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Volcano- and climate-driven changes in atmospheric dust sources and fluxes since the Late Glacial in Central Europe

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ABSTRACT

Atmospheric dusts are an important part of the global climate system, and play an important role in the marine and terrestrial biogeochemical cycles of major and trace nutrient elements. A peat bog record of atmospheric deposition shows considerable variation in dust deposition during the past 15 k.y., with abrupt changes in fluxes at 12, 9.2, 8.4, 7.2, and 6 cal. kyr B.P. Using Nd isotopes and rare earth elements, it is possible to clearly distinguish between volcanic inputs and those driven by climate change, such as the long-term aridification of the Sahara and regional erosion due to forest clearing and soil cultivation activities. Our results indicate that a major dust event in North Africa and Europe preceded the 8.2 kyr B.P. cold event by 200 yr. This dust event may have played an active role in the following climate cooling of the 8.2 kyr B.P. event. Nd isotope evidence also indicates a relatively slow change in dust regime over Europe from 7 to 5 kyr B.P. due to Sahara expansion. These findings show that the inorganic fraction in high-resolution peat records can provide remarkably sensitive indicators of dust load and sources. Our study supports the priority to better identify the impact of dust loading during the Holocene in terms of direct and indirect impacts on environmental and climate changes.

INTRODUCTION

Atmospheric mineral dusts from diverse natural sources affect the biogeochemical cycles of many elements in marine (Meskhidze et al., 2003) as well as terrestrial ecosystems (Goudie and Middleton, 2001). For example, in highly weathered soils of Hawaii, dusts from Asia have been found to represent an important source of phosphorus (P) to plants (Chadwick et al., 1999). Dust modifies the radiation budget and thus plays an important role in Earth's climate system (Goudie and Middleton, 2001; Harrison et al., 2001). The fluxes of these dusts are linked to their source areas (Grousset and Biscaye, 2005), mainly desert and arid regions, by the intensity and frequency of the transporting weather systems (Goudie and Middleton, 2001). Superimposed on the dust background are the episodic additions of particles from explosive volcanoes (Oppenheimer, 2003), and from large continental deserts during abrupt global cold events, as recorded in polar ice cores for the 8.2 kyr B.P. and the Younger Dryas events (Goudie and Middleton, 2001; Alley and Agustdottir, 2005). Detailed knowledge of the natural variations in atmospheric dust deposition is crucial for understanding the response of dust to climate change and the effects on ecosystems, but also to better understand the feedbacks that dust loading may have on climate. To date, despite the obvious importance of atmospheric mineral dusts, there are remarkably few continental records of their changing rates and sources. To help narrow this knowledge gap, a peat profile from Etang de la Gruère, a well-studied bog in the Jura Mountains of Switzerland, is used as an archive of atmospheric dust deposition in Central Europe.

MATERIALS AND METHODS

Etang de la Gruère is a raised ombrotrophic bog that receives inputs exclusively from the atmosphere. It consists of as much as 650 cm of peat directly overlying lacustrine clay. In an early study using peat cores from this bog, atmospheric Pb deposition was reconstructed using Pb isotopes, but the sampling thickness of these cores provided limited temporal resolution (Shotyk et al., 1998). A subsequent report employing a second set of cores from the same bog provided much better sampling resolution, but the focus of that study was Hg deposition (Roos-Barraclough et al., 2002). We use the Ti concentrations from this high-resolution peat core and the numerous ^{14}C age dates to create a detailed, high-resolution reconstruction of total dust deposition (see Figs. DR1–DR5 and text in the GSA Data Repository[1]). To distinguish between soil-derived mineral dusts and volcanic inputs, and to identify possible source areas, the rare earth elements (REE) were measured along with $^{143}Nd/^{144}Nd$ isotope ratios, with emphasis on the peat samples dating from the early to mid-Holocene, when abrupt dust pulses occurred. The dust fluxes and REE and $^{143}Nd/^{144}Nd$ results are compared with pollen data (see the Data Repository, including Fig. DR7) to try to resolve the sequence of changes in dust deposition and vegetation change with a view to identifying possible causes and effects.

ABRUPT DUST EVENTS DURING THE LATE GLACIAL AND THE HOLOCENE

Combining the Ti concentrations (Fig. 1A) with the peat accumulation rates allows the dust flux to the bog to be estimated (Fig. 1B) (see the Data Repository, including Fig. DR6 and Table DR1). Some of the periods of most rapid change, i.e., ca. 12, 9.2, 8.4, 7.2, and 6 kyr B.P., are discussed in detail here.

