Reports

Carbon-14 Dates at Grande Pile: Correlation of Land and Sea Chronologies

Abstract. *Sixteen radiocarbon dates extending back to 70,000 years provide a chronology for the continuous continental pollen record of Grande Pile. This record reflects climatic changes over the last 140,000 years in northeastern France. The cold period initiating the Middle Weichselian, dated previously at 55,000 years, is dated at 70,000 years before the present (B.P.) at Grande Pile. This event is marked by the disappearance of deciduous forests at this site. The Early Weichselian is placed before 70,000 years B.P. A correlation with the oxygen isotope stages from oceanic records is demonstrated until 70,000 years B.P. and attempted beyond.*

Grande Pile, located in northeastern France, is a key Pleistocene site (*1*) with finely laminated pollen-rich sediments that were deposited continuously during the past 140,000 years (*2*). The classical late-Pleistocene stratigraphic scheme for northwestern Europe as well as the stages of the deep-sea chronology seem recognizable within the pollen data from Grande Pile. The lower three major intervals of closed deciduous forests probably correlate with oxygen isotope stage 5 (Fig. 1). The lowermost interval corresponds to typical pollen profiles of the Eemian interglacial (*3*), the probable equivalent of oxygen isotope substage 5e (*4*), which is dated at 125,000 years. Without a series of ^{14}C dates, the acceptance of the correlations above the Eemian was uncertain. Only one absolute date of 29,980 ± 970 years before the present (B.P.) (Lv-748) was available (*2*). We now have a series of ^{14}C dates from Grande Pile sediments with an uninterrupted pollen record (Fig. 1), and we describe the correlation of the new dates for the continental record with the marine chronology that is based primarily on dates determined by use of the uranium-series method (*5–7*).

In the pollen diagram (Fig. 1), the values for total tree and shrub pollen range from 5 to 95 percent. When the percentages for this total are low, the percentages for herb pollen are high (Fig. 1). Increasing percentages of tree and shrub pollen imply a warming climate. The youngest ^{14}C date, 9750 ± 40 years (GrN-9049), is consistent with the pollen evidence for the Preboreal period starting the Holocene (zone 21). The dates of 10,175 ± 50 years (GrN-9050) and 11,170 ± 100 years (Lv-1046) seem about 1000 years too young according to the interpretation of the pollen data as showing the Bölling-Alleröd warming (zone 19) preceding the Younger Dryas (zone 20). The second date, although too old for the beginning of the Holocene, nevertheless confirms a Late Glacial age for the sediments at about 5 m. The ages of 20,050 ± 80 years (GrN-8745) and

