant macrofossils, pollen, and the insoluble bulk sediment fraction, and 21 IRSL dates (Fig. 1A; Tables DR1 and DR2 [see footnote 1]). Since most of our ^{14}C dates are older than the limit of the IntCal04 radiocarbon calibration curve (Reimer et al., 2004), we chose an updated calibration set (Hughen et al., 2006) for computing an age-depth model (Fig. 1B).

LES ÉCHETS—LAKE STATUS CHANGES

In accordance with lithostratigraphic observations, the age-depth model indicates a major hiatus at 28.00 m, spanning the time interval between 40.3 and 36.3 ka (Figs. 1B, 2A, and 2B). The lower limit of the hiatus coincides with the beginning of H4 (Thouveny et al., 2000; de Abreu et al., 2003) (Fig. 2D), one of the most severe H events (Sánchez Goñi et al., 2002; Vautravers and Shackleton, 2006), that caused a rapid decline in North Atlantic sea surface temperatures (Chapman et al., 2000; de Abreu et al., 2003) and led to distinctly cold and arid conditions over western Europe (Tzedakis et al., 2004; Roucoux et al., 2005). These cold and dry conditions likely resulted in a dramatic lowering of the water level in the basin. The extremely low concentration of diatoms before 36.1 ka and between 31.7 and 30 ka and 26 and 23.6 ka (Fig. 2B) coincides with intervals of increased catchment erosion, low lake organic productivity, and herb-dominated vegetation. The two latter intervals overlap with H3 and H2 (Bard et al., 2000; de Abreu et al., 2003; Roucoux et al., 2005) (Fig. 2D). We hypothesize that cold and arid conditions (Sánchez Goñi et al., 2002; de Abreu et al., 2003; Roucoux et al., 2005) caused the water level to drop in the lake, and that exposed shores and an open landscape facilitated eolian activity, increasing sediment supply to the basin. High concentrations of suspended sediment in a turbulent water column would have limited diatom growth during these intervals.

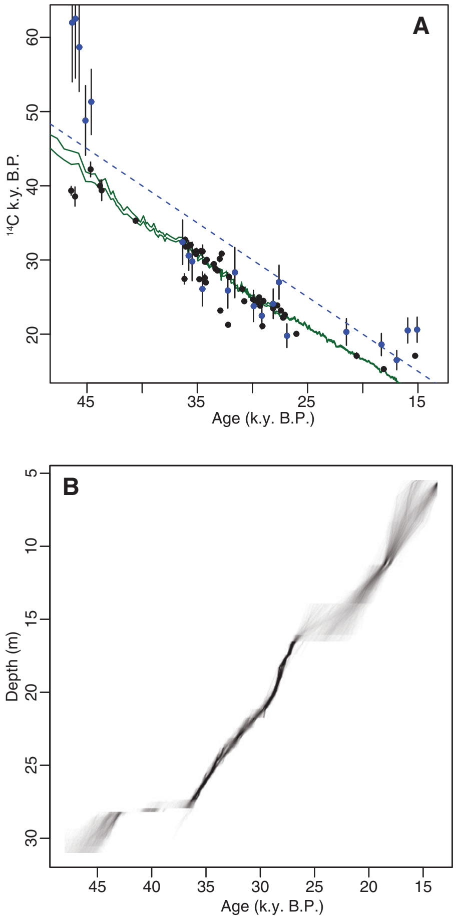

Figure 1. Age-depth model for Les Échets lake sediment core. A: Plot of ^{14}C and infrared stimulated luminescence (IRSL) dates shows that most of the ^{14}C dates (black circles) fit Cariaco comparison curve (Hughen et al., 2006) (green lines give 1 standard deviation envelope), although outliers exist ca. 37–30 ka B.P. IRSL dates (blue circles) are not fitted to Cariaco curve, but to blue dashed line (vertical age = horizontal age). B: Age-depth model for Les Échets sequence computed with Bayesian software Bpeat (GSA Data Repository; see footnote 1). Calendar-year uncertainties are estimated through more than 10^9 iterations, which provide the posterior distributions of all parameters involved (Blaauw and Christen, 2005). Histograms of calendar ages of all iterations give calendar-age distribution, and thus chronological uncertainty, for each depth of the core. Here we graph histograms as gray scales. Darker colors indicate more likely calendar ages. Age-depth model uncertainty is ~200–2000 yr (mean error ~460 yr between 36 and 27 ka B.P.).