Younger Dryas

A large peak of dust (>8 g m^{-2} yr^{-1}) is recorded from 12.8 k.y. to 11.7 kyr B.P., consistent with the Younger Dryas (YD) time window

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[1] GSA Data Repository item 2012093, details of age depth model, details of the two cores (complete pollen diagram), and details of dust flux calculation, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

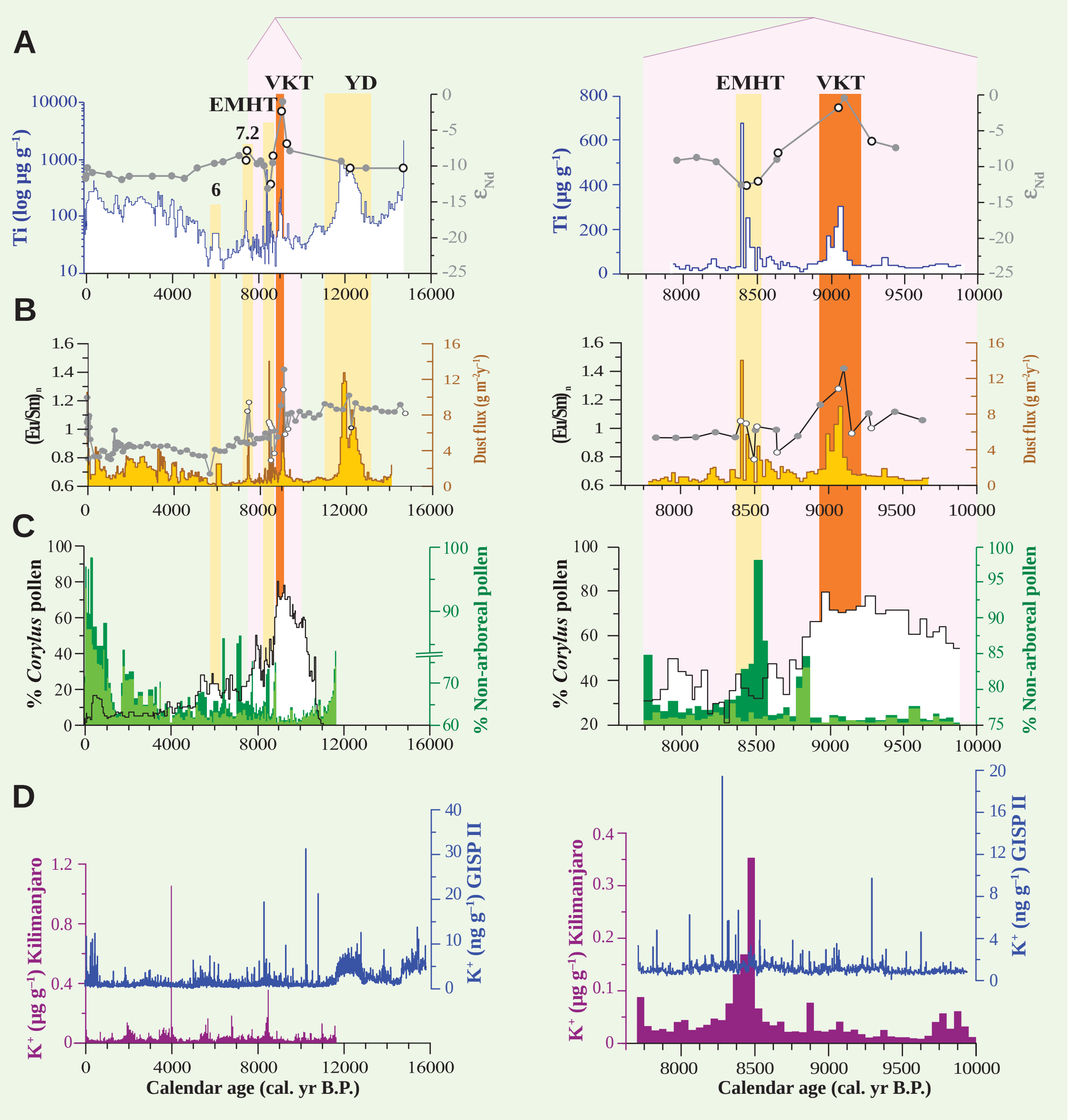

Figure 1. Proxies versus age measured at Etang de la Gruère (Switzerland). A: Ti concentration (log scale) in high-resolution core and composite Nd isotope curve using both samples from high-resolution (white circles) and low-resolution (gray circles) peat cores. VKT—Vasset and Kilian Tephras; YD—Younger Dryas; EMHT—early-middle Holocene transition. B: (Eu/Sm)$_n$ ratio in peat samples normalized to upper continental crust composition, and dust deposition rate reconstructed from high-resolution core. C: Percentage of *Corylus*, grassland (light green), and shrub pollen (dark green). D: K$^+$ measured in Kilimanjaro ice core (Thompson et al., 2002) and in Greenland (Greenland Ice Sheet Project 2, GISP II; Mayewski et al., 1997).

(Muscheler et al., 2008). The deepest peat layer, at the interface with the basal (Oxfordian) clay, reflects the composition of local sediments and has an ε_{Nd} of −9.6. This value is similar to the YD dust event (ε_{Nd} = −9.7). The ε_{Nd} isotope signature on its own does not allow a clear distinction between a mixing of local and regional sources (Lahd Geagea et al., 2008a), contributions from the Laacher See and the Vedde ash tephra layers (Lane et al., 2012), or possible remote source areas such as the great deserts of Asia (Grousset and Biscaye, 2005). However, the estimated dust flux during the YD (Fig. 1B) reveals two periods of enhanced deposition: the first of these (ca. 12.2 kyr B.P.) is characterized by a negative shift in the (Eu/Sm)$_n$ ratio (Fig. 1B) consistent with long-range transport of Asian desert dust (Svensson et al., 2000), and the second peak (ca. 12 kyr B.P.) is a positive shift that may correspond to a volcanic signature (Vedde Ash).

Early-Middle Holocene Transition

Another significant period of increased dust deposition consisting of two separate peaks is found between 9.3 and 8.8 kyr B.P., probably corresponding in time to two nearly contemporaneous volcanic eruptions in the Massif Central (France), evidenced by the Vasset and Kilian Tephras, which are also found in peat and lake cores from Switzerland (Juvigné, 1991) and dated precisely in the varve chronology of Lake Soppensee at between 9291 and 9412 kyr B.P. (Hajdas and Michczynski, 2010). The marked ε_{Nd} shift from an average −8 baseline to an average