cations therefore reflect variability in the EASM and IOSM respectively.

Global connections of the Asian monsoon recorded in peat

Comparison of the Hani and Hongyuan $\delta^{13}C$ records has revealed the phenomenon of antiphase variations between the EASM and IOSM on centennial to millennial timescales (Fig. 2). Abrupt strengthening of the EASM and simultaneous abrupt weakening of the IOSM appear to have occurred at times that correspond to the nine abrupt ice-rafted debris events in the North Atlantic (Hong et al., 2003, 2005), suggesting global teleconnections between the North Atlantic, Pacific Ocean and monsoon systems throughout the Holocene. The anti-phase variations of the two Asian monsoons correspond to both reduced solar activity in the late Holocene and to meltwater events in the early Holocene. A conceptual model of global climate changes that summarizes the connections between ice sheet variations at high northern latitudes, ocean-atmospheric process of the equatorial Pacific, monsoonal activity in the middle-low latitudes, and solar activity is shown in Figure 3. It remains for these interactive processes to be further examined and tested against new paleoclimate records. Peat cellulose isotope indicators could play an important role in this investigation because nearly all land regions affected by the processes mentioned above possess peatlands. A systematic global comparative study on peatland paleoclimatology would help test our hypotheses of monsoon variability as well as addressing other key paleoclimate questions (see e.g., Booth et al., this issue).

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Peat as an archive of atmospheric pollution and environmental change: A case study of lead in Europe

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Inorganic geochemistry in peat deposits provides unique and valuable indications of human activities and consequent environmental changes.

European heavy metal pollution

Ombrotrophic bogs are uniquely suited to provide records of natural and anthropogenic airborne particles because their surface layers are exclusively fed by atmospheric inputs (i.e., rain, snow, fog, dust), and hence offer the unique possibility to record atmospheric metal emissions at a relatively high time-resolution (centennial to decadal). Peat cores from such bogs are excellent continental archives of atmospheric lead (Pb) deposition not only because they receive Pb solely from the air but also because they efficiently retain this metal despite their low pore-water pH (c. 4) and the seasonal variations in redox potential that should promote particle dissolution (e.g., Shotyk and Le Roux, 2005, and references therein). The high abundance of natural complex-forming organic acids guarantees the preservation of metal-bearing particles, especially lead.

It is of particular importance to document both background and actual metal fluxes because the atmospheric geochemical cycle of lead and other metals has been profoundly affected by human activities throughout the Northern Hemisphere for more than 3 ka (Nriagu, 1983). Human activities have significantly impacted the atmospheric emissions of a broad range of metals and metalloids (e.g., Pb, copper (Cu), zinc, cadmium, mercury (Hg)), as a result of the smelting of metal sulfide ores and the combustion of coal, both releasing particulates and aerosols (Pacyna et al., 2007, 2009). Given the ease by which it can be smelted and the number of possible industrial and commercial applications, Pb has been used by humans for more than 8 ka (Wertime, 1973). In addition, the stable isotopes of Pb allow "natural" Pb to be distinguished from various anthropogenic sources (lead ores, coal, gasoline), allowing one to track pollution sources and tackle the origin of long-range natural dust contributions during the Holocene.

Long-term Pb emissions over Europe have been unambiguously documented by analysis of peat cores from ombrotrophic bogs (e.g., Shotyk et al., 1998). Using Pb isotopes, Kylander et al. (2005) in Spain and Shotyk et al. (1998) in Switzerland have also shown significant variability in Saharan dust input over Europe during the Holocene. From a paleotoxicity point of view, the pre-anthropogenic emissions of Pb-bearing particles are insignificant compared to late Holocene anthropogenic emissions. Moreover, their larger grain size (5-50 µm compared to 0.5 µm for anthropogenic particles) and low solubility in natural conditions render them largely harmless for the environment and humans (Shotyk and Le Roux, 2005). The anthropogenic lead-bearing particles, due to their sub-micronic grain size, are easily incorporated in the environment and also in human beings by inhalation or ingestion. In addition, the amount emitted in the atmosphere, although fluctuating with climate and therefore representing a potential tracer for Holocene paleoclimatic changes, is negligible compared to the amount of anthropogenic lead-bearing particles emitted during the second half of the Holocene.

