

17. VEGETATION AND CLIMATE OF THE NORTHWEST COAST OF NORTH AMERICA DURING THE LAST 500 K.Y.: HIGH-RESOLUTION POLLEN EVIDENCE FROM THE NORTHERN CALIFORNIA MARGIN¹

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ABSTRACT

Pollen analyses of sediments from Holes 1019C, 1019E, 1020C, and 1020D as well as piston Core EW9504-17 provide continuous, chronostratigraphically controlled proxy vegetation and climate data for coastal northwest North America for the last ~500 k.y. Systematic changes in the representation of the diagnostic components of northern California plant assemblages clearly show orbital-scale variations. Interglacials are all marked by an abrupt increase in alder followed by expansion of lowland oak woodland and redwood forests. Glacials are dominated by montane forest and woodland assemblages. This sequence reflects large-scale climatic controls (e.g., orbital-scale variation in insolation and Northern Hemisphere ice sheets) in western North America over the last five glacial cycles. Regional climatic control (variations in sea-surface conditions) is implied by the differential development of xeric oak and mesic redwood communities.

INTRODUCTION

It has been established that pollen deposited in marine sediments on continental margins provides terrestrial vegetation and climate records that are directly correlated with global chronostratigraphic events (Dupont, 1992; Heusser and van de Geer, 1994; Van Campo et al., 1982). Interpretations of past vegetation and climate of western North America from pollen deposited offshore are based on comparisons of downcore pollen spectra with modern marine and terrestrial pollen spectra (e.g., pollen assemblages from marine and terrestrial sediment traps and surface samples), vegetation, and climate (Heusser and Balsam, 1977; Heusser, 1988). Previous studies showed that Milankovitch-scale variations in vegetation of coastal Washington and Southern California reconstructed from pollen deposited in the northeast Pacific Ocean during the last glacial cycle were similar to those inferred from onshore pollen data ascribed to the same time (Heusser and Florer, 1973; Heusser, 1995). To extend these studies in space and time, we present preliminary results from pollen analyses of sediments deposited off Northern California during the last ~500 k.y.

Pollen from piston cores taken on the continental margin of western North America between 32°N and 43°N also showed systematically related short-term changes superposed on Milankovitch-scale oscillations of the past 60 k.y. During oxygen isotope Stage 3, for example, brief warming events in California and Oregon appear correlative with interstadial events in waters offshore (Heusser, 1998). Here we extend high-resolution pollen analyses of sediments deposited on the northern California margin over the last ~140 k.y.

BACKGROUND

Natural coastal vegetation of California changes from xeric, open oak woodland in the south to dense conifer rainforest in the north.

The complex mosaic of southern California scrub oak (*Quercus*), oak woodland savanna, and oak-dominated foothill woodlands with isolated groups of closed-cone pine and cypress (*Pinus radiata* and *Cupressus pygmaea*) interfingers with chaparral and lowland sage scrub. Conifer forests develop upslope in which open pine woodlands with small, scattered stands of incense cedar (*Libocedrus decurrens*) are succeeded at higher elevations by mid-montane parkland with pine and incense cedar, upper montane juniper (*Juniperus occidentalis*) woodland, and subalpine coniferous forests with lodgepole pine (*Pinus contorta*) (Barbour and Billings, 1988; Barbour and Major, 1977; Franklin and Dyrness, 1973).

In Northern California, redwood (*Sequoia sempervirens*) distinguishes the southern extension of the Pacific Northwest evergreen coniferous forests, which are unique in size and longevity among temperate forest regions of the world (Waring and Franklin, 1979). Associated with redwood are western hemlock (*Tsuga heterophylla*), spruce (*Picea sitchensis*), Douglas fir (*Pseudotsuga menziesii*), and western red cedar (*Thuja plicata*). Inland, xerophytic lowland deciduous oak communities (*Quercus garryana*, *Quercus lobata*, and *Quercus douglasii*) and oak/pine/grassland mosaics develop. At higher elevations in the Coastal Range, montane forest formations develop with fir (*Abies*), hemlock, Douglas fir, pine, and evergreen oaks (Barbour and Major, 1977). Just north of ~4°N in Oregon, western hemlock and Sitka spruce dominate along the Pacific Ocean, with hemlock on the coast and spruce more prominent in the interior. Common forest associates include Douglas fir, western red cedar (*T. plicata*), and alder (*Alnus*) in moist habitats. Above the narrow band of lowland forest are montane and subalpine forests of fir (*Abies concolor* and *Abies amabilis*), pine (*Pinus ponderosa* and *Pinus lambertiana*), and mountain hemlock (*Tsuga mertensiana*).

The two contrasting vegetation types of the California coast (southern California oak woodland and Pacific Northwest conifer forests) reflect significant differences in mean annual temperature and precipitation (first-order controls of vegetation distribution). South of ~40°N–42°N, mean annual temperatures and precipitation average 19°C and 30 cm, and upper montane temperature and precipitation are ~8°C and ~57 cm. To the north in Oregon, mean annual lowland temperature and precipitation are ~12°C and ~300 cm, and subalpine temperatures and precipitation average ~10°C and ~140 cm (Elford, 1974; Sternes, 1974). The south–north transition from excess evaporation to excess precipitation roughly coincides with the frequency and intensity of frontal storms south and north of the atmospheric and oceanic polar fronts.

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Close to the ocean, California and Oregon temperatures and effective precipitation are moderated by fog associated with upwelling (Barbour, 1988; Barbour et al., 1980) and by seasonal variations in sea-surface temperatures (SSTs) of the southward-flowing California Current and the poleward-flowing seasonal Davidson Current. South of $\sim 42^\circ\text{N}$, northerly winds drive near-coastal persistent seasonal upwelling; to the north, upwelling intensity is more variable. Off California and Oregon, waters north of 40°N – 42°N are subarctic in type with mean SSTs of $\sim 12^\circ$ to $\sim 13^\circ\text{C}$; off Southern California, mean SSTs of $\sim 14^\circ$ to $\sim 15^\circ\text{C}$ reflect the presence of subtropical waters (Gardner et al., 1997).

During the past glacial cycle, changes in the California Current system and in California maritime vegetation and climate inferred from pollen data appear to be related. Near-synchronous high-frequency variations in the abundance of oak in Southern California and SST in the Santa Barbara Basin characterize oxygen isotope Stage (OIS) 5 (Heusser, 1995). Similar variations in redwoods in Northern California correspond to temporal and geographic changes in offshore upwelling and in movement of the Polar Front during OISs 3–1 (Doose et al., 1997; Gardner et al., 1997; Heusser, 1998; Lyle et al., 1992; Sabin and Pisias, 1996; Sancetta et al., 1992). Here we use three pollen records from cores taken on the northeast Pacific continental margin to document millennial-scale variability of coastal North American ecosystems from OISs 1 through 13.

METHODS

Pollen records are from cores taken at two Ocean Drilling Program (ODP) drill sites (Site 1019: $41^\circ 40.696'\text{N}$, $124^\circ 55.981'\text{W}$, 989 meters below seafloor [mbsf]; Site 1020: $41^\circ 0.051'\text{N}$, $126^\circ 26.065'\text{W}$, 3050 mbsf) and from piston Core EW9504-17PC ($42^\circ 14.55'\text{N}$, $125^\circ 53.28'\text{W}$, 2671 mbsf; Fig. 1). The siliciclastic clays and silt from the upper 60 m (meters composite depth [mcd]) of Holes 1020C, 1020D, 1019C, and 1019E were routinely sampled at 20-cm intervals (Lyle, Koizumi, Richter, et al., 1997). Core EW9504-17PC, composed predominantly of hemipelagic clay (Lund and Mix, 1998), was sampled at 5-cm intervals. Standard processing procedures that included the addition of known amounts of an exotic tracer to calculate pollen concentration were preceded and succeeded by sieving through $7\text{-}\mu\text{m}$ nylon screening. Taxonomic identification of pollen was based on comparison with modern pollen reference collections from western North America. Specific epithets are indicated for grains that were clearly identified; otherwise, pollen and spores are assigned to genera or higher rank. Other than the papillate grains of *Sequoia* (redwood) and the large inaperturate grains assumed to represent *P. menziesii*, inaperturate pollen of other genera in the Taxodiaceae, Cupressaceae, and Taxaceae that cannot be satisfactorily separated using light microscopy (e.g., *Juniperus*, *Torreya*, *Cupressus*, *Libocedrus*, *Chamaecyparis*, and *Thuja*) are here referred to as cedar type. Other synthetic pollen groups include chaparral (sclerophyllous shrubs and other members of the Anacardiaceae, Rhamnaceae, and Rosaceae) and herbs (Gramineae, Cyperaceae, and Compositae, including *Artemisia* or sage). A minimum of 300 pollen grains were identified in each sample from Core EW9504-17PC; the initial pollen counts from Sites 1019 and 1020 presented here averaged ~ 110 and ~ 150 pollen grains, respectively. Pollen percentages were based on the sum of terrestrial pollen (excluding fern spores), and pollen concentration was calculated on the number of pollen grains per gram dry weight of sediment (gdws).

