15. Estimates of Temperature and Precipitation Variations During the Eemian Interglacial: New Data From the Grande Pile Record (GP XXI)

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ABSTRACT

New data were obtained from previously unanalysed Grande Pile core samples (GP XXI) corresponding to the penultimate glacial up to the St. Germain 1 interstadial. Parallel sampling for pollen and carbon isotopes was performed. The biostratigraphy is based on pollen grains as proposed by Woillard (1978) for Grande Pile X. The age scale is from Kukla *et al.* (1997) except for the start of Eemian, which follows the timing defined by Shackleton *et al.* (2002). The pollen data were first processed to determine their biome scores. The BIOME4 vegetation model was then run in the inverse mode using the determined biome scores and measured $\delta^{13}C$ values as constraints to reconstruct the climate parameters. These results are compared with those previously published and show that the Eemian *sensu stricto* and more generally the penultimate interglacial period was not stable or uniform contrary to previous terrestrial reconstructions but is in agreement with variations observed in the North Atlantic Ocean.

An earlier comparison of the bottom part of the Grande Pile record (E. France) (Woillard, 1978), covering the Linexert glaciation through the Ognon stadials, with the marine record V29-191 from the North Atlantic Ocean (McManus *et al.*, 1994) covering MIS 6 to 4, provoked a wide debate in the palaeoclimatology community (Kukla *et al.*, 1997). First, assuming a constant sedimentation rate in both records, the comparison between the variation in continental arboreal and temperate deciduous trees with the IRD occurrences and *Neogloboquadrina pachyderma sinistral* counts showed that all events characterizing the sea-surface conditions in the North Atlantic Ocean are recorded in the terrestrial record. Indeed, all the observed changes in the vegetation, mostly declines in arboreal pollen, are related to events of strong iceberg discharges, named C events in the marine record, and high values of *N. pachyderma sinistral* (Fig. 15.1). Second, in the earlier comparison (Kukla *et al.*, 1997), the observed variation in benthic forams $\delta^{18}O$ showed that the terrestrial interglacial, named Eemian *sensu lato* after Woillard (1978), was not only associated with marine isotope substage (MIS) 5e as previously assumed (Shackleton, 1969; Mangerud *et al.*, 1979), but also included part of MIS 5d. This observation was