of −1 (Fig. 1A) is clear evidence of a mantle-derived material, i.e., volcanic dust (Grousset and Biscaye, 2005) (Fig. 1). Because the Fe-bearing components of volcanic ash may be partially or completed altered subsequent to burial in acidic, anoxic peat (Hodder et al., 1991), the ε_{Nd} provides a promising alternative method with which to detect cryptotephras. The elevated dust flux (to ~8 g m^{-2} yr^{-1}) during this period of <100 yr shows a following relative increase in *Graminae* pollen **(**Fig. 1C). We suggest that the profound increase in dust deposition, the rapid dissolution of fine-grained volcanic ash components, and the subsequent release and availability of plant nutrients may have catalyzed the change in surrounding bog vegetation.

One of the most pronounced peaks in dust flux (>12 g m^{-2} yr^{-1}) occurred during the early-middle Holocene transition, ca. 8.4 kyr B.P. (Fig. 1B). Based on the peat accumulation rate, it lasted ~180 yr and is marked by a local vegetation change with a relative increase in shrubs like *Empetrum* sp., which corresponds to drier conditions. The ε_{Nd} signature declines from −8 to −12.5, an uncommon value for erodible European soils (Lahd Geagea et al., 2008a) but comparable to those of old continental shields (i.e., lower ε_{Nd} values) such as those of the Sahara (Grousset and Biscaye, 2005). Evidence of enhanced Saharan dust deposition during the same period can also be found in lake and ice records from Africa (Gasse, 2000; Thompson et al., 2002). As in the Swiss peat bog studied here, in these other cases the dust peak precedes the well-known 8.2 kyr B.P. cold event recorded in polar ice (Mayewski et al., 1997), as shown in Figure 1D. It also precedes the maximum decline of *Corylus* (Fig. 1C), which is dated as 8175 ± 45 yr ago in varved sediments from Lake Soppensee and related to the 8.2 kyr B.P.cold event (Tinner and Lotter, 2001). Our results, which are highly time constrained, suggest that (1) Saharan desertification and enhanced windiness triggered abrupt dust events in Africa and Europe ca. 8.4 kyr B.P., and (2) these dust events may not be related to the 8.2 kyr B.P. cold event as recorded in Greenland and Europe (Alley and Agustdottir, 2005), or emphasize a series of forcing factors acting almost simultaneously during the early Holocene, evidencing a multicentury climate deterioration (Rohling and Palike, 2005; Bond et al., 2001). Another dust event is distinguished on the high-resolution core ca. 7.4–7.2 kyr B.P. (Fig. 1); the ε_{Nd} coupled with the Eu/Sm suggests a third unknown dust source (distinct from Sahara and volcanism). The event was followed by a slow (200 yr) vegetation change beginning with a relative decrease in tree pollen 7.2 kyr B.P.