Age models were constructed by correlating the CaCO_3 and C_{org} records to the best radiocarbon-dated sections and oxygen isotope records. Methods are reported in detail in Lyle et al. (Chap. 32, this volume). Age control for Core EW9504-17PC was achieved by (1) correlating the CaCO_3 and C_{org} records from Lyle et al. (Chap. 32, this volume) with Core W8709-13PC (time scale of Lund and Mix, 1998) for 0–50 ka, (2) correlating the oxygen isotope record from 50 to 140

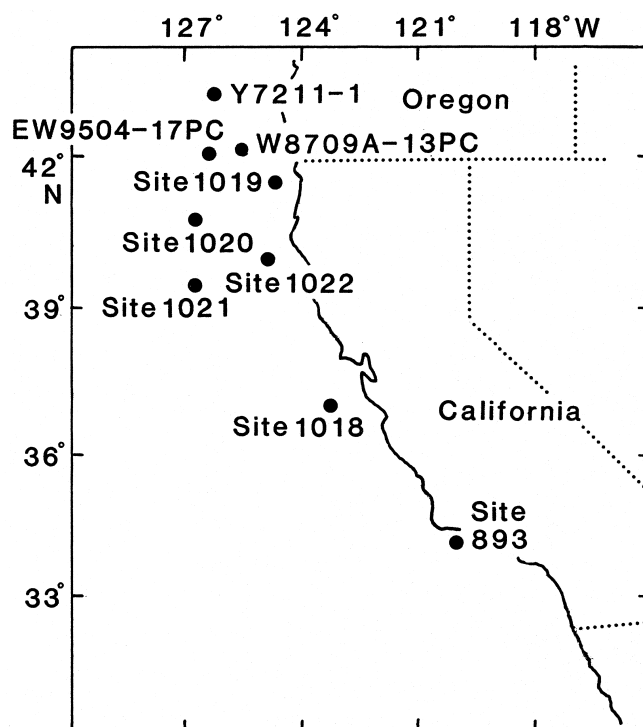


Figure 1. Map of the northeast Pacific continental margin showing core locations. Site 1019 is in the coastal upwelling system. Site 1020 and Core W8709-17 are under the northern California Current, south of the North Pacific Subpolar Front.

ka in the core (Lund and Mix, 1998) with the Martinson et al. (1987) age model, (3) allowing minor shifts in the record to minimize sedimentation rate changes without losing significant correlation, and (4) comparing the oxygen isotope record on the final age model to the Martinson et al. (1987) age model to see if the two age models remained consistent.

To construct an age model for Site 1020, we correlated the dated carbonate and organic carbon records from Core EW9504-17PC with the carbonate and organic carbon records of nearby Site 1020 and hence were able to transfer the age model from Core EW9504-17PC to Site 1020 (Lyle et al., Chap. 32, this volume). Below 140 ka, our age model for Site 1020 is based upon reconnaissance-scale oxygen isotope stratigraphy and biostratigraphic datums.

Development of an age model for Site 1019 was more problematic (Lyle et al., Chap. 32, this volume). The preliminary age model used here is based on reconnaissance-scale oxygen isotope stratigraphy supplemented by radiocarbon age control from 6 to 24 ka. We note that these preliminary age models will be modified when more age control (radiocarbon and stable isotope data) is available. Using the age models described above, the average sampling interval in Core EW9504-17PC was ~ 500 yr, the average sampling interval in the upper 57 mcd of Holes 1020C and 1020D was ~ 1700 yr, and the average sampling interval in the upper 40 m of Holes 1019C and 1019E was ~ 800 yr (Lyle, Koizumi, Richter, et al., 1997).

RESULTS AND DISCUSSION

In the hemipelagic sediments from Core EW9504-17 and from Sites 1019 and 1020, pollen concentration is high, with slightly more pollen in sediments deposited closest to land (Fig. 2). Mean pollen abundance in sediments deposited at Site 1019 (~ 59 km west of the California coast) is 5500 grains/gdws compared with mean concentrations of 4000 grains/gdws in sediments deposited at Core

EW9504-17 (~120 km offshore) and 3600 grains/gdws in sediments deposited at Site 1020 (~167 km offshore). Rapid oscillations in pollen abundance that occur in pollen records from each of the three localities display high-amplitude peaks that show systematic variations in Core EW9504-17 and Site 1019. Age plots (Fig. 2) show that although the overall trends of pollen abundance in Core EW9504-17 broadly correspond to interglacial–glacial climate change (e.g., maxima occur in warm intervals such as the Holocene and OIS 5, and minima are associated with cold intervals such as OIS 2), correlation between pollen concentration and climatic events is not consistent. At Site 1019, maxima in total pollen abundance coincide with some (OISs 5 and 7) but not all major warm intervals, whereas variations in mass accumulation rates of redwood at Site 1020 (like that of terrigenous minerals; see Hovan et al., Chap. 18, this volume) correspond fairly closely to global $\delta^{18}\text{O}$ variations. Pollen concentration on the California continental margin reflects vegetation density, pollen sedimentation (including fluvio-marine sedimentary processes), and climatic processes (regional and global; Heusser and Balsam, 1977; Traverse, 1988; Fig. 2).

The pollen records from Sites 1019 and 1020 as well as Core EW9504-17 are composed of taxa that presently grow in northwest America. Paleoecologic interpretations of these pollen spectra are based on several assumptions: (1) the diagnostic components of pollen assemblages from marine cores, like those from terrestrial cores, reflect in varying degrees the composition of vegetation formations from which they are derived (Heusser, 1983, 1988; Heusser and Bal-

sam, 1977); (2) modern climatic tolerances of vegetation with pollen spectra similar to fossil pollen spectra provide a reliable foundation for reconstructing past vegetation and climate (Heusser et al., 1980; Whitlock and Bartlein, 1997); and (3) changes in the Quaternary vegetation of California and southern Oregon reflect regional and global climatic change (Axelrod, 1977; Huntley and Webb, 1988).

At all three localities, pollen spectra of the uppermost samples are marked by a succession of alder, oak, and redwood peaks accompanied by ferns and lesser amounts of western hemlock, spruce, and cedar (Figs. 3–5). These distinctive assemblages of pollen representative of natural north coast forest and oak woodland communities occur repeatedly downcore: between ~13 and ~15 m in Core EW9504-17 (Fig. 3); also, between ~38 and ~32 mcd and between ~46 and ~66 mcd at Site 1019 (Fig. 4). In the record from Site 1020, the alder-oak-redwood-fern assemblage is repeated five times (Fig. 5). Although the basic composition is essentially the same in the three records, differences exist in the sequence and relative abundance of taxa. In Holes 1019C and 1019E, the redwood maxima at 33.48 mcd precedes that of oak (32.68 mcd). At Site 1020, redwood maxima vary in amplitude from ~35% at 44 mcd to ~10% at 26–28 mcd, and alder maxima range from ~22% at ~55 mcd to ~7% at 14 mcd. Except for the peak at ~14 mcd, oak peaks display less variation.