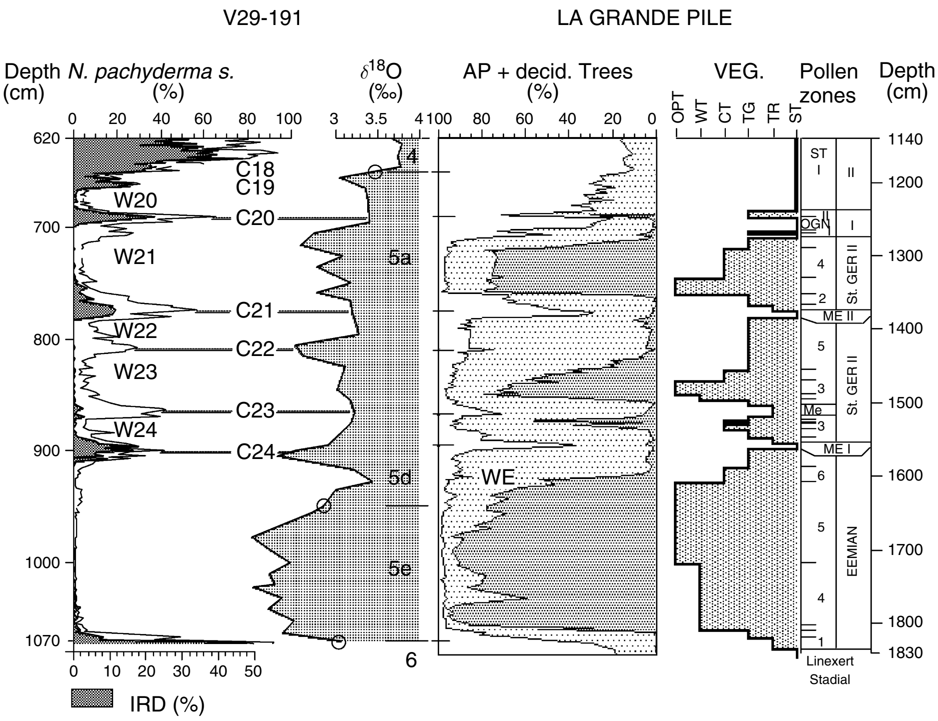

Fig. 15.1 Comparison between marine (McManus et al.*, 1994) and terrestrial (Woillard, 1978) proxies during marine isotope stage (MIS) 5, showing coeval variations in the North Atlantic sea-surface and in the terrestrial vegetation. The benthic δ^{18}O indicates that the Eemian interval includes MIS 5e and part of MIS 5d (from Kukla* et al.*, (1997) modified). W20–24, warm sea-surface water intervals; C18-24, cold sea-surface water intervals; 4, 5a, 5d, 5e, 6 marine isotope stages; WE: Woillard event; AP, arboreal pollen; decid, deciduous; VEG, vegetation zones (Woillard, 1978); OPT, forest of climatic optimum; WT, warm temperate forest; CT, cold temperate forest; TG, taiga; TR, treeless shrubland; ST, steppe; ST I St. Germain I interstadial, OGN, Ognon stadial; ME I, II, Melisey I and II stadials; Me, Montaigu event.*

important as the strong change to open steppe vegetation identified in the Grande Pile record as Melisey 1 is not contemporaneous with the continental ice-sheet inception, but is instead related to a strong discharge of icebergs in the North Atlantic Ocean (McManus *et al.*, 1994). This Heinrich-like event implies the presence of ice caps prior to this calving and release of icebergs. Lastly, the duration of the Eemian interglacial was questioned, considering whether or not it was restricted only to the time of deciduous forest. Further studies indicated that the duration of the Eemian varies according to the geographical position of the analysed sites (Kukla, 2000; Kukla *et al.*, 2002a, 2002b, 2002c; McManus *et al.*, 2002; Turner, 2002a, 2002b; Tzedakis *et al.*, 2002; van Kolfschoten and Gibbard, 2000).

Since then, other studies have supported the main conclusions of the paper by Kukla *et al.* (1997) especially that the last interglacial on the continent is not the equivalent of MIS 5e. The best evidence comes from the combined δ^{18}O and pollen analyses from a core off Portugal, MD95-2042 (Sánchez Goñi *et al.*, 1999; Shackleton *et al.*, 2002). This record, located south of the iceberg limit defined by Ruddiman and McIntyre (1981), and south of the main IRD belt, indicates that the Eemian in southern Europe includes part of MIS 5e and part of MIS 5d (Sánchez Goñi *et al.*, 1999; Shackleton *et al.*, 2002). A recent synthesis of Eemian records in Europe and δ^{18}O and IRD from North Atlantic cores supports the interpretation by Kukla *et al.* (1997) on the continental–marine correlation (Müller and Kukla, 2004), showing that the vegetation variation has a strong geographical gradient, which is related to variations in the North Atlantic circulation affecting the NADW formation zone. Climatic estimates proposed for this period are rare and based only on methods referring to modern conditions (analogs) calibrated on modern pCO_2 values (Guiot *et al.*, 1989; Guiot, 1990; Cheddadi *et al.*, 1998; Klotz *et al.*, 2003; Müller *et al.*, 2003; Sánchez Goñi *et al.*, 2005).

Recently, a new method was developed to reconstruct climatic parameters by inverse modelling of biomes and $\delta^{13}C$ on loess organic matter (Hatté and Guiot, 2005). We applied this method to new data from the Grande Pile locality, GPXXI. This was performed on the levels showing C/N ratio higher than 15 to ensure an atmospheric origin of the organic matter and not a mixture between superior plants and algae (qualified levels are above 1810 cm, younger than 127.7 kyr). Furthermore, a preliminary study combining inverse modelling and the possible $\delta^{13}C$ ranges for each expected biomes was performed in the study conditions (altitude, latitude and longitude of La Grande Pile) and under different CO_2 concentrations (Hatté *et al.*, 2006). This study allowed characterizing a bacterial degradation mostly inducing a 1‰ depletion of the original isotopic composition of the plants along the whole record. We therefore applied the inverse modelling procedure to the C/N qualified levels and taking into account a −1‰ shift of the measured $\delta^{13}C$.