Geological archives are commonly employed to assess the extent of metal release to the environment, including the atmospheric fluxes and other predominant sources. During the past 50 years, bogs have become increasingly recognized as the best continental archives of atmospheric Pb deposition, especially in Europe (Fig. 1), a region that has contributed so much to global atmospheric pollution. A number of European bogs have yielded high-resolution reconstructions of atmospheric Pb deposition (e.g., Shotyk et al., 1998; Le Roux et al., 2004; De Vleeschouwer et al., 2009, and references therein). Since the last decade, there has been growing interest in: (1) the reconstruction of Pb inventories within and between regions, (2) the use of Pb and other trace elements to help solve archeological problems pertaining to archeometallurgy, and (3) the combination of palynological and geochemical studies to investigate human-environment relationship in mining areas (Jouffroy-Bapicot et al., 2007). In the first case, to better constrain pollutant inventories, it is necessary to first determine the pre-anthropogenic deposition rate of these compounds, and assess their natural variation in space and time (e.g., Kylander et al., 2005; Shotyk et al., 2001). In the second and the third cases, peat records offer the unique opportunity to provide a detailed, reliable chronology of metal pollution where archeological and/or historical evidences are lacking (e.g., Mighall et al., 2009; Renson et al., 2008).

Studies on European bogs have yielded records of Pb contamination varying in intensity that are consistent with the known history of lead sulfide mining (Fig. 1). Isotopic studies covering the beginning of early metallurgy show local- to regional-scale Pb pollution (e.g., Baron et al., 2005; Cloy et al., 2005; Le Roux et al., 2004, 2005). During the Middle Ages, new mining areas in Europe (e.g., Harz, Germany; Wales, UK) were explored and consequently European bogs were more impacted in the vicinity of those new mining areas (e.g., Kempter and Frenzel, 2000; Le Roux et al., 2004; Fig.1). A strong link between mining activity and deforestation for charcoal production is also suspected in many places in Europe (e.g., Baron et al., 2005; Monna et al., 2004; Mighall et al., 2009). Since the Industrial Revolution beginning ca. 1750 AD, a dramatic increase in atmospheric Pb pollution began in Europe. Bogs also bear witness to long range atmospheric transport of pollutant aerosols. For example, Pb from mining in the Iberian Peninsula more than 3 ka has been detected in a Swiss bog (Shotyk et al., 1998), and atmospheric Pb (and antimony (Sb)) contamination dating from the Roman Period has been recorded in peat from the remote Faroe Islands (Shotyk et al., 2005). After the 2nd World War, the Pb isotopic signal in western Europe tends to be more spatially homogeneous due to massive Pb emissions from leaded gasoline combustion (e.g., De Vleeschouwer et al., 2007, 2009). However, many peat records show clearly that coal mining was also an important, and sometimes dominant (especially in eastern Europe) source of Pb during the second half of the 20th century (e.g., Farmer et al., 1997; Shotyk et al., 2003, 2005; Novak et al., 2003; De Vleeschouwer et al., 2009).

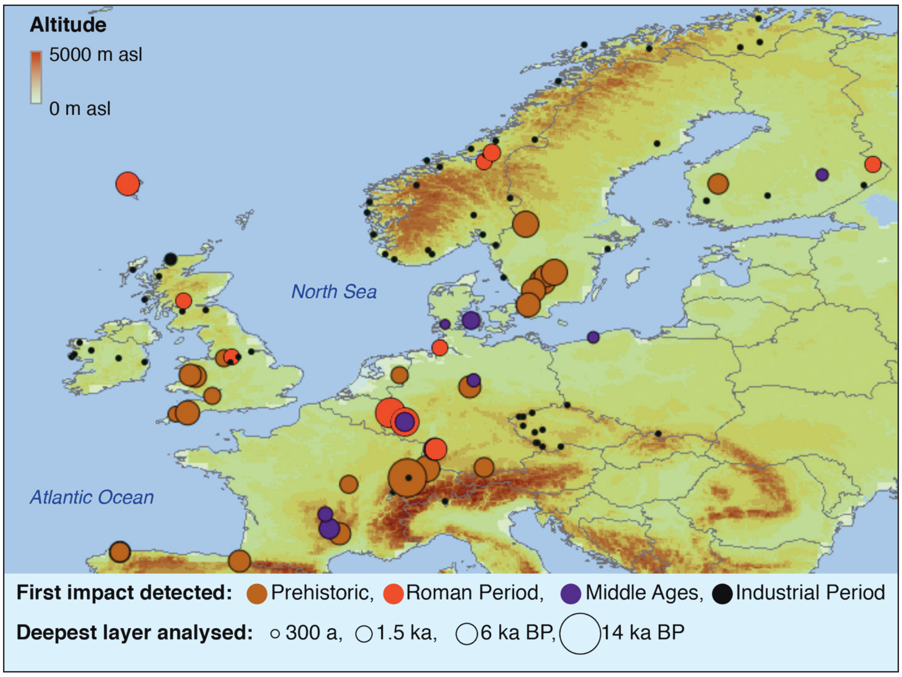

Figure 1: Map of atmospheric Pb contamination in Europe reconstructed using age-dated peat cores. Data used to produce this figure are referenced in the online reference list, indicated by an asterix. A detailed excel database is available upon request to G. Le Roux (gael.leroux@ensat.fr). Some early references, which may not be easily accessible for the reader, have been omitted. For more information, please consult: www.rzuser.uni-heidelberg.de/~i12/estandforlit.htm