The peaks of alder that initiate abrupt expansions of coastal lowland forest types reflect the pioneer role of alder in aggressively colonizing areas disturbed by catastrophic events (flooding and infrequent wildfires) or by reorganization of plant communities related directly

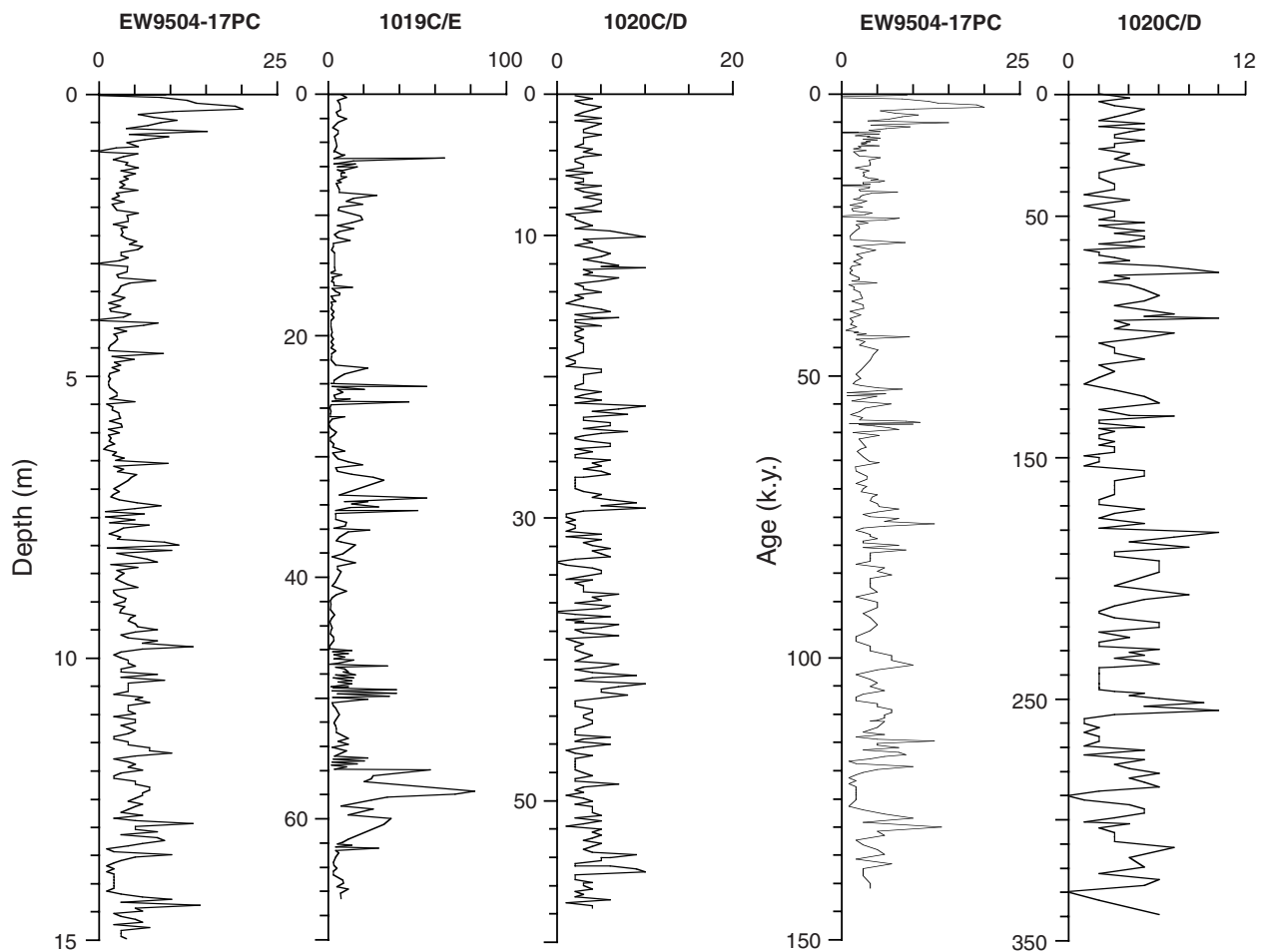


Figure 2. Depth plot of pollen concentration in number of pollen grains per gram dry weight of sediment at Sites 1019 and 1020 and piston Core EW9504-17 (left), and time series of pollen concentration at Site 1020 and in piston Core EW9504-17 (right). Depths of samples from Holes 1019C, 1019E, 1020C, and 1020D are meters composite depths (Lyle, Koizumi, Richter, et al., 1997). Age models are based on time scales developed by Lyle et al. (Chap. 32, this volume).

or indirectly to climate change. The apparent lack of systematic variation in charcoal fragments found in pollen samples suggests that wildfires were probably not the primary cause of the high-amplitude alder events. Alder habitats are wet, along streams and in marshy places in redwood and mixed evergreen forests (*Alnus oregona* and *A. tenuifolia*), and moist places in the north Coastal Range (*A. tenuifolia*; Barbour and Billings, 1988; Munz, 1968). Increased alder in sediments deposited on the California margin thus may reflect expansion and/or recolonization of alder habitats related to increased precipitation and/or increased runoff from snowmelt during deglaciation (Heusser and Shackleton, 1979). Alder expansion in areas of revegetation following disturbance is well documented in the Pacific Northwest (Barbour and Billings, 1988; Grigg and Whitlock, 1998; Heusser, 1985).

Subsequent expansion of the two different north coast lowland habitats—mesic redwood forests along the narrow band adjacent to the Pacific Ocean and xeric oak woodland farther inland—may be related to changes in temperature, precipitation, and other atmospheric and oceanic processes. Higher temperatures and change in the amount and seasonal distribution of rainfall that enhanced summer drought (increased summer moisture stress related to decreased effective precipitation and increased summer temperatures, for example) would favor development of lowland oak communities. Such conditions would not be conducive to redwood expansion. Coastal redwood requires much lower diurnal and annual temperature fluctuations than oak and is now restricted to that part of the coast where temperature extremes and summer moisture stress are modified by

prolonged cloudy periods and marine fog associated with offshore upwelling (Zinke, 1977). We suggest that redwood expansion was probably closely related to the development of maritime conditions (changes in the distribution and intensity of upwelling in the California Current, for example), which moderated north coast climate. Detailed statistical analyses of radiolarian species and pollen taxa from Core EW9504-17 show a very high degree of correlation between radiolarians associated with coastal upwelling and redwood (N.G. Pisias, pers. comm., 1998).

All the pollen records contain lengthy intervals dominated by seemingly uniform assemblages composed of pine, herbs, and cedar, along with spruce, hemlock, and mountain hemlock (*T. mertensiana*, a subalpine species; Barbour and Billings, 1988). To some extent, the apparent uniformity reflects limitations of pollen analysis; that is, the presence of genera and families that cannot be discriminated into more ecologically specific taxonomic taxa. The composition of these conifer-dominated assemblages alternates between coastal forest taxa like those now growing north of the present distribution of redwood (in northern Oregon, Washington, and British Columbia) and forests or open pine woodlands not unlike those that now occur at higher elevations (Barbour and Major, 1977). Oscillations in herbs that occur throughout indicate variable development of vegetative cover.