This new core was retrieved at the same time and same location as the other cores studied by Woillard (1973, 1978, 1979a) and is preserved in the LDEO core repository. The Grand Pile site (47°44′N, 6°30′E, 330 m a.s.l) is located in a bog in the southern Vosges Mountains in France. A preliminary study of the bulk density of the base of the sequence permitted the identification of different stratigraphical units, especially the mineral intervals corresponding to the Linexert glaciation (sandy clay) and the Melisey 1 stadial (silty clay), the time interval we focus on here, the Eemian, being represented by a gyttja. The thickness of the units fits with what has been already described in other previously studied cores from the Grande Pile locality (Woillard, 1973, 1978, 1979a, 1979b, 1980; Woillard and Frenzel, 1991; de Beaulieu and Reille, 1992). The new sequence has been sampled every 10 cm for pollen and $\delta^{13}C$ measurements (Fig. 15.2) using this preliminary stratigraphy. The pollen preparation followed the classical protocol, and the bulk $\delta^{13}C$ was measured in Montpellier using an elementary analyser coupled with a Micromass optima mass spectrometer. All the used methods are described in Hatté *et al.* (2006) and Rousseau *et al.* (2006).

The pollen analysis of 45 samples results in the identification of the classical vegetation succession defined by Woillard (1978) for the interval including the Linexert glaciation to the St. Germain I interstadial. This allows a comparison of our results with the previous analyses of Woillard. Note that the new core yields a complete record of the Linexert glaciation to St. Germain 1 interval. We then applied the classical Grande Pile pollen biostratigraphy and use the age model defined in Kukla *et al.* (1997) for the top of the studied interval and Shackleton *et al.* (2002) for the refined chronology of the base of the Eemian (Fig. 15.3). The measurement of the bulk $\delta^{13}C$ indicates values varying between about −32 and −22‰, with the lightest measurements yielded by the lowest samples in the core. Conversely, the upper part of the sequence shows values varying around a mean value of −29‰. The biomisation of the pollen data, following the protocol defined by Prentice *et al.* (1996), yields scores for 12 different possible biomes among 28 potential ones. The inverse modelling of the biomes and of the $\delta^{13}C$ allows the palaeoclimate reconstruction to be constrained with this method (Hatté *et al.*, 2006; Rousseau *et al.*, 2006). It also takes into account variations in the

