Direct Marine-Continental Correlation: 150,000-Year Oxygen Isotope–Pollen Record from the North Pacific

Abstract. *Core Y72 11 1 (43°15′N, 126°22′W) contains sediment of oxygen isotope stages 1 through 6 (substages 5a through 5e are well developed) and abundant pollen from the nearby continent, enabling us for the first time to obtain a direct marine-continental correlation of events in the last interglacial sensu lato. From stage 6 to substage 5e the vegetational record resembles that during the waning of the last glacial. During substage 5e, after a rapid increase of alder, western hemlock was abundant and significant amounts of redwood, oak, and Douglas fir appeared. These results suggest that vegetation on the adjacent continent during substage 5e was similar to that of the temperate conifer forests which developed in the Pacific Northwest during the Holocene. The vegetation record since that brief episode (which like the Eemian in northwest Europe lasted only a few thousand years) has been complex.*

Much of the dispute over the nature, duration, and age of the last interglacial (*1*) stems from the fact that, although interglacial is a clear concept in the minds of most Quaternary geologists, evidence for its existence is generally contained in sediment not accessible to dating techniques and not deposited continuously. A few continental deposits do apparently contain continuous records extending to the last interglacial (*2*). Nevertheless, only in marine deposits has a global, standard stratigraphy with chronometric control been established. Thus, the best hope for establishing the sequence of continental events is through direct correlation with the marine record (*3*).

Marine sediment of the northeast Pacific Ocean contains pollen and spores whose distribution reflects the vegetation of the adjacent continent. The record of short cores reflects the vegetational succession of the past 10,000 years as known from pollen studies in continental peat deposits (*4, 5*). Efforts to obtain long marine cores to extend the record have been hampered by the rapid sedimentation rate on the Washington-Oregon continental margin. The longest core in the area, core Y72 11 1 (43°15′N, 126°22′W), was sampled at 5-cm intervals. Foraminifera for isotopic analysis were taken from the fraction retained on a 150-μm sieve, and pollen was taken from the finer fraction. In the extraction and analysis of isotopes and pollen, we followed the procedures described in (*6–8*).

It is clear from the pollen and oxygen isotope records of core Y72 11 1 (Fig. 1) that the uppermost sediment was lost in the coring process. For comparison, the pollen and isotope records of this interval from a nearby core, core TT63 13, are shown in Fig. 1 (*5, 9*). Overall, the pollen diagram shows intervals in which pollen of coastal lowland forest, especially western hemlock (*Tsuga heterophylla*), dominates, alternating with intervals in which herbaceous plants are relatively more important. Alder (*Alnus*) percentages are very high in pollen zone 1. In the early Holocene, an interval with high alder abundance is well documented in peat sections from the adjacent continent (*10*). This feature, the result of alder colonizing recently deglaciated ground, would vary in age from place to place with the progressive retreat of glaciers; nevertheless, it must everywhere have been within the time encompassed by the isotopic transition from stage 2 to stage 1, reflecting the end of the last glacial. The vegetational sequence of the 8000 years since the widespread alder was succeeded by spruce (probably *Picea sitchensis*) and western hemlock is recorded in the *T. heterophylla-Alnus* assemblage of pollen zone 1 in core TT63 13 (Fig. 1).

Below the alder peak is a zone of abundant nonarboreal pollen (Compositae-Gramineae-Cyperaceae) and decreased abundance of western hemlock and alder pollen. Representation of thermophilous vegetation [redwood (*Sequoia*), oak (*Quercus*), and Douglas fir (*Pseudotsuga menziesii*)] is much reduced, and pollen of subalpine mountain hemlock (*Tsuga mertensiana*), although never abundant, is fairly persistent. In zone 3 (broadly synchronous with isotope stage 3) we see prominences of lowland arboreal pollen (*T. heterophylla-Picea* assemblage). The transition, marked by a slight increase in alder, between pollen zone 4 (Compositae-Gramineae-Cyperaceae assemblage) and pollen zone 3 is difficult to delineate precisely because of the disturbed nature of the sediment in this part of the core. Pollen zones 5 through 9 show a rapid alternation between assemblages dominated by arboreal pollen with progressively increasing amounts of western hemlock, oak, Douglas fir, and redwood (zones 5, 7, and 9) and assemblages with relatively high amounts of nonarboreal pollen (zones 6 and 8). Percentages of pollen from temperate lowland coastal forest in zone 9 are comparable to those of zone 1. The beginning of the *T. heterophylla-Alnus* zone (pollen zone 9) slightly precedes the onset of substage 5e in exactly the same manner as the beginning of pollen zone 1 precedes the onset of isotope