A last 6 kyr B.P. dust event is only marked by a change in REE (Fig. 1). Its timing corresponds to Bond Event 4 (Bond et al., 2001). This event was noticed in a change in Ti/Sc ratio at Etang de la Gruère (Shotyk et al., 2002), and it was suggested that it corresponded to massive eruptions in Iceland or the Faroe Islands, based on Pb isotope evidence in European peat bogs (Chambers et al., 2012). The absence of a positive ε_{Nd} shift seems to contradict this hypothesis.

LONG-TERM DUST DEPOSITION OVER CONTINENTAL EUROPE

The abrupt events described here are superimposed on a long-term trend in REEs and ε_{Nd} (Fig. 1). Early Holocene stability is evidenced by ε_{Nd} between –8 and –9. Enhanced Ti concentrations (~25 to ~150 µg g^{-1}) and dust flux (~0.2 to ~3 g m^{-2} yr^{-1}) (Fig. 1B) with a decrease in the ε_{Nd} signature are evidence of the increase of Saharan dust loading from 7 to 4.5 kyr B.P. This timing of Sahara expansion is supported by paleoenvironmental data from the West Africa Atlantic coast (deMenocal et al., 2000) and models of past Saharan vegetation cover (Claussen et al., 1999; Liu et al., 2007) (Fig. 2). Our results suggest a clear stabilization of Saharan dust input over Europe after 5 kyr B.P. (Fig. 2, period T2). The change in dust regime occurred over a 2 k.y. period (Fig. 2, period T1). It is longer and smoother than registered in Atlantic marine records (deMenocal et al., 2000) and more similar to a Holocene sediment record from the Somalian coast (Jung et al., 2004). The last 2 k.y. are clearly marked by human impacts on the regional landscape (Fig. 1, increase in nonarboreal pollen; Fig. 2, period T3). Agriculture and grazing changed the pollen assemblage (increase in cereal, *Plantago lanceolata*, and *Rumex* pollen) and enhanced local erosion, marked by an increase in dust deposition that is in agreement with other regional human-induced dust changes (Sjogren, 2006). It is further supported by the slight ε_{Nd} increase to –9.6 after 1.5 kyr B.P., in agreement with a central Alpine crustal ε_{Nd} signature (Lahd Geagea et al., 2008a, 2008b), and mirroring the increasing contribution of local particles. The two youngest samples (A.D. 1967 and 1991) show a decreased ε_{Nd}. This decrease is linked to an increase in tree pollen (i.e., reforestation), thus a decrease of the local dust contribution and/or a recent increase of Saharan dust load. Anthropogenic aerosol contributions with lower ε_{Nd} signature cannot be excluded (Lahd Geagea et al., 2008b).

IMPLICATIONS FOR FUTURE WORK

Dust deposition chronology recorded at Etang de la Gruère coupled with REE and Nd isotope data show that dust loading and sources were very variable during the Holocene (Fig. 3), with large dust events