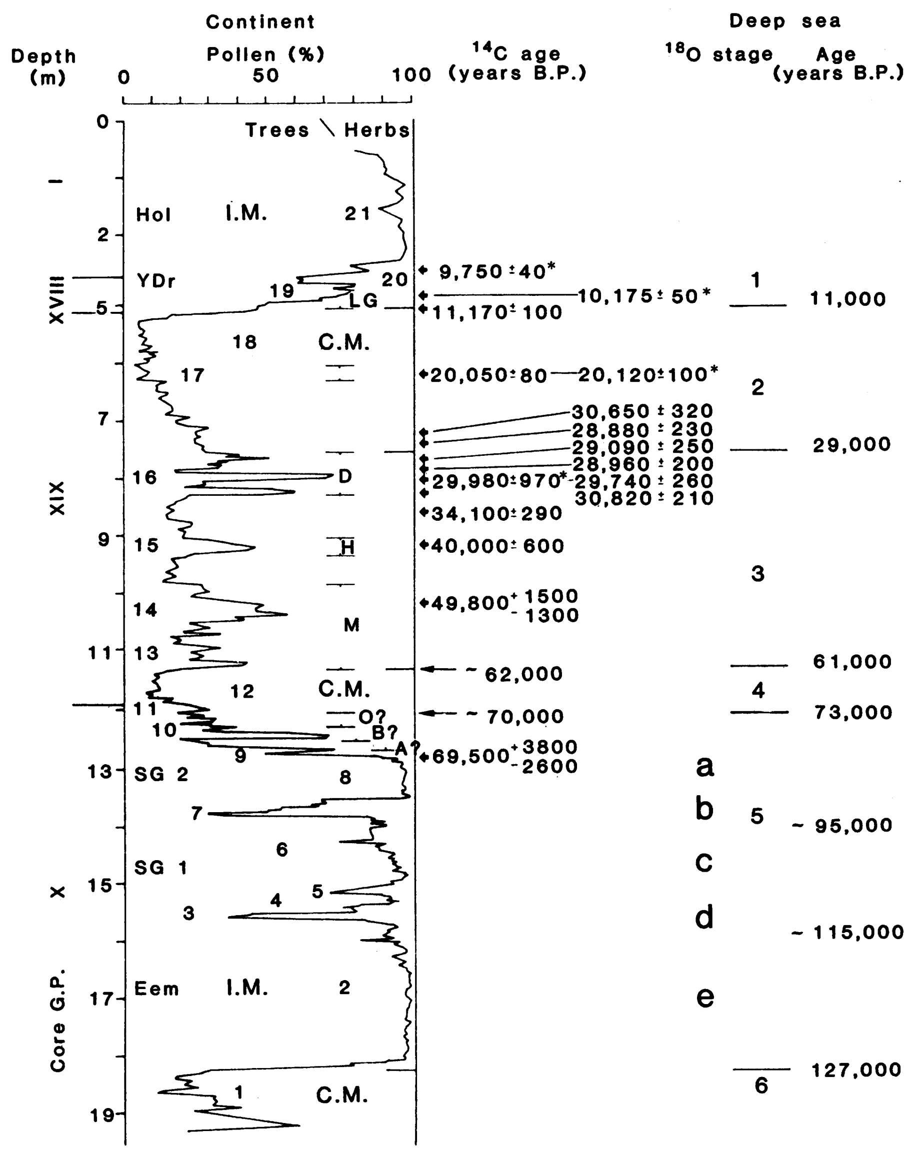

Fig. 1. Correlation between the Grande Pile (*G.P.*) continental deposit and the deep-sea record: time series of total tree and shrub pollen versus herb pollen from Grande Pile (*18*). The depth scale is uniform except between G.P. XVIII and I (2.5 to 4.5 m), but verifications have shown that the pollen record has to be considered as perfectly continuous. Pollen zones are designated by the numbers 1 to 21 on this time series; local stratigraphic names are designated as follows (*2*); Eemian, *Eem*; St. Germain I, *SG 1*; St. Germain II, *SG 2*; Amersfoort, *A*; Brörup, *B*; Odderade, *O*; Moershoofd, *M*; Hengelo, *H*; Denekamp, *D*; Late Glacial, *LG*; Younger Dryas, *YDr*; Holocene, *Hol*; cold maximum, *C.M.*; and interglacial maximum, *I.M.* All the ^{14}C ages (*19*) are expressed in conventional ^{14}C years B.P. Asterisks indicate dates obtained on a parallel core. The ages ~ 62,000 and ~ 70,000 years B.P. are deduced (Fig. 2). The ^{18}O stages are after Emiliani (*20*) and Shackleton (*21*). The ages of stage boundaries are after Hays *et al.* (*6*) and Kominz *et al.* (*7*).

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20,120 ± 100 years (GrN-9660) date the late Weichselian period (zones 17 to 20) (*8*). Variation in the composition of herbaceous species (expansion of aquatic plants) reflects a warming (zone 17) within the last glacial maximum (zone 18). But neither the pollen spectra nor the absolute datings enable us to make reliable correlations with the Lascaux (at 17,500 years B.P.) or Laugerie (at 19,500 years B.P.) interstadials of southern France (*9*).