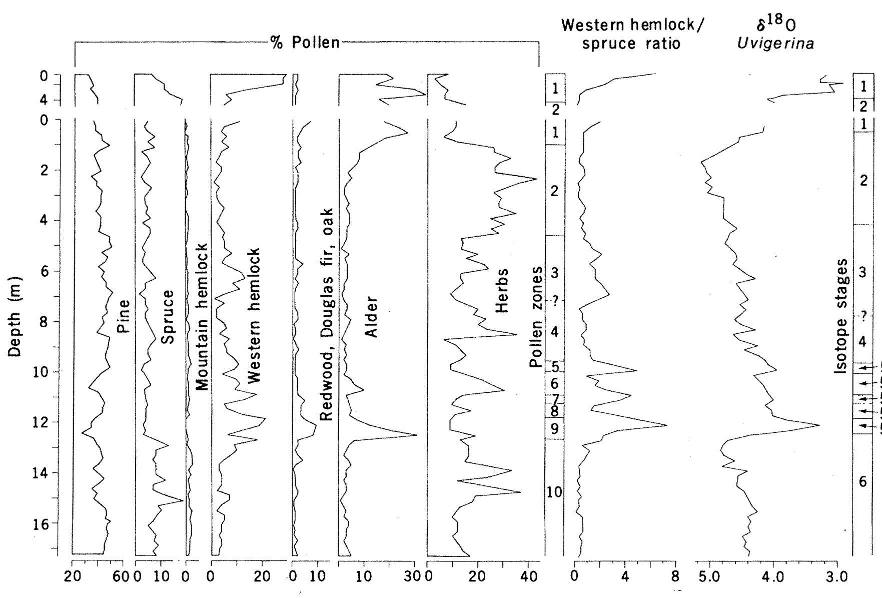

Fig. 1. Depth plots of the following parameters measured in core Y72 11 1 (bottom) and core TT63 13 (top): the relative frequency of significant pollen (percent of the total pollen), pollen zones, the western hemlock–spruce ratio, the oxygen isotope record $\delta^{18}O$, and oxygen isotope stages. Isotope and pollen data in core Y72 11 1 represent the average of 20-cm increments. Isotope and pollen data in core TT63 13 were averaged to the same approximate time interval, about 1500 years, as represented by the data points in core Y72 11 1 so that we might more readily compare the data. Differences in the sedimentation rate in core TT63 13 (based on ^{14}C data and the presence of a dated volcanic ash horizon) account for the difference in the position of the pollen and isotope data with relation to depth.

0036-8075/79/0525-0837$00.50/0

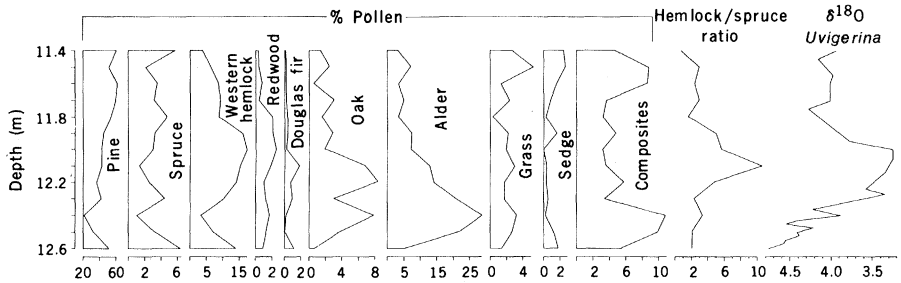

Fig. 2. Depth plots of the following parameters measured in core Y72 11 1 during the transition from isotope stage 6 to substage 5d: the relative frequency of significant pollen (percentage of the total pollen), the western hemlock-spruce ratio, and $\delta^{18}O$.

stage 1 in this core. Spruce, herbs, and pine (*Pinus*) dominate pollen zone 10.

The smoothed vegetational record of core Y72 11 1 shows a complex sequence of climatic changes during the past 150,000 years. The two intervals in which optimal development of the thermophilous components occurred (isotope stage 1 and substage 5e) were both preceded by extended intervals (isotope stages 2 and 6) in which these components were reduced or absent. In isotope substage 5d climatic conditions similar to those of stages 2 and 6 rapidly replaced the climatic optimum inferred from pollen deposited during isotope substage 5e.