Similar sequences of temperate lowland conifer forest and oak woodland assemblages alternating with those of montane forest/woodland occur in upper Quaternary pollen records from sites in Northern California, western Oregon, and Washington as well as in

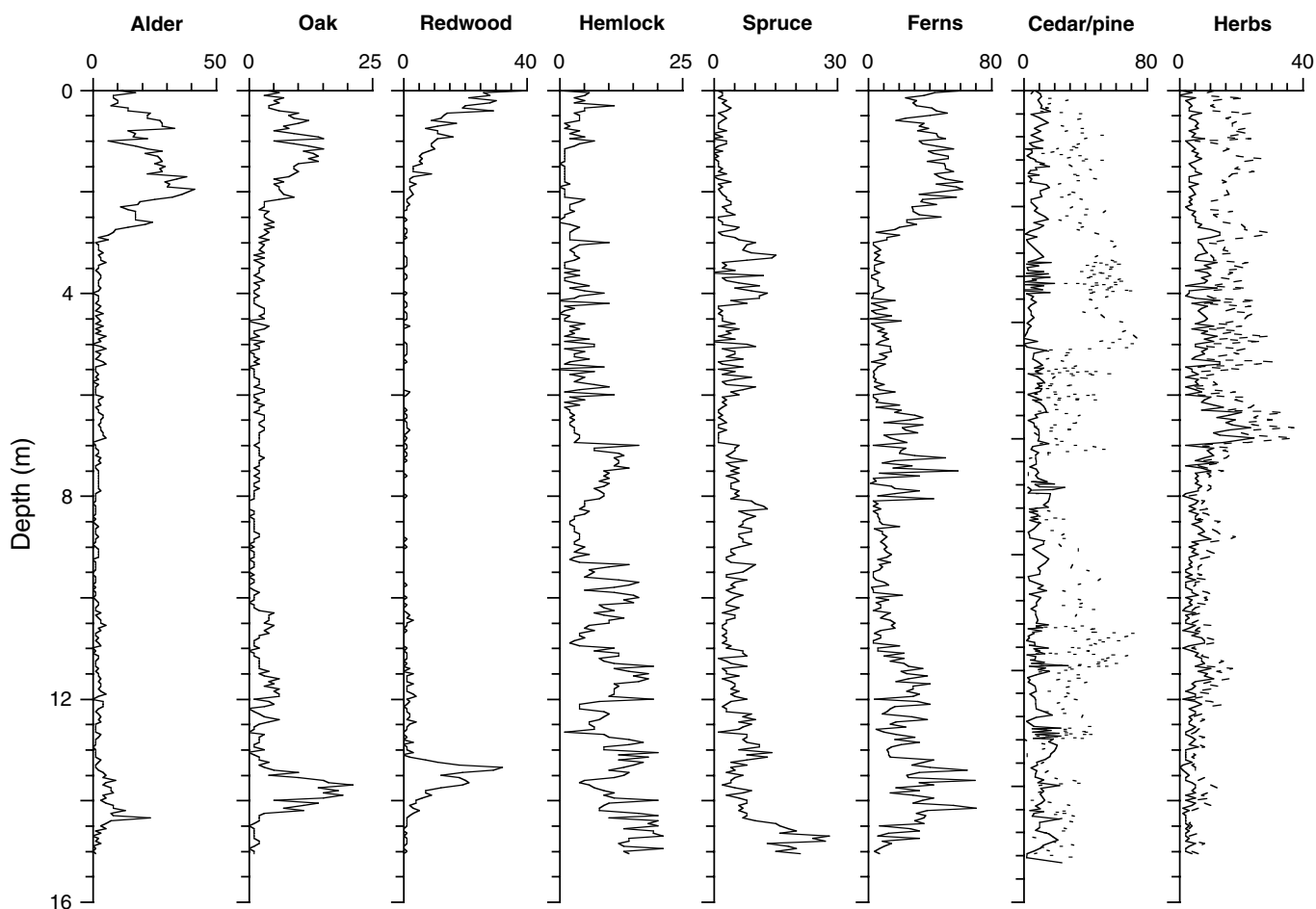


Figure 3. Depth plots of percentages of selected pollen types from piston Core EW9504-17. The relative abundance of sage (*Artemisia*) is shown as a solid black line in the herbs plot; other herb percentages are shown by a dotted line. The percentage of cedar is a solid black line; pine percentages are plotted with a dotted line. Note that scales vary for different taxa.

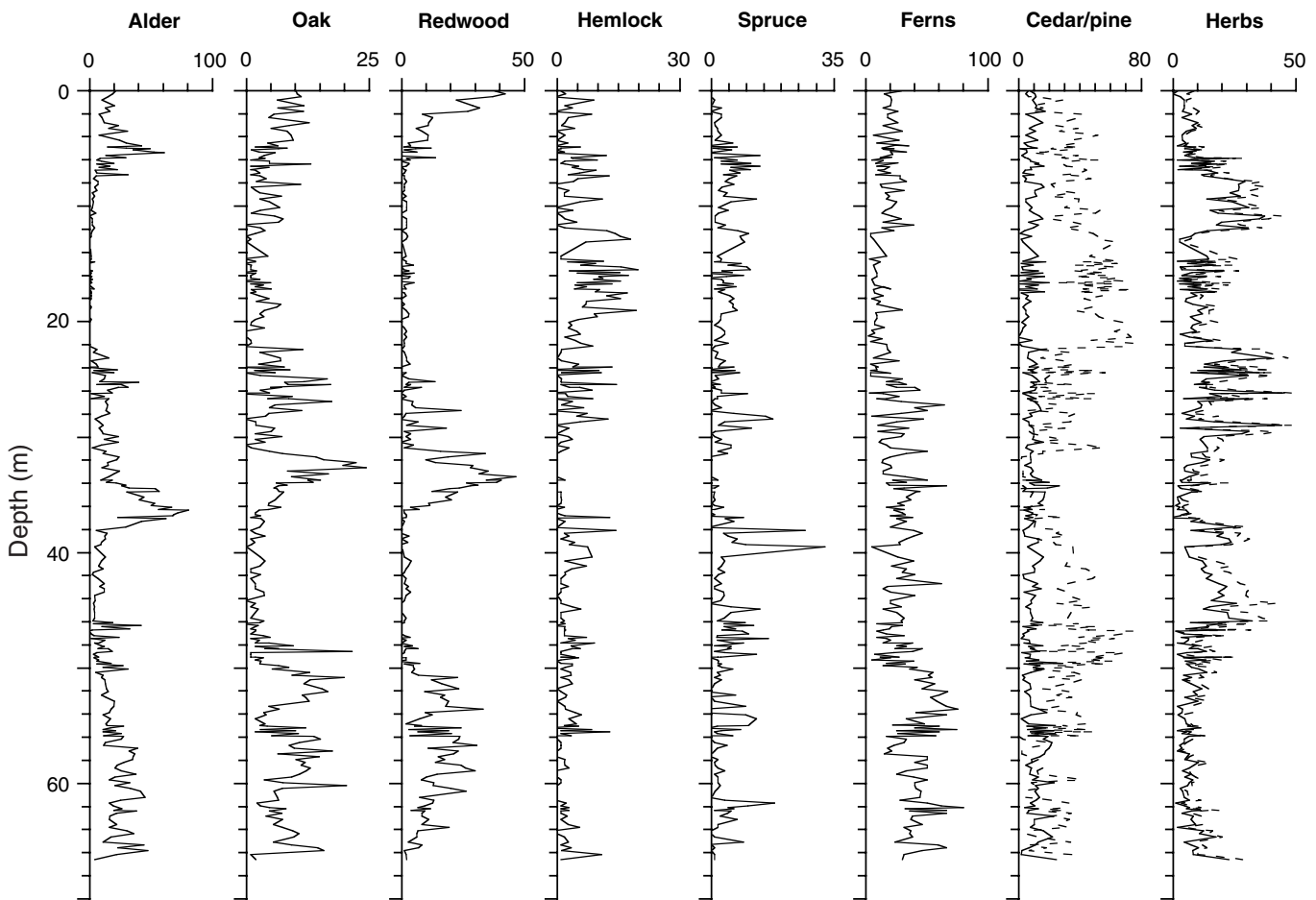


Figure 4. Depth plots of percentages of selected pollen types from the upper 66 m of Holes 1019C and 1019E. The relative abundance of sage (*Artemisia*) is shown as a solid black line in the herbs plot; other herb percentages are shown by a dotted line. The percentage of cedar is a solid black line; pine percentages are plotted with a dotted line. Note that scales vary for different taxa.