Seven dates close to each other span the interval between 28,880 and 30,820 years. Two of these, 30,650 ± 320 years (GrN-8767) and 28,880 ± 230 years (GrN-9659), date the samples from the transitional zone of the Middle-Late Weichselian boundary defined at 25,000 years B.P. (*8*). The other five dates are located within three obvious episodes of open pine-birch forests (zone 16): 29,090 ± 250 years (GrN-9051), 29,980 ± 970 years (Lv-748), and 28,960 ± 200 years (GrN-9052) date the youngest oscillation; 29,740 ± 260 years (GrN-9053) the middle one; and 30,820 ± 210 years (GrN-8768) the oldest. These datings are comparable to the ^{14}C dates gained for the Denekamp interstadial described in the Netherlands (*10*). The date of 40,000 ± 600 years (GrN-8746) is obtained from an older interval of open birch-pine forests (zone 15) that may represent the Hengelo interstadial of the Netherlands (*10*); 34,100 ± 290 years (GrN-9054) dates the middle of the upper cold stadial. The open birch-pine forests of zones 14 and 13 are probably equivalent to the Moershoofd interstadial "complex" defined in the Netherlands (*11*).

The age of 49,800 $^{+1500}_{-1300}$ years (GrN-8769) obtained for the top of this interval is some 6000 years older than the values hitherto known. This age, however, is in good agreement with the dates from zones 16 and 15 if a constant sedimentation rate is assumed (Fig. 2, solid line). The homogeneous lithology from zones 19 to 12 (gyttja-clay with only little variations, except gyttja within zone 16) (*2*) makes it reasonable to assume a constant sedimentation rate within this section (zone 16 excluded). The ^{14}C dates for the section from zones 16 to 14 (Fig. 2, solid line) support this assumption. Based on this evidence and with the assumption of a constant sedimentation rate through pollen zones 14 and 13 (Fig. 2, solid line), an age of about 62,000 years B.P. can be assessed for the lower limit of the warming that can be inferred at the boundary between zones 13 and 12.