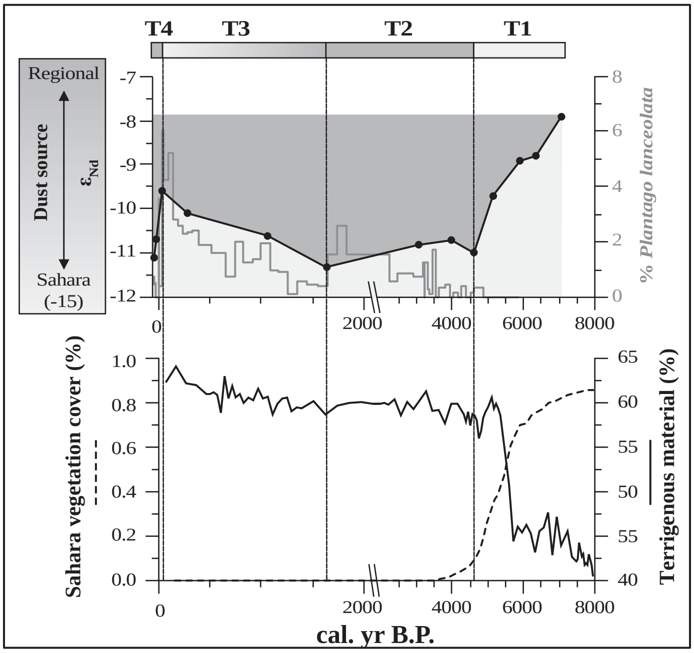

Figure 2. The ε_{Nd} isotope signal as recorded in low-resolution Etang de la Gruère peat core, percentage of *Plantago lanceolata*, percentage of terrigenous material in core from African Atlantic coast (deMenocal et al., 2000), and modeled percentage of Sahara vegetation cover (Claussen et al., 1999). T1–T4 are time periods (see text).

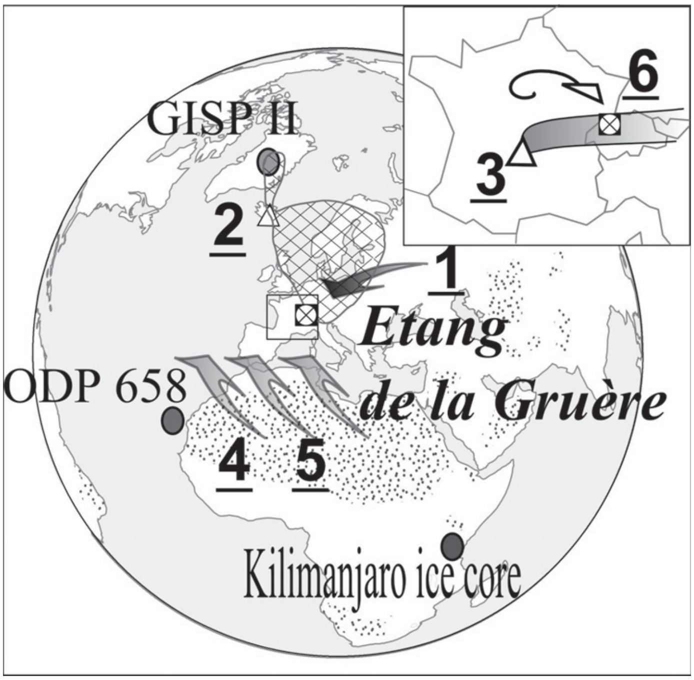

Figure 3. Map summary of major dust events that have affected continental Europe over Holocene. 1—Younger Dryas; 2—Vedde ash eruption; 3—Vasset and Kilian eruptions; 4—8.4 cal. kyr B.P. Saharan dust event; 5—Sahara aridification; 6—regional soil erosion. Dotted areas are main deserts; gray area in inset is distribution of Vasset and Kilian ash tephras; hachured area is distribution of Vedde ash tephra. GISP II—Greenland Ice Sheet Project 2; ODP—Ocean Drilling Program.

caused by explosive volcanoes and eolian transport of desert particles. The Vasset-Kilian eruption and the Saharan dust event 8.4 kyr B.P. represent 2.4% and 4.6%, respectively, of the dust deposited during the past 10 k.y. Dust events, such as the 8.4kyr B.P. Saharan dust event, may have played an essential role in succeeding climate change, i.e., by fertilizing oceanic areas and oligotrophic terrestrial areas, thus changing the radiative and hydrological properties of the atmosphere. It may, for example, have partly initiated the CO_2 negative drop of 25 ppm observed at 8.2 kyr B.P. (Wagner et al., 2002). Using REEs and Nd isotopes, we show that Saharan dust has played an essential role in dust loading over Europe on a long-term basis, Saharan dust having increased after the end of the African Humid Period ca. 6 kyr B.P. Such variability must be taken into account when modeling future environmental changes, i.e., nutrient inputs or light occultation by future Saharan dust pulses. Our study supports carefully constraining abrupt dust events both spatially and temporally in order to better understand their role on global environmental and climate changes.

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