High-resolution, multi-metal studies

In Figure 2, a peat core from Lindow Bog (Manchester, UK) shows the potential of bogs as archives of paleo-pollution and archeology (Le Roux et al., 2004). Metal/titanium (Ti) ratios can be used to investigate anthropogenic deposition levels because Ti is a conservative element principally derived from soil erosion and not from smelting, combustion or gasoline use like metals. Therefore, by comparing the Pb/Ti and Cu/Ti ratios in the samples with those in the upper continental crust (i.e. the source of non-anthropogenic Pb and Cu), it is possible to calculate the contribution of anthropogenic Pb and Cu, and to derive their flux (Shotyk et al., 2000). The first Pb and Cu contamination appear ca. 1000 BC, which clearly pre-dates Roman mining activities. The timing of the ancient and medieval Pb pollution, as shown in Figure 2a, is also directly related to socio-economic events (warfares, plague epidemics). The $^{208}Pb/^{206}Pb$ and $^{206}Pb/^{207}Pb$ data from the Lindow Bog indicate that English ores were the predominant sources for Pb atmospheric deposition in England during the pre-Roman, Roman, and medieval periods (Fig. 2b inset). This correlates well with palynological studies by Birks (1965) on the same peat profile of Lindow Bog, which indicate that different phases of vegetation clearance during the aforementioned periods are not only due to animal breeding pressure but also due to human settlements for mining activities.

Changes in atmospheric Hg deposition can also been found using peat cores. Thus, comparison of these three elements, derived from different sources that were worked at different times, and varying in geochemical behavior, can add value to the peat bog studies (Fig. 2). As it is true for Pb, some small peaks of Cu appear in the Lindow profile before the Roman Period. Unlike Pb, Cu is less susceptible to long-range transport and its enrichment in the peat from Lindow reflects local sources. Mercury does not show variations related to ancient metallurgy, but the clear increase beginning 0.5 ka ago is consistent with the onset of coal burning. The differences in the timing of the Pb, Cu, and Hg deposition during the past five centuries remind us of the importance of multi-element studies in deciphering the changing rates and sources of atmospheric pollution (Fig. 2).

Perspectives

Until recently, the key parameters for a better understanding of heavy metal records in peat have focused upon the ombrotrophic character of the peat deposits, high-resolution multi-metal chronologies, and high quality lead isotope analyses. However, more recent studies have demonstrated that other parameters, such as the local/regional background variations, are crucial for a fully constrained interpretation and assessment of metal inventories, because the natural rates of atmo-