Quaternary pollen data from other marine cores taken off Northern California, Oregon, and Washington (Adam and West, 1983; Grigg and Whitlock, 1998; Heusser, 1985, 1998; Heusser and Shackleton, 1979). Regional differences in vegetation are readily apparent in the composition of the warm temperate pollen assemblages (i.e., the prominence of redwood and/or oak in the south and of western hemlock and spruce in the north) and in the composition of the more homogeneous pollen assemblages in the intervening cooler intervals, which are characterized by the greater prominence of juniper and cedar types in cores from the south. The similarity between the systematic downcore variations in marine and continental records from the same geographic area implies that marine pollen records, like those on land, capture systematic variations in regional vegetation and climate.

When pollen data are plotted against age (Figs. 6–8), it is evident that in Core EW9504-17, alder, oak, redwood, and fern maxima correspond to benthic $\delta^{18}\text{O}$ minima and that downcore variations in pollen stratigraphies of Sites 1019 and 1020 also reflect orbital-scale global climate fluctuations. Small differences in the relative abundance of the mesophytic, temperate taxa between OISs 1, 5, 7a, 7c, and 9 suggest that the development and composition of interglacial vegetation in Northern California was not always identical in each of the last four interglacials. Because of the preliminary nature of age models for Sites 1019 and 1020 (Lyle et al., Chap. 32, this volume), we focus on the well-dated EW9504-17 time series.

The double beat of OIS 7 $\delta^{18}\text{O}$ at Site 1020 (Fig. 8) is mirrored in muted alder, oak, and redwood peaks that are more robust (as are

ferns) in the preceding interglacial (OIS 9). The OIS 6/5e transition in Core EW9504-17 and at Site 1019 is marked by an abrupt rise in alder that is rapidly succeeded in OIS 5e by oak and redwood peaks in Core EW9504-17. At Site 1019, the redwood maximum precedes that of oak. Multiple oscillations in these taxa occur in OIS 5c. These large-scale patterns also occur in pollen assemblages in the upper ~130 k.y. of the lower resolution Site 1020 pollen record (Fig. 8). It is worth noting that in all three records, pollen assemblages from OIS 5e are not exact replicates of those in OIS 1. During the last interglacial, oak was more abundant than in the Holocene; the converse is true for alder and redwood in Core EW9504-17 and at Site 1020.

Pine, dominant in OIS 5d and 5b, became increasingly important during the last full glacial, as did sage and other herbs. In OIS 3, brief pine events occurred at ~14, ~16, ~35, ~38, and ~42 k.y. in Core EW9504-17 (Fig. 6). Two well-defined events coincide with major episodes of North Atlantic ice rafting (Heinrich Events H1 and H4). The low amplitude of redwood and oak oscillations during OIS 3, which partly reflects overrepresentation of pine (a common feature of pollen dispersal and sedimentation; Traverse, 1988), precludes correlation with interstadial events elsewhere.

In Holes 1020C and 1020D, the rhythmic pattern of downcore variation in the alder, oak, redwood, and fern maxima (Fig. 5) is evident through OIS 13 (M. Lyle, pers. comm., 1998). Between ~43 and ~45 mcd (OIS 11), the robust redwood acme is preceded by a substantial peak in alder and ferns. Oak percentages are comparable to those of previous interglacials (excluding OIS 5). The high-amplitude pulse of alder between ~51 and ~55 mcd (OIS 13) leads a lesser

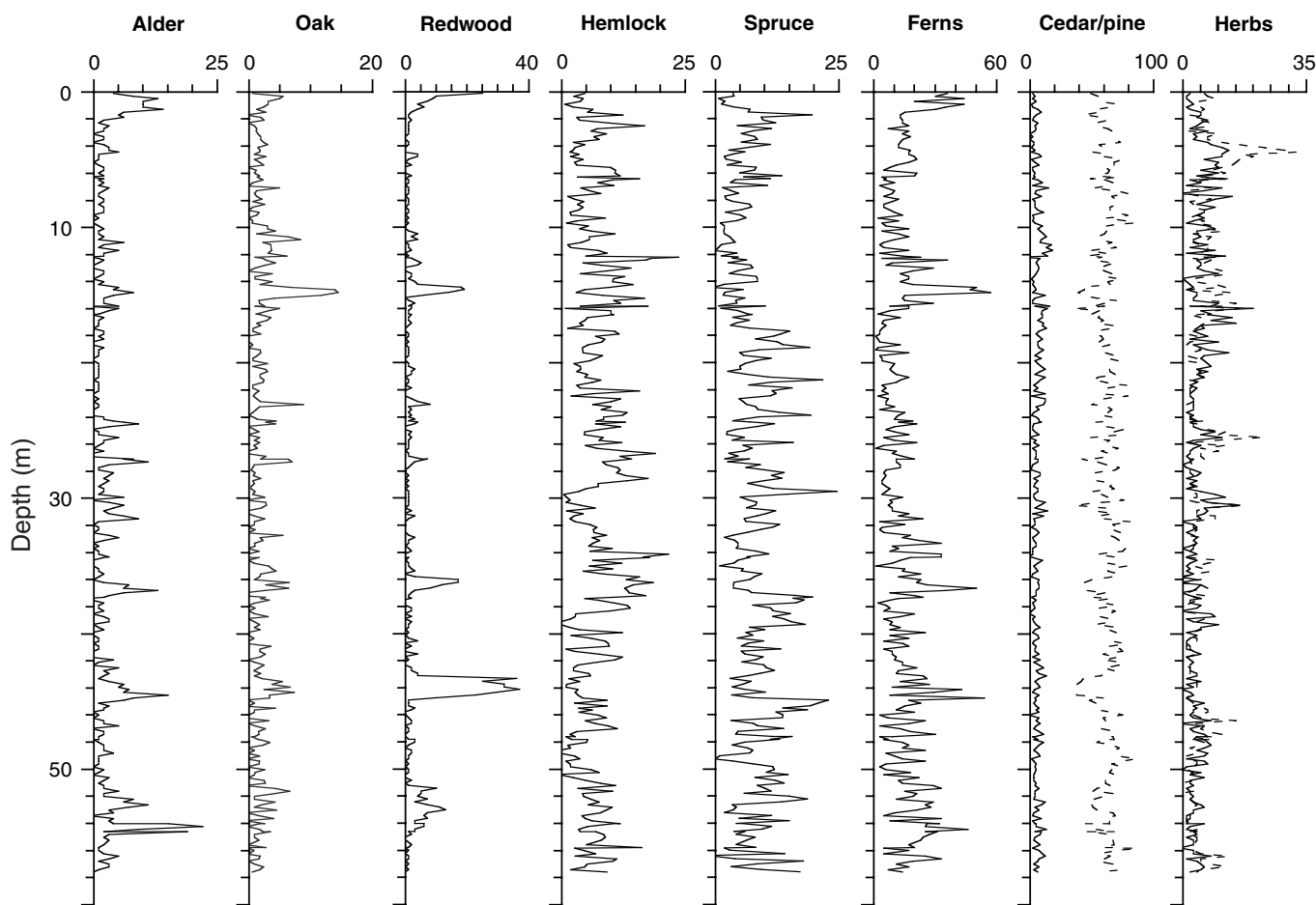


Figure 5. Depth plots of percentages of selected pollen types from the upper 60 m of Holes 1020C and 1020D. The relative abundance of sage (*Artemisia*) is shown as a solid black line in the herbs plot; other herb percentages are shown by a dotted line. The percentage of cedar is a solid black line; pine is plotted with a dotted line. Note that scales vary for different taxa.

rise in redwood, oak, and ferns. As in the younger part of the pollen record, interglacial assemblages display individualistic variations.