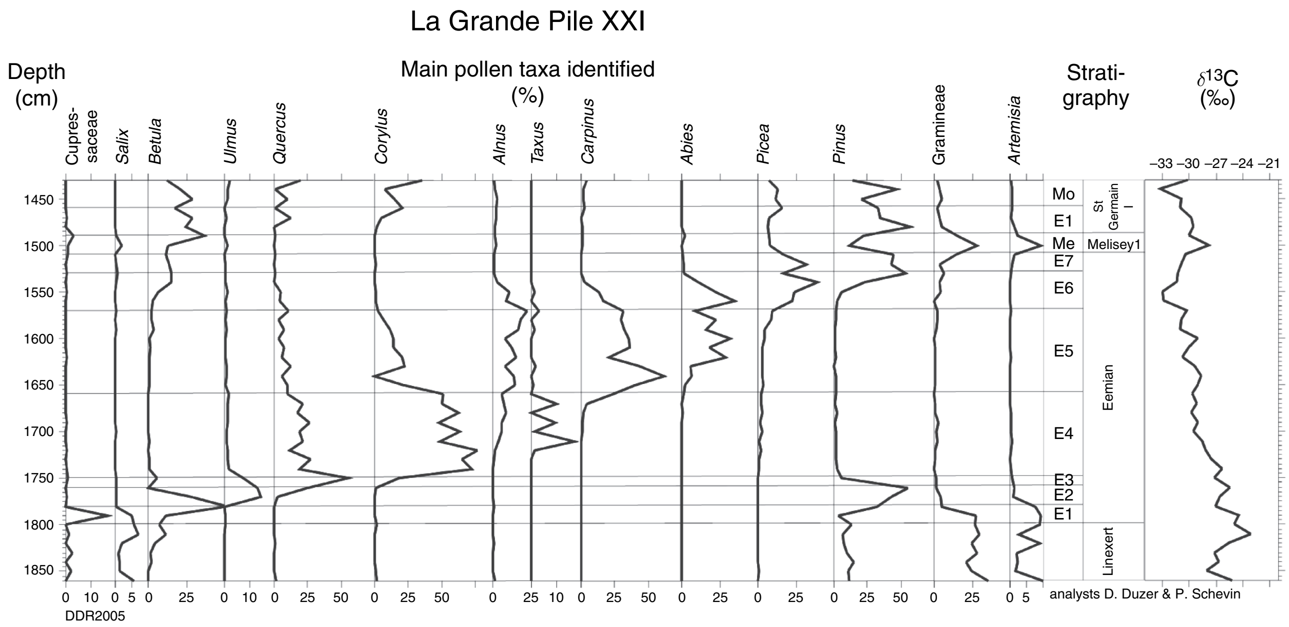

Fig. 15.2 Biostratigraphy of Grande Pile XXI. Plot of the percentage of the main pollen taxa showing the classical vegetation succession occurring during the penultimate interglacial. δ^{13}C measures from parallel samples of the pollen ones. Biostratigraphy nomenclature according to Woillard (1978) (from Rousseau et al. *(2006) modified).*

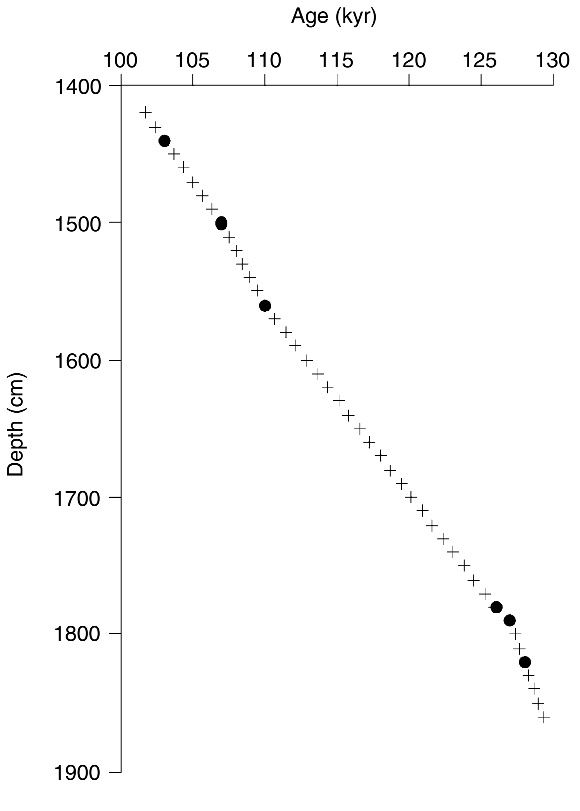

Fig. 15.3 Age model used for La Grande Pile core XXI, with solid circles representing control ages. Ages interpolated between control points (from Rousseau et al. *(2006) modified).*

global CO_2 concentration and the isotopic composition of atmospheric CO_2. The mean annual temperature, the mean temperatures of the coldest and warmest months and the annual precipitation are then reconstructed.