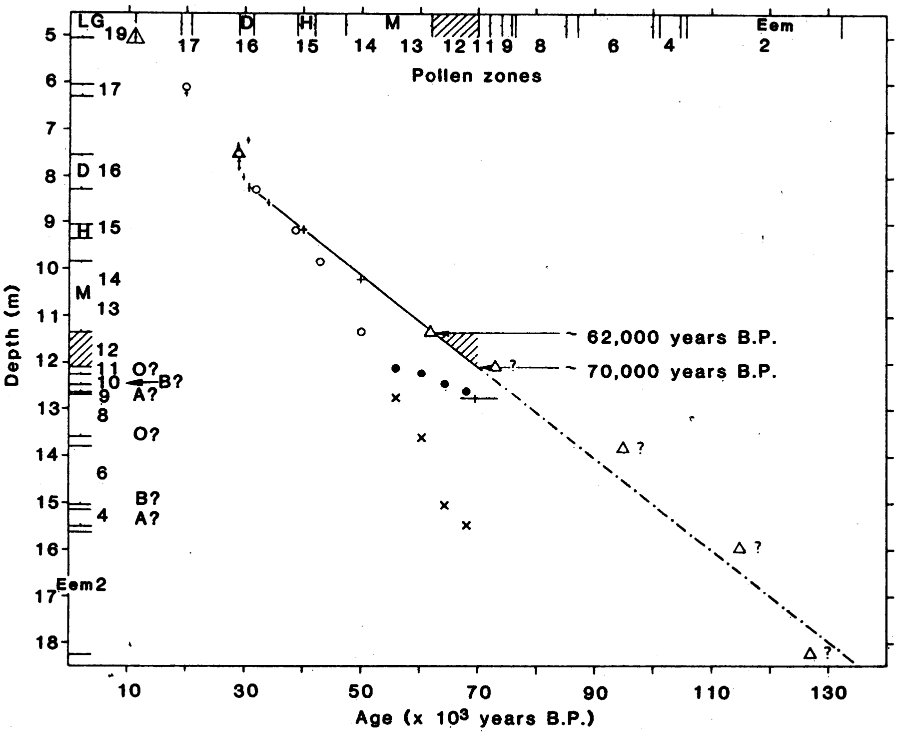

Fig. 2. Depth-date plot of ^{14}C dates (+) of Grande Pile sediments. (The vertical length of each plus sign is the sampling interval, and the horizontal length signifies the error bar for the ^{14}C date.) Pollen zones and local stratigraphic names are as in Fig. 1. Pollen-stratigraphic dates (○, ●, and x) follow the radiocarbon time scale of Grootes (*12*), with both alternatives for the correlations of pollen zones 9, 10, and 11 (●) or 4, 6, and 8 (x) with Amersfoort (*A*), Brörup (*B*), and Odderade (*O*), respectively. The assumed constant sedimentation rate through homogeneous sediments from the base of zone 16 to zone 12 is represented by a solid line, which is extended as a dashed-dotted line through the nonhomogeneous sediments below zone 12. The implied dates for zones at Grande Pile by the dashed-dotted line are, however, unverified. The ages of deep-sea stage boundaries (△) are placed as they were given in Fig. 1; (?) indicates a nonassured level within the pollen diagram.

Given this series of ^{14}C dates that are directly connected with pollen analytic evidence, we suggest that the beginning of the prominent cooling episode (zone 12), well known as marking the start of the Middle Weichselian in northern Europe, may have occurred before 60,000 years B.P. It is clear from the pollen and the radiocarbon data that the previous date of 55,000 years B.P. (*12*), derived from the base of the equivalent of this cold period, cannot be correct. Following our earlier assumption about the constant sedimentation rate between zones 16 and 12 (Fig. 2, solid line), we have estimated the age of this level (boundary between zones 12 and 11) to be about 70,000 years B.P.

Thermal diffusion isotopic enrichment of ^{14}C (*12*) has been used to date the top of pollen zone 8. Because of the limitations inherent in this method, the result of 69,500 $^{+3800}_{-2600}$ years (GrN-9187) might be regarded as a minimal age. To understand the chronostratigraphic position of zone 8, we describe here the interpretation of the intervals occurring below it. The correlation between pollen zone 2 and the Eemian interglacial of northern and western Europe, as recognized by its typical vegetational succession (*3*), has been demonstrated (*2*). Following the chronostratigraphic definition of the Eemian stage (*13*), we are inclined to correlate the Eemian-Weichselian stage boundary with the boundary between zones 3 and 2 of Grande Pile.

As a result of this correlation, several investigators (*4, 14*) would like to see the Early Weichselian interstadials Amersfoort, Brörup (*3, 15*), and Odderade (*16*) as matching Grande Pile pollen zones 4, 6, and 8, respectively, locally named St. Germain I (zones 4 through 6) and St. Germain II (zone 8). This possibility appears, however, to be in conflict with the old date inferred for the top of zone 8 (Fig. 2). A direct biostratigraphic correlation, moreover, is impossible between the interglacial-like vegetational development of St. Germain I and St. Germain II and the completely different vegetation described for the Early Weichselian interstadials (*2*). On the other hand, Grande Pile zones 9, 10, and 11 (locally named Ognon I, Ognon II, and Ognon III) clearly precede the Middle Weichselian and take place in the Early Weichselian, if one refers to the classical stratigraphic scheme. In view of their vegetational and climatic character, we might regard these zones as equivalent to the Early Weichselian interstadials. If pollen zones 9, 10, and 11 were to be correlated with these interstadials, we should conclude that a large hiatus exists between the end of the Eemian and the Amersfoort in the Netherlands, but evidence in support of this conclusion does not appear to exist. The radiocarbon time scale used earlier for the Weichselian stratigraphic events has the Amersfoort starting at 68,200 ± 1100 years, the Brörup at 64,400 ± 800 years, and the Odderade at 60,500 ± 600 years B.P. (*12*). If this chronology is correct, our ^{14}C date of 69,500 $^{+3800}_{-2600}$ years B.P. for the end of zone 8 supports the correlation between zones 9, 10, and 11 and these Early Weichselian interstadials (Fig. 2). Further data are needed to resolve this dilemma.