At glacial–interglacial transitions (OISs 8/7, 6/5e, 2/1, and most probably 10/9), the abrupt changes in west coast vegetation (identified by the rapid expansion of the pioneer alder) and global warming (higher benthic $\delta^{18}\text{O}$) are nearly synchronous (Figs. 6, 8). The initial increase in alder and the shift in $\delta^{18}\text{O}$ at glacial terminations occurs in exactly the same sample depths in Core EW9504-17 and at Site 1020. Directly correlative pollen and $\delta^{18}\text{O}$ data from two other northeast Pacific cores (Core Y7211-1 taken at $43^{\circ}15'N$, $126^{\circ}22'W$; Site 893 taken at $34^{\circ}17.25'N$, $120^{\circ}02.19'W$; Fig. 1) showed similar relationships at the OIS 6/5e transition (Heusser, 1995; Heusser and Shackleton, 1979). These data imply that glacial–interglacial variations in northwest North American climate and vegetation over the last 350 k.y. were (within constraints of sample resolution) apparently nearly synchronous with orbital-scale global ice-volume variations. Directly correlative terrestrial/marine records from piston cores taken in the northwest Pacific (Morley and Heusser, 1997) and from Site 594 in the southwest Pacific (Heusser and van de Geer, 1994) showed that large-scale variations in Japanese and New Zealand ecosystems over the last ~350 k.y. could be attributed to orbital forcing of global climate mechanisms.

To display pollen data in a form less affected by overrepresentation of pine, we use pollen ratios (Fig. 9). The redwood and western hemlock/spruce ratio can be regarded as a temperature indicator of mesophytic lowland forests because average July temperatures in ar-

reas now dominated by redwood and/or western hemlock are $\sim 1^{\circ}$ to 2°C higher than in areas dominated by spruce (Heusser, 1985; Heusser and Shackleton, 1979; Zinke, 1977). The oak/pine ratio serves as an indicator of temperature trends in the more arid northern California interior since temperatures in the lowland oak woodlands are several degrees higher than temperatures in montane pine forests (Adam and West, 1983). At $\sim 42^{\circ}N$, maximum mean monthly temperatures at 332-m elevation in the nearby mountains are 6.2°C higher than on the coast (Barbour and Major, 1977). Although we describe these climate proxies as temperature indicators, we recognize that effective precipitation is a major factor in vegetative composition and cannot be effectively separated from temperature in our paleoclimatic proxies.

The close correspondence between pollen ratio, insolation, and $\delta^{18}\text{O}$ curves implies that north coast environmental fluctuations were broadly synchronous with changes in global climate over the last ~150 k.y. (Fig. 9). As suggested earlier, the lag in the response of redwood/western hemlock communities probably reflects the significant role of sea-surface conditions in the development of north coast maritime vegetation (Lyle et al., Chap. 32, this volume).

SUMMARY

Pollen records from the northern California and southern Oregon margin of the northeast Pacific Ocean (Sites 1019 and 1020 and pis-

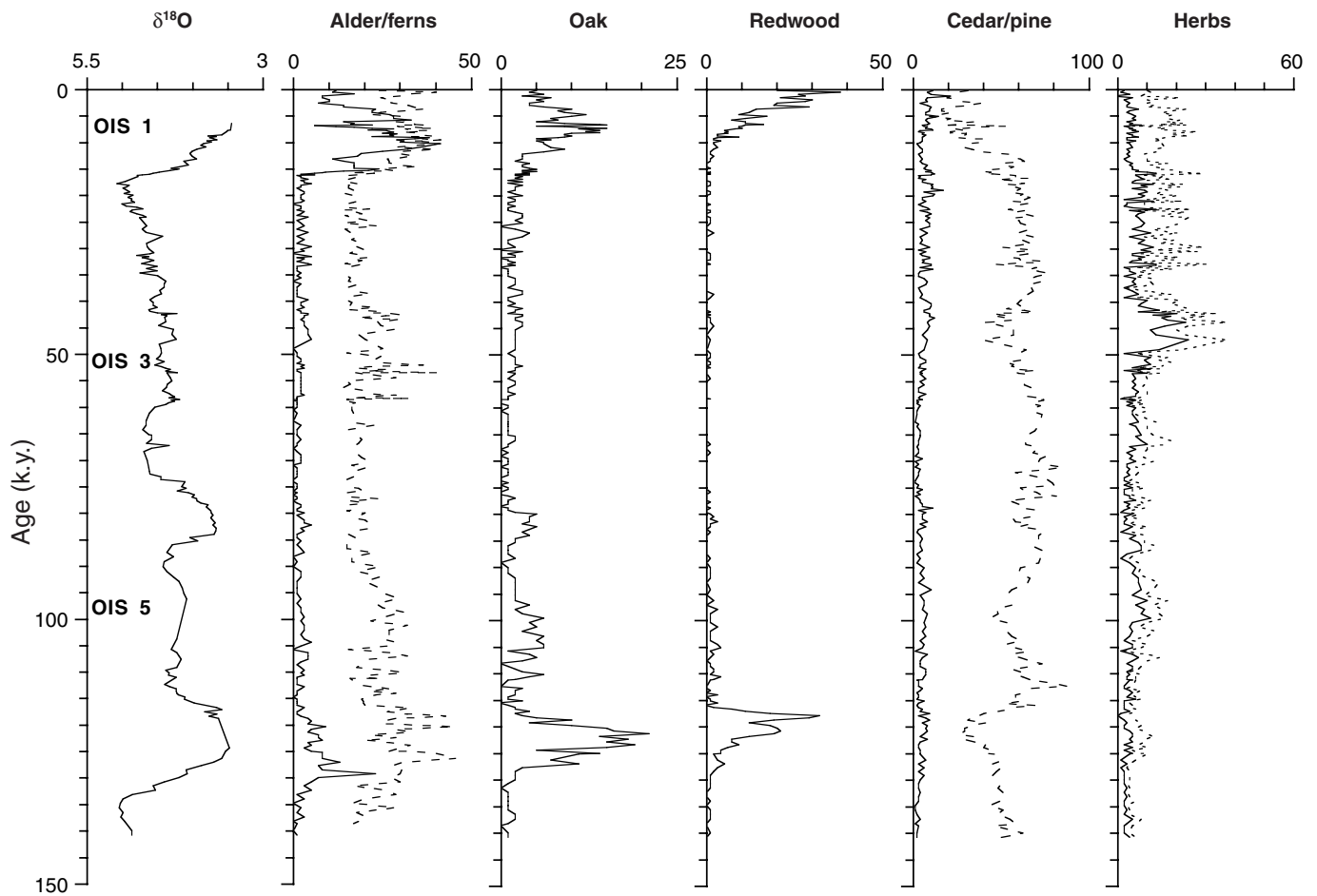


Figure 6. Time series of selected pollen types and stable isotope data from Core EW9504-17 with benthic oxygen isotope Stages (OISs) 1 through 5 superimposed. The percentage of sage is shown as a solid black line in the herbs plot; percentages of ferns, pine, and herbs (excluding sage) are shown as dotted lines.

ton Core EW9504-17) capture vegetational-environmental changes on the North American northwest coast. Glacial vegetation is dominated by montane conifer types accompanied by a significant amount of herbs. Major climatic thresholds such as glacial-interglacial transitions are marked by high-amplitude peaks of the pioneer alder that precede the expansion of interglacial lowland oak woodlands and coastal redwood forests. The similarity in the structure of oak- and redwood-based pollen ratios, insolation, and $\delta^{18}\text{O}$ curves implies that environmental fluctuations on the Pacific Northwest coast reflect large-scale variations in global climate over the last ~150 k.y. Comparison of preliminary pollen and oxygen isotope data from Sites 1019 and 1020 indicates that similar relationships prevailed over the last 500 k.y. We suggest that differences in the development of lowland oak- and redwood-dominated vegetation on the northwest coast of North America reflect fluctuations in large-scale climate controls and fluctuations in regional maritime conditions offshore.