The temperature and precipitation estimates show three successive warm intervals prior to a strong cooling at the end of the penultimate interglacial. The first Eemian warming at about 125 kyr at La Grande Pile is marked in all temperature parameters (about 12° C for the mean annual temperature) and is associated with a strong increase in annual precipitation (Fig. 15.4). This warming appears to have been strong in both summer and winter as expressed by the warmest and coldest months, respectively (anomalies of about 19° and 20° C) (Fig. 15.4). A cooling trend first occurs at about 124 kyr, just after the interglacial optimum, as is indicated by all the temperature parameters (124.5–123.8 kyr for mtwa and Tann, and 123.8–123 kyr for mtco), while the mean annual precipitation signal does not show

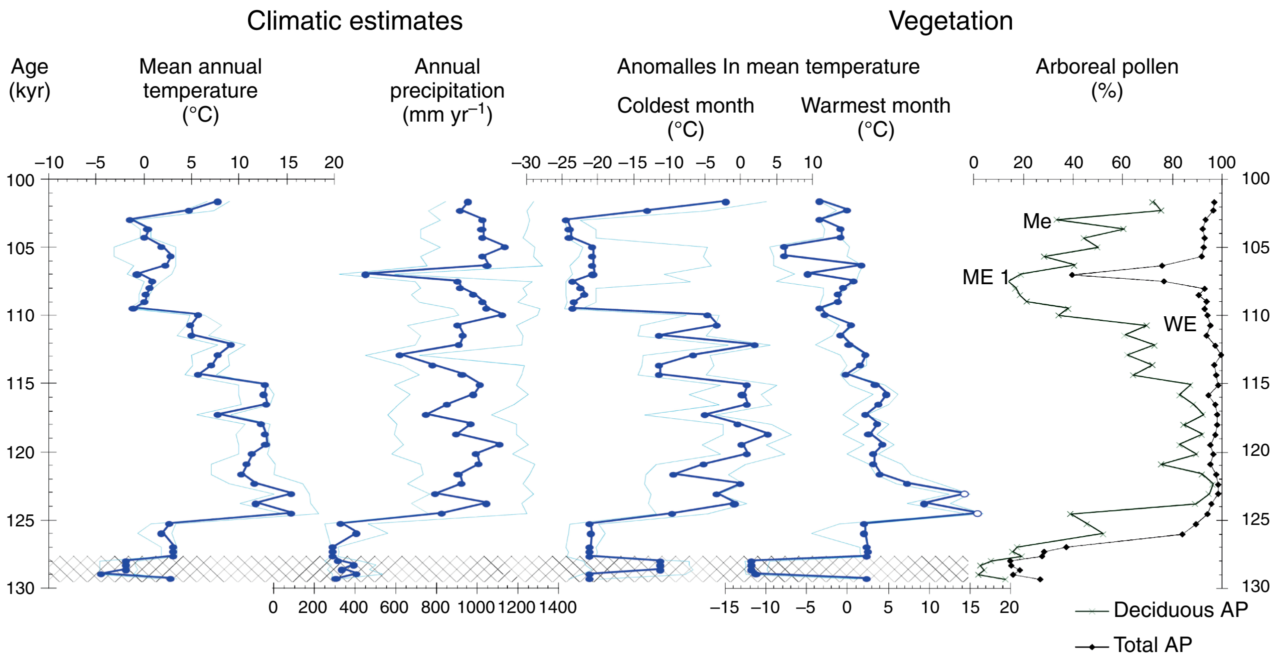

Fig. 15.4 Climate estimates from the last interglacial at Grande Pile XXI compared to vegetation indices corresponding to the arboreal (AP) and deciduous arboreal pollen (DAP) percentages. The modern values at Grande Pile are Tann: 9.5°C, Pann: 1080 mm, mtco: −0.5°C, mtwa: 18.5°C. The fat lines show the most probable values, whereas the 95 % confidence level intervals are presented with hair lines. The two open circles in mtwa reconstructions correspond to estimates, which remain questionable. Me, Montaigu event; ME1, Melisey I stadial; WE, Woillard event (from Rousseau et al. *(2006) modified).*