The pollen and ^{14}C data taken together enable us to attempt correlations between the Grande Pile continental sequence and the ocean records (Figs. 1 and 2). Three minima in the time series for total tree and shrub pollen indicate three maximum cold periods, zones 1, 12, and 18, which can be correlated with the prominent ice-growth phases reflected in deep-sea sediments by oxygen isotope stages 6, 4, and 2, respectively. Absolute datings from land and ocean, respectively, fix the cold maximum (zone 12) initiating the Middle Weichselian between about 62,000 and 70,000 years B.P. and deep-sea stage 4 between 61,000 and 73,000 years B.P. Both interglacial maxima (pollen zones 2 and 21), identified as the Eemian and Holocene interglacials, are well correlated with oxygen isotope substage 5e and stage 1, respectively. The former correlation has recently been demonstrated (*4*). The Middle Weichselian, located here between 29,000 and about 62,000 years B.P., can be regarded as the equivalent of oxygen isotope stage 3. Pollen zones 3 to 11 then might correlate with the deep-sea substages 5d through 5a. The correlations suggested in Fig. 1 within this interval are, however, still unproved.

The results of our study show a good agreement between land and sea chronologies, reflecting a primary change from "interglacial" to glacial conditions at about 70,000 to 73,000 years B.P. This time corresponds to the start of the Middle Weichselian at Grande Pile and to the boundary between oxygen isotope stages 5 and 4 in the oceanic records (*17*). Uncertainty remains about the correlations between our pollen zones 4 to 11 and the classical stratigraphy: (i) zones 4, 6, and 8 as well as zones 9, 10, and 11 do not resemble the pollen records of the Early Weichselian interstadials; if zones 9, 10, and 11 correspond to these interstadials, a hiatus exists at Amersfoort and other places. (ii) If the present knowledge about the Early Weichselian ages is accepted as correct, zones 4, 6, and 8 cannot represent the classical interstadials Amersfoort, Brörup, and Odderade. (iii) Our continental record is in good agreement with the deep-sea record to about 70,000 years B.P. (that is, oxygen isotope stage 4), but we are still uncertain about how to correlate the classical interstadials with the substages of oxygen isotope stage 5.

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18. The pollen curve is based in part on published data (*2*). It has been established with the four parallel cores I, XVIII, XIX, and X (core I being 350 m apart from the others), connected by palynology; a regular scale of depths has been applied in each core to draw the curve. About 500 pollen grains were counted in each of 370 samples; 120 taxa were recognized. Methods of processing the samples were described earlier in (*2*).
19. The radiocarbon samples were treated with acid, alkali, and acid prior to combustion of the residue. For the enriched date of 69,500 $^{+3800}_{-2600}$ years B.P. (GrN-9187), a 15-cm section was taken from the three parallel cores XVI, XVII, and XIX. The enrichment sample was rigorously extracted with alkali. The alkali extract was dated at > 49,000 years B.P. (GrN-9383). The alkali treatment was omitted for the radiocarbon sample dated at 11,170 ± 100 years B.P. (Lv-1046) because of the low content of organic material (too small a sample).
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22. We are grateful to H. J. Streurman who carried out the ^{14}C enrichment and the GrN ^{14}C datings and to E. Gilot who obtained both Lv ^{14}C datings. We thank W. Mullenders, B. Frenzel, J. Mangerud, and A. V. Munaut for critical review of the manuscript. In 1980, G.M.W. was a research fellow of the Alexander von Humboldt Foundation at Hohenheim University, Stuttgart.
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The Coalescence of Two East Australian Current Warm-Core Eddies

Abstract. *Two warm-core eddies coalesced in about 20 days as their centers rotated around a point on the contracting line that joined them. In the process of forming the new eddy, the subsurface isothermal-isohaline "signature" layer of one eddy was uplifted and somewhat depleted while that of the other was depressed.*

The warm-core eddies that are a notable feature of the East Australian Current (EAC) system were first described by Hamon (*1*). Since then they have been studied sporadically, sometimes as part of broader EAC studies (*2*) and sometimes in their own right (*3, 4*). The picture that emerges from the studies may be summarized as follows: (i) warm-core eddies about 250 km in diameter form from the pinch-off of EAC meanders; (ii) they have lifetimes of about 1 year; (iii) they can drift along complicated paths; (iv) they can rejoin EAC meanders; (v) the surface layers of an eddy cool and mix down to ~350 m in winter to form an isothermal core; and (vi) the formation of a summer surface "cap" of warmer water insulates this core from further changes so that it becomes, in effect, a signature for subsequent identification.

The first suggestion that warm-core eddies may coalesce came during 1979–1980 when the evolution of eddy J near

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