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REFERENCES

- Adam, D.P., and West, G.J., 1983. Temperature and precipitation estimates through the last glacial cycle from Clear Lake, California, pollen data. *Science*, 219:168–170.
- Axelrod, D., 1977. Outline history of California vegetation. In Barbour, M.G., and Major, J. (Eds.), *Terrestrial Vegetation of California*: New York (Wiley), 139–194.
- Barbour, M.G., 1988. Californian upland forests and woodland. In Barbour, M.G., and Billings, D. (Eds.), *North American Terrestrial Vegetation*: Cambridge (Cambridge Univ. Press), 131–164.
- Barbour, M.G., and Billings, W.D., 1988. *North American Terrestrial Vegetation*: Cambridge (Cambridge Univ. Press).
- Barbour, M.G., Burk, J.H., Pitts, W.D., 1980. *Terrestrial Plant Ecology*: Menlo Park, CA (The Benjamin/Cummings Company).
- Barbour, M.G., and Major, J., 1977. *Terrestrial Vegetation of California*: New York (Wiley).
- Doose, H., Prah, F.G., and Lyle, M.W., 1997. Biomarker temperature estimates for modern and last glacial surface waters of the California Current system between 33° and 42°N. *Paleoceanography*, 12:615–622.
- Dupont, L., 1992. Marine palynology of interglacial-glacial transitions. In Kukla, G.J., and Went, E. (Eds.), *Start of a Glacial*: New York (Springer-Verlag), 137–156.
- Elford, C.R., 1974. The climate of California. In van der Leeden, F., and Troise, F.L. (Eds.), *Climates of the States*: Port Washington, NY (Water Info. Center), 538–594.
- Franklin, J.F., and Dyrness, C.T., 1973. Natural vegetation of Oregon and Washington. *U.S. Dep. Agr. For. Serv. Gen. Techn. Rep.*, PNW-8.
- Gardner, J.V., Dean, W.E., and Dartnell, P., 1997. Biogenic sedimentation beneath the California Current system for the past 30 kyr and its paleoceanographic significance. *Paleoceanography*, 12:207–225.

- Grigg, L.D., and Whitlock, C., 1998. Late-glacial vegetation and climate change in Western Oregon. *Quat. Res.*, 49:287–298.
- Heusser, C.J., 1985. Quaternary pollen records from the Pacific Northwest Coast: Aleutians to the Oregon-California border. In Bryant, V.M., Jr., and Holloway, R.G. (Eds.), *Pollen Records of Late-Quaternary North American Sediments*. Am. Assoc. Stratigr. Palynol., 141–165.
- Heusser, C.J., and Florer, L.E., 1973. Correlation of marine and continental Quaternary pollen records from the Northeast Pacific and western Washington. *Quat. Res.*, 3:661–670.
- Heusser, C.J., Heusser, L.E., and Streeter, S.S., 1980. Quaternary temperatures and precipitation for the north-west coast of North America. *Nature*, 286:702–704.
- Heusser, L., 1998. Direct correlation of millennial-scale changes in western North American vegetation and climate with changes in the California Current system over the past ~60 kyr. *Paleoceanography*, 13:252–262.
- Heusser, L., and Balsam, W.L., 1977. Pollen distribution in the northeast Pacific Ocean. *Quat. Res.*, 7:45–62.
- Heusser, L.E., 1983. Contemporary pollen distribution in coastal California and Oregon. *Palynology*, 7:19–42.
- , 1988. Pollen distribution in marine sediments on the continental margin off Northern California. *Mar. Geol.*, 80:131–147.
- Heusser, L.E., 1995. Pollen stratigraphy and paleoecologic interpretation of the 160-ky. record from Santa Barbara Basin, Hole 893A. In Kennett, J.P., Baldauf, J.G., and Lyle, M. (Eds.), *Proc. ODP, Sci. Results*, 146 (Pt. 2): College Station, TX (Ocean Drilling Program), 265–279.
- Heusser, L.E., and Shackleton, N.J., 1979. Direct marine-continental correlation: 150,000-year oxygen isotope-pollen record from the North Pacific. *Science*, 204:837–839.
- Heusser, L.E., and van de Geer, G., 1994. Direct correlation of terrestrial and marine paleoclimatic records from four glacial-interglacial cycles—DSDP Site 594 Southwest Pacific. *Quat. Sci. Rev.*, 13:273–282.
- Huntley, B., and Webb, T., III., 1988. *Vegetation History*: Boston (Kluwer Academic).
- Lund, D.C., and Mix, A.C., 1998. Millennial-scale deep-water oscillations: reflections of the North Atlantic in the deep Pacific from 10 to 60 Ka. *Paleoceanography*, 13:10–19.
- Lyle, M., Koizumi, I., Richter, C., et al., 1997. *Proc. ODP, Init. Repts.*, 167: College Station, TX (Ocean Drilling Program).
- Lyle, M., Prah, F.G., and Sparrow, M.A., 1992. Upwelling and productivity changes inferred from a temperature record in the central equatorial Pacific. *Nature*, 355:812–815.
- Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Jr., and Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. *Quat. Res.*, 27:1–29.
- Morley, J.J., and Heusser, L.E., 1997. Role of orbital forcing in East Asian monsoon climates during the last 350 kyr: evidence from terrestrial and marine climate proxies from core RC14-99. *Paleoceanography*, 12:483–494.
- Munz, P.A., 1968. *A California Flora*: Berkeley (Univ. Calif. Press).
- Sabin, A.L., and Pisias, N.G., 1996. Sea Surface temperature changes in the Northeastern Pacific Ocean during the past 20,000 years and their relationship to climate change in Northwestern North America. *Quat. Res.*, 46:48–61.
- Sancetta, C., Lyle, M., Heusser, L., Zahn, R., and Bradbury, J.P., 1992. Late-glacial to Holocene changes in winds, upwelling, and seasonal production of the Northern California current system. *Quat. Res.*, 38:359–370.
- Sternes, G.L., 1974. The climate of Oregon. In *Climates of the States*: Port Washington, NY (Water Information Center Inc.), 841–860.
- Traverse, A., 1988. *Paleopalynology*: Boston (Unwyn Hyman).
- Van Campo, E., Duplessy, J.C., and Rossignol-Strick, M., 1982. Climatic conditions deduced from a 150-kyr oxygen isotope-pollen record from the Arabian Sea. *Nature*, 296:56–59.
- Waring, R.H., and Franklin, J.F., 1979. Evergreen coniferous forests of the Pacific Northwest. *Science*, 204:1380–1386.
- Whitlock, C., and Bartlein, P., 1997. Vegetation and climate change in north-west America during the past 125 kyr. *Nature*, 388:57–61.
- Zinke, P.J., 1977. The redwood forest and associated North Coast Forests. In Barbour, M., and Major, J. (Eds.), *Terrestrial Vegetation of California*: New York (Wiley & Sons), 679–698.

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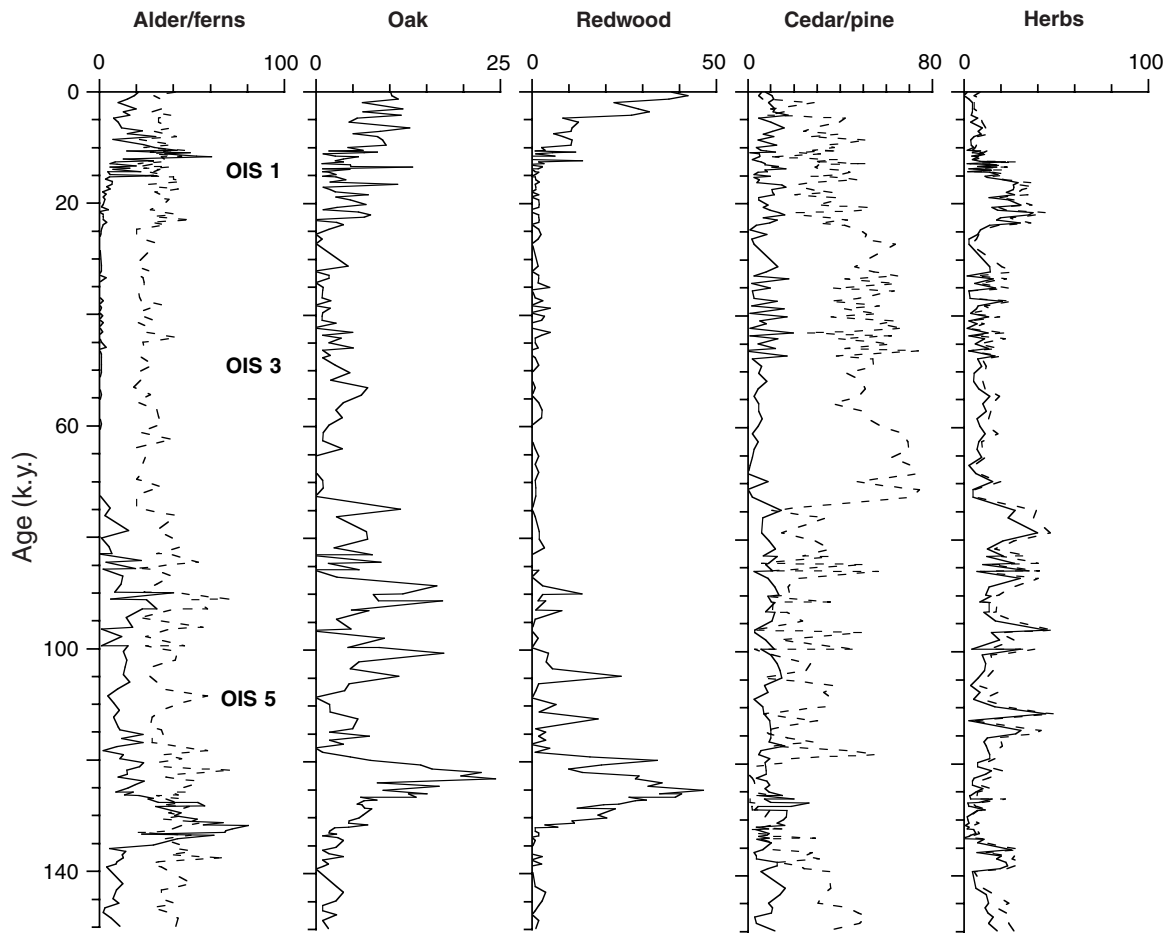