One difficulty in interpreting the pollen record in deep-sea sediments is the selective effect of fluviomarine transport on pollen sedimentation. Pine is generally overrepresented and increases in relative abundance seaward (*4*). In order to display the pollen data in a form not affected by the overrepresentation of pine, we show in Fig. 1 the ratio of western hemlock to spruce. Despite oscillations, the ratio shows an overall decrease from a maximum during isotope substage 5e to a minimum during stage 2. This pollen ratio can be regarded as a temperature indicator, since average July temperatures in areas dominated by western hemlock are at least 1° to 2°C higher than in areas dominated by spruce (*10*). The close correlation between the western hemlock-spruce ratio and the $\delta^{18}O$ curve suggests that temperature fluctuations in the Pacific Northwest during the past 150,000 years were broadly synchronous with changes in global ice volume.

The record over the interval from stage 6 to substage 5d is shown in detail in Fig. 2 (*11*). The transition between stages 6 and 5 is complex, with an early alder-western hemlock succession followed by a considerably stronger alder expansion. Early in substage 5e, abundant western hemlock is accompanied by the relatively xerophytic oak and Douglas fir. The later part of substage 5e and the transition to substage 5d show an increase in mesophytic components (western hemlock and redwood) and a marked drop in oak that are suggestive of a general moisture increase. Spruce also increases at this time, whereas herbs and pine all show distinct increases in substage 5d. Maximum values of the western hemlock-spruce ratio occur close to the $\delta^{18}O$ minimum.

Most workers agree that oxygen isotope stage 5, which extends from 125,000 years before the present (B.P.) to 75,000 years B.P., encompasses the "last interglacial." Emiliani has drawn attention to important fluctuations within stage 5 (*12*). Shackleton regarded the fluctuations as sufficiently important to formalize and suggested that only substage 5e was the marine equivalent of the Eemian interglacial stage of northwest Europe (*13*). The isotopic record was such that at substage 5d world climate must have been considerably different from that of the past few thousand years, which represents a model for interglacial climate. More refined oxygen isotope measurements showed that in substage 5d ice sheets in the Northern Hemisphere had over half the volume of the maximum ice sheet development (*7, 8, 14*). Corroborative geomorphic evidence from New Guinea (*15*) includes a sea-level low stand 70 m below that of the peak of substage 5e. However, this evidence does not show a direct correlation between the Eemian and substage 5e, and strong arguments have been offered which suggest correlating the Eemian with substage 5a or with all of stage 5 (*16*).

In this context, the record of core Y72 11 1 is extremely informative. Vegetational succession in the section of the core from late stage 6 to stage 5 is like the transition from stage 2 to stage 1, and like the succession well demonstrated in the northwestern United States (*17*). However, there is no question of a stable vegetation through stage 5. Three intervals of temperate conifer forest were interrupted by two intervals of nonarboreal prominence during isotope stage 5, and only pollen zone 9 (isotope substage 5e) is comparable to pollen zone 1. This is true not only in the marine section but also in terrestrial sections on the adjacent coast (*18*). Therefore, it is clear that the last interglacial in the Pacific Northwest as represented by pollen assemblage zone 9 in core Y72 11 1 is correlative with oxygen isotope substage 5e.

We conclude that, outside the range of ^{14}C dating, the best chance for deciphering the vegetational-environmental record of the Pacific Northwest is through the pollen record contained in deep-sea sediments on the adjacent continental margin. Within the established oxygen isotope record we have obtained a detailed vegetational record of the past 150,000 years in which there is evidence for a single episode of vegetational succession analogous to that of the Holocene. This interval (pollen zone 9) spanned a few thousand years during oxygen isotope substage 5e, around 125,000 years B.P. Throughout the time in which the sediments of core Y72 11 1 were deposited, the correlation of climatic evidence derived from pollen and oxygen isotopes suggests that the core gives a good representation of the complexity of world and regional climatic history.