any particular trend. The temperature estimates indicate a warming, between 120 and 118 kyr, mainly expressed in the coldest month mean temperatures, although the anomaly values remain negative and follow a small cold interval between 122 and 121 kyr. The third Eemian warm interval at Grande Pile is between 117 and 115 kyr and is mostly expressed in the annual and coldest month mean temperatures, but only slightly in the warmest month mean temperature. The precipitation again does not show any particular trend. A decrease in mean annual, coldest month and warmest month temperatures associated with decreasing annual precipitation occurred at about 115 kyr (Fig. 15.4). This corresponds to a decrease in the deciduous arboreal vegetation (Fig. 15.1). Estimates of mean annual and coldest month temperature indicate colder conditions from the Woillard event (WE) (Woillard, 1979b) until the Melisey I stadial and are correlated with cold marine events C25 and C24 (McManus *et al.*, 1994; Kukla *et al.*, 1997). The change in the vegetation at Melisey I had been interpreted previously as resulting from the IRD released in the North Atlantic, thus following the first glacial inception. Indeed, the Melisey I stadial at about 107 kyr is marked by low temperature values and is characterized by a strong decrease in annual precipitation of about 500 mm yr^{-1} as can be seen from our reconstruction, even if due to the sampling resolution this corresponds to only one point. Precipitation remained high between 110 and 107 kyr, while the mean annual and the coldest month temperatures were already very low. The decrease in precipitation lags the cooling by ~3000 yr.

The discussion of the reconstructed climatic patterns based on the new Grande Pile core requires comparing them with other evidence, especially from the North Atlantic Ocean. The first warming observed at the base of the Eemian could correspond to the northward migration of the polar front within the Greenland Seas described at 126–125 kyr. The temperature decrease reconstructed at 124 kyr fits with the first cooling described in the Nordic Seas (Fronval *et al.*, 1998), which corresponds to reduced influx in this region of Atlantic water and dominance of Arctic waters. Indeed, records from the Norwegian Sea and Northeast Atlantic Ocean (Cortijo *et al.*, 1994; Maslin *et al.*, 1995; Fronval and Jansen, 1996; Fronval and Jansen, 1997) indicate a sharp decrease in both temperature and salinity. This change in the thermohaline circulation in the Norwegian Sea may have been important enough to be related to our cooling trend. The cold interval estimated on land at about 123–121 kyr could correspond to the increase in IRD deposition recorded at about 122 kyr in the northern Greenland Sea (Fronval *et al.*, 1998). The third warming matches the second warm interval during which the Arctic front reached its most westerly location in the Iceland Sea region. The cold decrease at about 115 kyr could be related, considering our time resolution, to the C26 cold event corresponding to a surface cooling in the North Atlantic (Shackleton *et al.*, 2002). Finally, the WE at about 110 kyr may correspond to the IRD event C25 in the Nordic Seas interpreted as an advance of the Scandinavian, Svalbard-Barents and Greenland ice sheets surrounding the Nordic Seas. This event was also identified in the North Atlantic as the first large-scale cooling of the surface water after MIS 5e (Chapman and Shackleton, 1999; McManus *et al.*, 2002). The strong seasonality recorded between 110 and 107 kyr appears to be in agreement with the results of the 2D earth model of intermediate complexity (EMIC) MoBidiC performed to simulate the climate between 126 and 100 kyr (Sánchez Goñi *et al.*, 2005). Indeed, the model indicates no continental ice in the Northern Hemisphere between 124 and 119 kyr. Ice sheets then grow until 109 kyr, with partial melting afterwards until 104 kyr. Our results indicate a decreasing trend in all temperature parameters from about 117 kyr until the lowest values estimated at 110 kyr, with a severe decrease in precipitation occurring at about 107 kyr.

One of the main results of our investigation is that the climate of the last interglacial was not uniformly warm. Our results are in agreement with other continental western European records (Guiot *et al.*, 1993; Thouveny *et al.*, 1994; Klotz *et al.*, 2004, Muller *et al.*, 2005) and marine records (McManus *et al.*, 1994; Fronval and Jansen, 1997; Fronval *et al.*, 1998; Chapman and Shackleton, 1999; Shackleton *et al.*, 2002), and could support the hypothesis of a modified thermohaline circulation during the Eemian affecting the climate on the western side of Europe (Broecker, 1998). On the other hand, the characterization of the several coolings disagree with the interpretation from the same locality (Field *et al.*, 1994; Cheddadi *et al.*, 1998; Rioual *et al.*, 2001) or off the Iberian peninsula (Sánchez Goñi *et al.*, 2005) which show a roughly regular warm interval at the same time.

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