The most remarkable features of our sediment sequence are the distinct and synchronous changes in all paleoenvironmental proxies. Phases of relatively high and low lake organic productivity, as inferred from fluctuations in LOI, TOC, TN, C/N, $\delta^{13}C_{org}$, HI, and BSi, oscillate markedly between 36.3 and 31.7 ka (Fig. 2B). Coincident with increased lake organic productivity phases A–E (Figs. 2B, 2C), higher amounts of arboreal pollen (AP) reflect the presence of trees in the region and warmer, more humid climatic conditions. Lower values for catchment erosion indicators suggest that runoff was minimal, although C/N ratios >15 signify the addition of terrestrial organic material to the organic carbon pool (Meyers and Lallier-Vergès, 1999). Marked increases in planktonic diatoms imply seasonally stratified surface waters through the presence of *Cyclotella comensis*, *C. ocellata*, and *C. delicatula*. In contrast, intervals with low lake organic productivity are characterized by large amounts of nonarboreal pollen (NAP), suggesting open, treeless vegetation and a cold, dry climate. Higher values for catchment erosion indicators show that sediment supply increased; if conditions were arid, as implied by high NAP values, this sediment may be eolian in origin. Low lake organic productivity phases are dominated by benthic diatoms, primarily *Fragilaria*, typical for lakes with long-lasting ice-cover. The synchronous response of limnic and terrestrial proxies between 36.3 and 31.7 ka demonstrates clearly the tandem response of the lake and terrestrial ecosystems to abrupt climate oscillations. After 31.7 ka, shifts in lake organic productivity (phases F–H in Figs. 2B, 2C) are more attenuated, and the decoupling of NAP and AP values from lake productivity and catchment erosion may reflect a change in the pollen source area, increased long-distance transport of tree pollen, and/or pollen reworking.

The changes in NAP and AP frequencies resemble closely vegetation reconstructions from North Atlantic marine sediments (Sánchez Goñi et al., 2002; Roucoux et al., 2005) that indicate the development of steppe vegetation and increased aridity in southwestern Europe during DO stadials and the expansion of forest

[1]GSA Data Repository item 2008098, details on analytical methods and geochronology, Table DR1 (^{14}C accelerator mass spectrometry ages for Les Échets core EC 1), Table DR2 (infrared stimulated luminescence ages for Les Échets core EC 1), and references, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