LINDA E. HEUSSER
New York University, Post Office Box 608, Tuxedo, New York 10987
NICHOLAS J. SHACKLETON
Sub-Department of Quaternary Research, University of Cambridge, Cambridge, England

References and Notes

1. R. P. Suggate, *Quat. Res. (N.Y.)* **4**, 246 (1974).
2. G. M. Woillard, *ibid.* **9**, 1 (1978); T. A. Wijmstra, *Acta Bot. Neerl.* **18**, 511 (1969); A. P. Kershaw, *Nature (London)* **272**, 159 (1978).
3. G. J. Kukla, *Earth Sci. Rev.* **13**, 307 (1977).
4. L. E. Heusser and W. L. Balsam, *Quat. Res. (N.Y.)* **7**, 45 (1977).
5. C. J. Heusser and L. E. Florer, *ibid.* **3**, 661 (1973).
6. N. J. Shackleton and N. D. Opdyke, *Geol. Soc. Am. Mem. 145* (1976).
7. D. Ninkovich and N. J. Shackleton, *Earth Planet. Sci. Lett.* **27**, 20 (1975).
8. N. J. Shackleton, *Colloq. Int. C.N.R.S.* **219**, 203 (1974); W. L. Balsam and L. E. Heusser, *Mar. Geol.* **21**, 121 (1976). Where they were present, we analyzed specimens of *Uvigerina senticosa* and *U. peregrina* for isotopes. When *Gyroidina soldanii* and *Planulina wellerstorfi* were used, we made corrections for departure from isotopic equilibrium. Although some samples had insufficient material to permit isotopic analysis, averaging 20-cm increments produced data comparable to isotopic records from other parts of the ocean (about 1500-year intervals). We recognize that the use of this procedure in certain parts of the core obscures real high-frequency variations, which are not the subject of the present study. The isotopic record of core Y72 11 1 is readily correlated with the stages and substages of core V19 29 (*7*). The $\delta^{18}O$ values of 4.14 and 4.24 per mil plotted for 20 to 60 cm and 60 to 80 cm correspond approximately to the value for the boundary between stages 2 and 1 in core V19 29. The boundary between stages 3 and 2 (often difficult to delineate accurately) was placed in

core V19 29 where the observed value changed from 4.61 to 4.79 per mil. We suggest that this transition correlated with a depth of about 415 cm in the present core. Such a procedure is difficult to apply with absolute rigor since the two records to be correlated are both approximations to the actual time sequence of isotopic fluctuations. However, the use of this procedure enables us to pick confidently all the stage and substage boundaries except the boundary between stages 4 and 3, which is poorly developed in core Y72 11 1.

With few exceptions, 500 pollen grains were counted in each sample. Relative frequency and concentration data for the roughly 50 taxa recognized will be discussed elsewhere (L. E. Heusser and N. J. Shackleton, in preparation). The most significant pollen types (> 2 percent) are presented here as the percentages of the total arboreal and nonarboreal pollen. Pollen zones are those discussed in (*18*).

9. Core TT63 13 was raised from a depth of 1502 m at 47°9′N, 125°16′W.
10. C. J. Heusser, *Quat. Res. (N.Y.)* **8**, 282 (1977).
11. Pollen analyses are from 10-cm intervals, and isotope analyses are from 2.5- to 5-cm intervals. We intend to analyze both pollen and isotopes from this part of the core at 2.5-cm intervals, and so we do not draw zone boundaries at present.
12. C. Emiliani, *Ann. N.Y. Acad. Sci.* **95**, 521 (1961).
13. N. J. Shackleton, *Proc. R. Soc. London Ser. B* **174**, 135 (1969).
14. _____, *Philos. Trans. R. Soc. London Ser. B* **280**, 169 (1977).
15. J. Chappell, *Quat. Res. (N.Y.)* **4**, 405 (1974).
16. W. H. Zagwijn, paper presented at the International Quaternary Association meeting, Birmingham, England, August 1977.
17. C. J. Heusser, *Geol. Soc. Am. Bull.* **85**, 1547 (1974).
18. L. E. Heusser and C. J. Heusser, paper presented at the International Quaternary Association meeting, Birmingham, England, August 1977.
19. We thank C. J. Heusser and G. J. Kukla for critical review of the manuscript. L.E.H. was supported by NSF grant DEB76 12561; N.J.S. was assisted by NSF grant OCE76 22893. We thank T. C. Moore, Jr., and the curating staff of the School of Oceanography, Oregon State University, and the curating staff of the Department of Oceanography, University of Washington, for assistance.

4 December 1978; revised 27 February 1979

Power-Line Harmonic Radiation: Can It Significantly Affect the Earth's Radiation Belts?