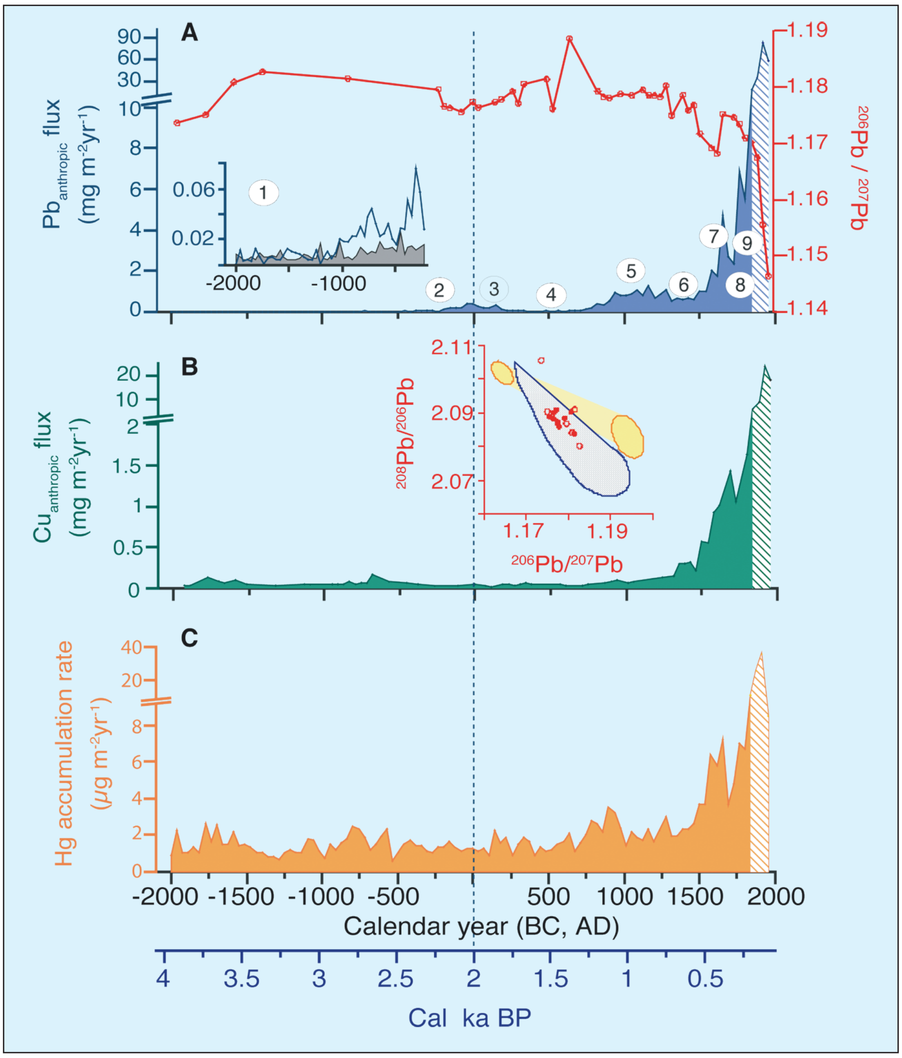

*Figure 2: Lead (Pb), copper (Cu) and mercury (Hg) chronologies in Lindow Bog (UK). **A**) Fluxes of anthropogenic Pb and $^{206}Pb/^{207}Pb$ from 2000 BC to 1800 AD with focus on the pre-Roman period (Inset) to emphasize the early increase in Pb deposition at ~1000 BC (from Le Roux et al., 2004). The natural estimated Pb flux is also represented (light gray). 1) Begin of use of leaded bronze in Great Britain, 2) Iron Age, 3) Roman Occupation (43 AD–410 AD), 4) Dark Ages, 5) Norman-Medieval Period, 6) Hundred Years War, plague epidemic (1349 AD), 7) German workers brought to re-organize the mines (16th century), 8) plague epidemic (1645 AD), 9) Industrial Revolution. **B**) Flux of copper (green, unpublished data) and Pb three-isotope plot (inset) with peat samples (red), UK ores (blue) and Spanish ores (yellow), indicating UK ores as the likely source of Pb atmospheric deposition over Iron Age and Roman Occupation. **C**) Hg accumulation rate (unpublished data). Hatched section: recent period possibly disturbed by peat farming.*

spheric dust deposition may have varied considerably with climate change during the Holocene (e.g., Kylander et al., 2005; Shotyk et al., 2001). There is also a clear need for interdisciplinary studies linking paleoenvironments, geochemistry and archeology (i.e., archival records), as well as atmospheric chemistry and transport modeling. There is tremendous opportunity to employ new analytical tools for the characterization of pollutant aerosols (e.g., Scanning electron microscope, Laser Ablation inductively coupled plasma mass spectrometry) as well as to investigate other elements that have been less studied (e.g., Rare Earth Elements, Platinum Group Elements) but may provide new insights into both nutrient input by natural atmospheric dusts during pre-anthropogenic times, and human impacts on the environment.

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The northern peatland carbon pool and the Holocene carbon cycle

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Understanding the role of peatlands in the Holocene carbon cycle will help predict the response of northern carbon stores to a changing climate.

Northern peatlands hold a large proportion of Northern Hemisphere land carbon (equivalent to as much as 1/3 of total global soil carbon) and are significant and active players in the global carbon cycle. An improved understanding of the controls and future dynamics of these carbon-rich ecosystems is possible from study of their Holocene history and previous carbon response to climate change. Peatland information relevant to Earth system dynamics includes the spatiotemporal pattern of expansion to the current ~4x10^6 km^2 occupied by northern peatlands, the variations in carbon accumulation at millennial and multi-centennial timescales, and the distribution of today's 270-450 Pg (1 Pg = 1 gigatonne = 10^{15} g) of peatland carbon as it relates to current climate.

Peatland expansion

Recently published datasets of basal ^{14}C (radiocarbon) dates from extant peatlands indicate that northern peatlands have been sequestering atmospheric CO_2 and cycling land carbon at least since the early Holocene (Figs. 1 and 2; MacDonald et al., 2006; Gorham et al., 2007; Yu et al., 2009; Korhola et al., 2010). By 8 cal ka BP, peatlands had developed extensively across the continents in the Northern Hemisphere (Fig. 2e). This rapid wetland expansion contributed to the early Holocene rise and sustained peak in CH_4 concentrations after the Younger Dryas until about 8 cal ka BP (Fig. 2c; MacDonald et al., 2006), and

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Data used in the production of figure 1 are indicated with an asterix.

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