Figure 7. Time series of selected pollen types from Hole 1019C/E and Core EW9504-17 with benthic OISs 1 through 5 superimposed. This preliminary time series is based on the initial time scale developed by Lyle et al. (Chap. 32, this volume). Percentages of ferns, pine, and herbs (excluding sage, which is shown as a solid line in the herbs plot) are shown as dotted lines. OIS = oxygen isotope stage.

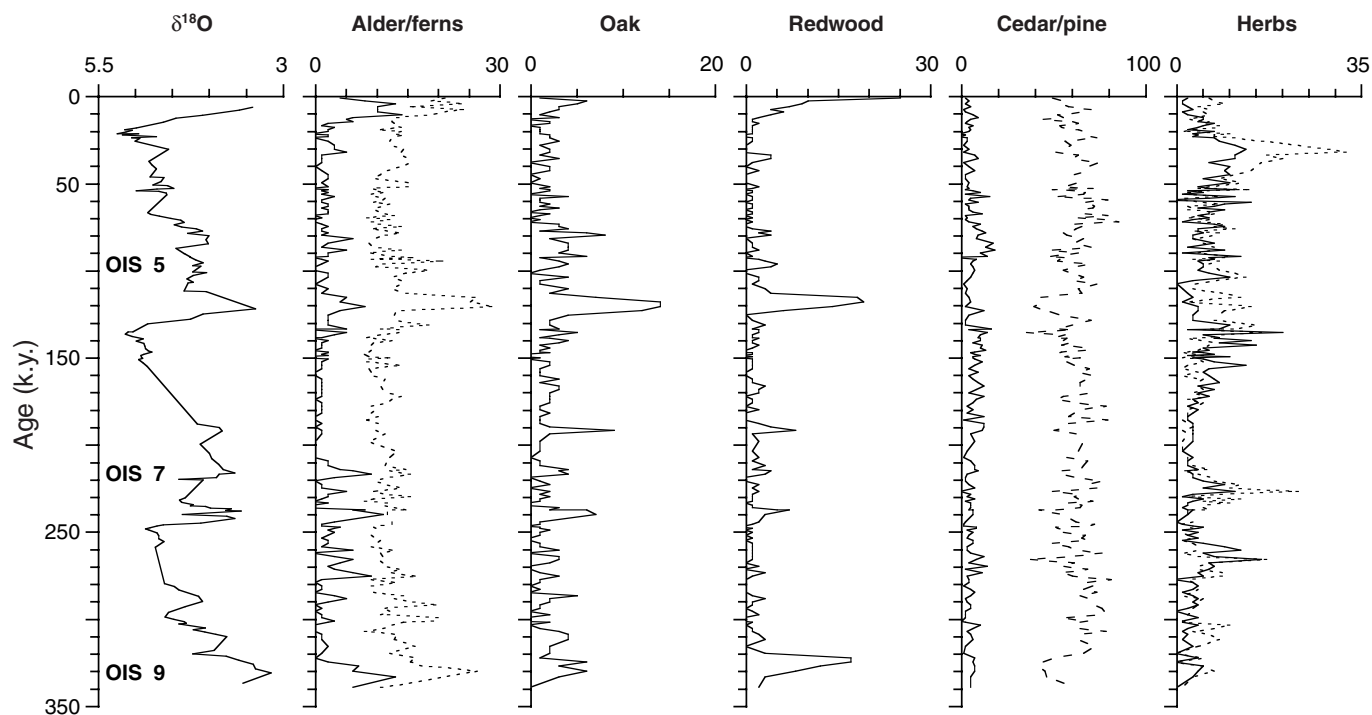


Figure 8. Time series of selected pollen types and preliminary stable isotope data from Holes 1020C and 1020D with benthic OISs 1 through 9 superimposed. Percentages of ferns, pine, and herbs (excluding sage, which is shown as a solid line in the herbs plot) are shown as dotted lines. OIS = oxygen isotope stage.

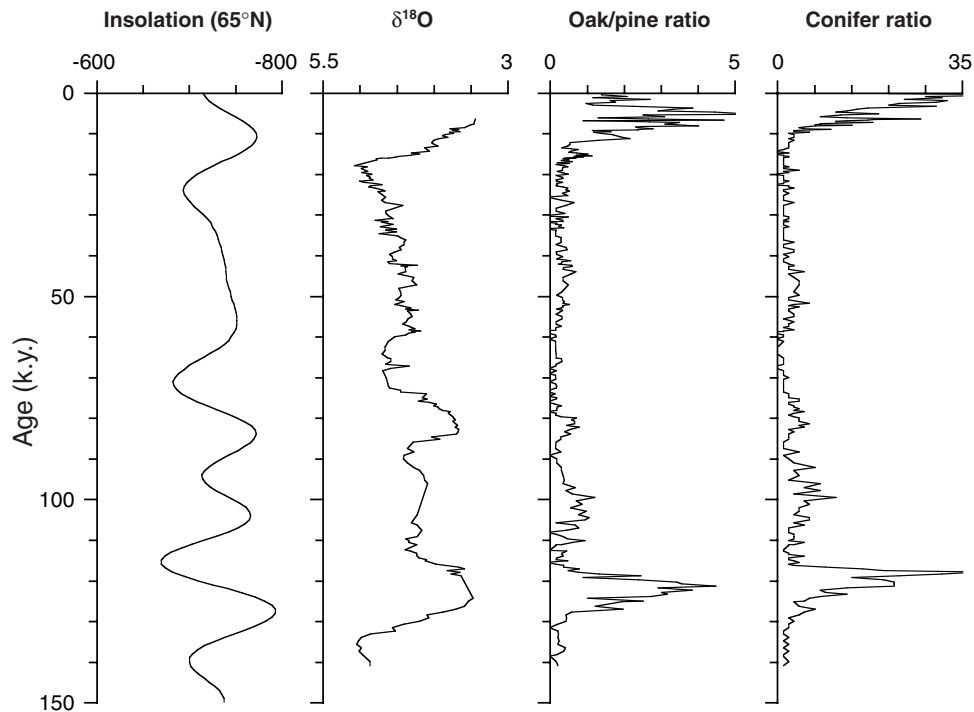


Figure 9. Comparison of July insolation with time series of $\delta^{18}\text{O}$ and pollen ratios (oak/oak + pine and redwood + western hemlock/spruce) from piston Core EW9504-17.