Abstract. *It has been suggested that harmonic radiation from the earth's 50- and 60-hertz power transmission lines might significantly influence the distribution of electrons in the radiation belts. On the basis of observations presented here, it seems advisable to accept such a hypothesis with caution. New evidence suggests that power-line radiation does not play any major role in the nonadiabatic dynamics of radiation belt electrons.*

Considerable attention has recently been paid to the possibility that man-made radio signals (in particular, harmonic radiation from the earth's 50- and 60-Hz power transmission lines) can significantly influence the distribution of energetic electrons in the radiation belts (*1*–*3*). Although power-line radiation (PLR) itself has yet to be directly reported deep in the magnetosphere, the premise is that such radiation can leak into the magnetosphere and there act as a source of embryonic emission which subsequently grows to measurable amplitudes as a result of resonant wave-particle interactions. The enhanced waves then strongly scatter electrons, causing electron precipitation loss to the atmosphere. The question that we raise here is the relative importance of scattering by such triggered waves as compared to that from naturally generated emissions.

There are three categories of magnetospheric waves that are known to exert a major effect on radiation belt electrons.

1) Close to the earth within the relatively high-density region termed the plasmasphere, there is an essentially continuous, broad-band, structureless, electromagnetic emission with frequencies between a few hundred hertz and a few kilohertz (*4*). It has been explicitly shown that this emission, called plasmaspheric hiss, can account for both the observed flux distribution and the gradual precipitation loss of electrons after their injection into the inner magnetosphere during geomagnetic disturbances (*5*).

2) Outside the plasmasphere, an intense electromagnetic emission, termed chorus, is detected during substorm electron injection events (*6*, *7*). In contrast to hiss, these waves have a discrete frequency-time structure and their growth is clearly nonlinear (*8*). When present, the waves are sufficiently intense to cause rapid precipitation of electrons in the outer radiation zone (*7*).

3) Electrostatic waves with frequencies above the electron gyrofrequency (Ω_-) are continuously present on auroral field lines (*9*) and are commonly found throughout the outer radiation zone, especially during substorms. These waves are thought to be the principal cause of diffuse auroral precipitation (*10*, *11*) (1 to 10 keV) and an important source of outer-zone electron scattering during disturbed times.

If PLR is to be considered as a significant means of modifying the earth's radiation belts, one must inquire whether any of these emissions are predominantly triggered rather than excited naturally.

In the case of plasmaspheric hiss, the waves exhibit no perceptible frequency structure which might indicate stimulation by power-line harmonics. As a further test for man-induced triggering, we have analyzed (*12*) the occurrence of extremely low-frequency emission in over 1800 samples of data taken during an 18-month period on the polar-orbiting satellite (Orbiting Geophysical Observatory) OGO-6. We found no tendency for the emissions to be enhanced during weekdays (as opposed to weekends when power-line currents are smaller). Furthermore, whereas waves stimulated by PLR should exhibit strong geographic control, the hiss activity (Fig. 1C) is essentially independent of geographic longitude; this result has recently been confirmed by an independent study of signals from 500 to 1000 Hz measured on Ariel 4 (*3*). We therefore conclude that plasmaspheric hiss originates naturally [an adequate source is the cyclotron resonant amplification of background thermal emissions (*13*)] and that the nonadiabatic dynamics of inner-zone and slot-region electrons are primarily controlled by natural processes (*14*). Powerful very-low-frequency transmitters might locally enhance the electron precipitation flux (*2*), but, because of the narrow-band nature of these waves, the scattering is confined to a limited number of resonant electrons in a restricted region of the magnetosphere. Such monochromatic waves, no matter how intense, are therefore unable to significantly affect the overall evolution of the radiation belts.

When considering man-induced effects on the outer radiation belt, one must inquire into the source of electromagnetic chorus and the intense electrostatic electron cyclotron waves. Ashour-Abdalla and Kennel (*11*) have recently shown that the electrostatic waves have very small group speed; consequently, these waves can readily grow from thermal levels to finite amplitude before propagating out of the generation region. The waves are also found in bands centered near odd half harmonics of the electron gyrofrequency, $(n + \frac{1}{2})\Omega_-$, with no indication of enhancement at the power-line harmonics. It is therefore unlikely that such waves are stimulated by PLR. In the case of electromagnetic chorus, one cannot immediately rule out the possibility of triggering. However, chorus is predominantly observed in the outer magnetosphere under highly disturbed conditions when rapid wave growth can be expected. In addition, the increased electron fluxes present during such conditions will lead to enhanced thermal noise (incoherent cyclotron or Cherenkov radiation); there is no a priori reason to discard this mecha-

0036-8075/79/0525-0839$00.50/0