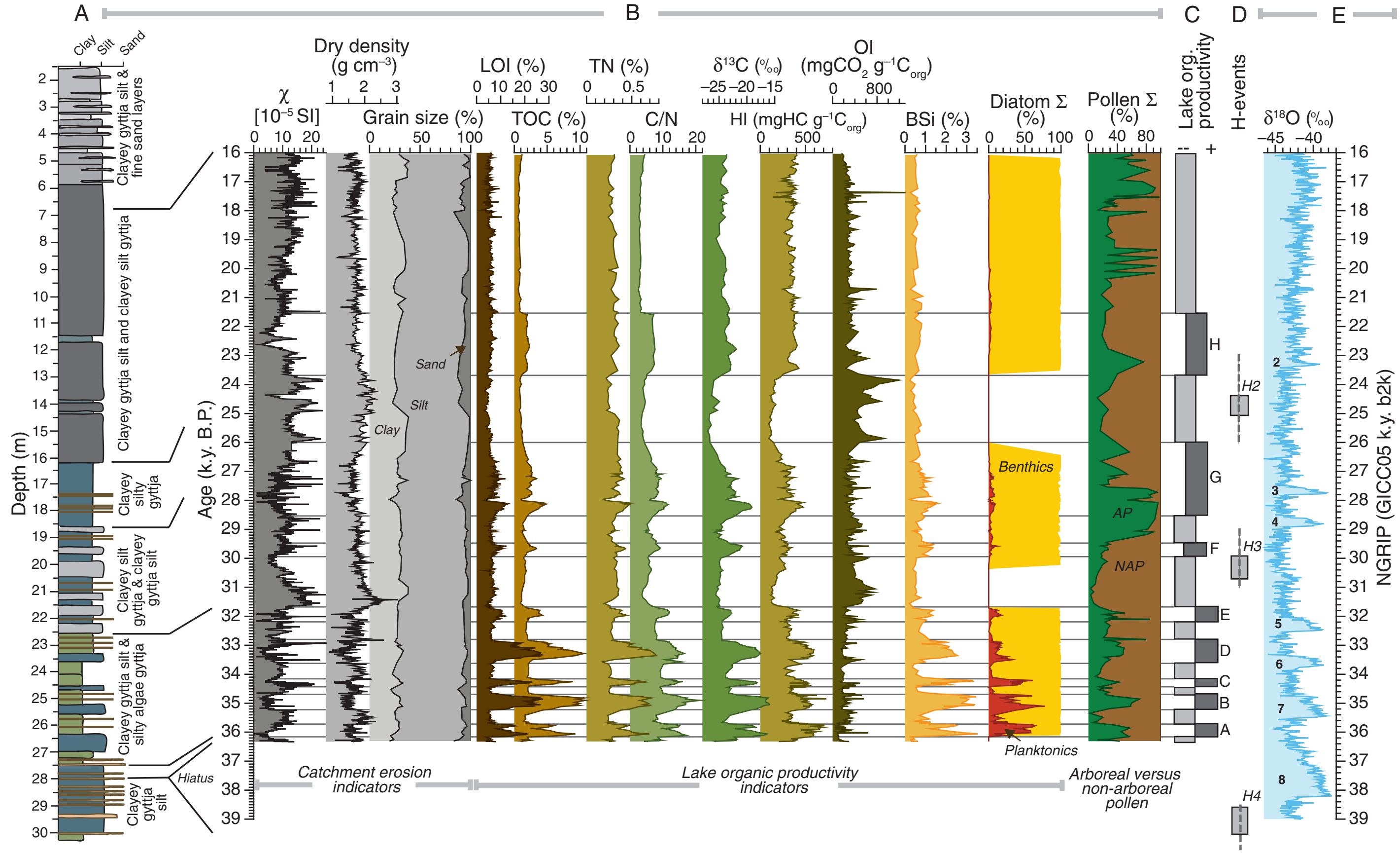

Figure 2. Les Échets lithostratigraphy and paleoenvironmental records. A: Schematic lithostratigraphy of core EC 1 on depth scale. Sequence above 6 m was not analyzed because of postdepositional disturbance. B: Multiproxy data for core EC 1. Higher lake organic productivity is inferred from higher values of loss on ignition (LOI) (Veres et al., 2007), total organic carbon (TC), total nitrogen (TN), $\delta^{13}C_{org}$, hydrogen index (HI), and biogenic silica (BSi), and lower lake organic productivity is reflected by decreases in these parameters. These changes are paralleled by shifts in catchment erosion indicators (magnetic susceptibility χ, dry density, and grain size), which decrease during higher and increase during lower lake organic productivity phases. Distinct peaks in χ coincide with thin, fine sand layers shown in A that are interpreted as wind-blown material. Benthic diatoms dominate most of the sequence while planktonic diatoms are only frequent during higher lake organic productivity phases. C/N is used to discriminate between limnic and terrestrial organic matter, and oxygen index (OI) indicates state of decomposition of organic matter. Changes in nonarboreal (NAP) and arboreal pollen (AP) percentages reflect alternations between open, herb-dominated vegetation and dominance by trees. C: Phases of increased lake organic productivity (labeled A–H) reflect warmer conditions and higher nutrient availability. D: Calibrated age ranges (Bard et al., 2000; Sánchez Goñi et al., 2002; de Abreu et al., 2003) (stippled lines) and calculated ages (Thouveny et al., 2000, filled gray bars) for Heinrich (H) events 4, 3, and 2. E: $\delta^{18}O$ curve for North Greenland Ice Core Project (NGRIP) (Andersen et al., 2006) with Dansgaard-Oeschger (DO) interstadials 8–2. GICC05 b2k—Greenland Ice Core Chronology 2005 before the year 2000.

during interstadials, when sea surface temperatures were higher and humidity increased. We argue that fluctuations between low and high lake organic productivity in our record are the terrestrial equivalent of DO stadials and interstadials recorded in marine sediments and the Greenland ice cores (Fig. 2E).

The differences in timing and amplitude of the relatively high and intervening low lake organic productivity phases (Figs. 2B, 2C) indicate that ecosystem response to climate change varied through time. High-resolution analyses of LOI (<25 yr) and χ (<5 yr) allow us to estimate the duration of each phase and the ecosystem response time. For example, high lake organic productivity phases A–D lasted for ~200–600 yr, while phase H spanned ~2200 yr. Low lake organic productivity phases persisted initially for 200–700 yr, but became progressively longer after 31.7 ka, coincident with the shift to lower amplitude productivity peaks. These marked ecosystem changes occurred rapidly i.e., in 40–230 yr, including sedimentation rate uncertainties.

REGIONAL VERSUS LOCAL CLIMATIC FACTORS

The transition from low to higher lake organic productivity at Les Échets parallels the abrupt temperature rise at the beginning of DO interstadials in Greenland (Dansgaard et al., 1993; Andersen et al., 2006; Jouzel et al., 2007). The rapid shift back to low productivity differs, however, from the sawtooth-shaped and progressively declining Greenland $\delta^{18}O$ values (Figs. 2B and 2E) and resembles more the step shape of the ice core deuterium excess record, which is considered a proxy for climatic conditions in the oceanic moisture source region (Jouzel et al., 2007). Although air temperatures over Greenland gradually decreased soon after peak DO interstadial temperatures had been reached, sea surface temperatures in the moisture source region and air temperatures over adjacent land areas remained high until Greenland attained its coldest temperatures. The decoupling between central Greenland and North Atlantic temperatures may have been caused by a gradual southward shift of the Polar Front (Jouzel et al., 2007). The sudden temperature drop in the moisture source region subsequently triggered the shift from higher to low lake organic productivity in the Les Échets paleolake. Recovery from this cold lake status occurred when North Atlantic sea surface temperatures and air temperatures over land increased again, simultaneously with Greenland air temperatures (Jouzel et al., 2007). This scenario suggests asynchroneity between Greenland temperatures and ecosystem response following peak DO warming, and cautions that teleconnections to the Greenland $\delta^{18}O$ record may be misleading if not underpinned by independent chronologies.

After 30 ka the lake system changed dramatically and long-lasting low lake organic productivity phases alternated with attenuated higher productivity phases. This transformation coincides with the expansion of alpine glaciers into the foreland (Preusser et al., 2007). The presence of the Rhône glacier, indicated by terminal moraines and glacial outwash <30 km from Les Échets, would have rendered the lake ecosystem less susceptible to changes in the position of the Polar Front. The transition from large-scale climate controls to regional factors emphasizes their importance in modulating ecosystem response to climate change.

CONCLUSIONS

The independently dated paleoenvironmental record from Les Échets demonstrates distinct ecosystem response to DO climate variability and H events. Synchronous changes in limnic and terrestrial proxies highlight the involvement of all parts of the terrestrial system and demonstrate that lake system response was unique for each climatic event and was influenced greatly by local and regional conditions. Transitions between different states occurred within as little as 40–230 yr, emphasizing the sensitivity of ecosystems once critical thresholds are crossed (Maslin, 2004). The paleoenvironmental record from Les Échets supports modern ecological studies (Walther et al., 2002; Parmesan and Yohe, 2003) that indicate that current and future climate change will have dramatic consequences for our remaining natural ecosystems.

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