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Multiproxy Record of the Last Interglacial (MIS 5e) off Central and Northern California, U.S.A., from Ocean Drilling Program Sites 1018 and 1020

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By R.Z. Poore, H.J. Dowsett, J.A. Barron, L. Heusser, A.C. Ravelo, and A. Mix

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Environmental and climatic conditions during the last interglacial (about 125,000 years ago) along the central and northern California coastal region are interpreted from study of marine cores recovered by the Ocean Drilling Program.

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

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FIGURES

TABLE

CONVERSION FACTORS

Multiply	By	To obtain
	Length	
nanometer (nm)	0.0000000394	inch
micrometer (µm)	0.0000394	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
	Volume	
cubic centimeter (cm^3)	0.06102	cubic inch

For temperature conversions from degrees Celsius (°C) to degrees Fahrenheit (°F), use the following:

$$°F = (1.8 \times °C) + 32$$

Multiproxy Record of the Last Interglacial (MIS 5e) off Central and Northern California, U.S.A., from Ocean Drilling Program Sites 1018 and 1020

By R.Z. Poore,[1] H.J. Dowsett,[1] J.A. Barron,[2] L. Heusser,[3] A.C. Ravelo,[4] and A. Mix[5]

ABSTRACT

Marine microfossil and pollen assemblages, benthic foraminifer $\delta^{18}O$, physical properties, and calcium carbonate content in sediments from Ocean Drilling Program (ODP) Sites 1018 and 1020 off central and northern California in the eastern North Pacific reveal strong links between the marine and terrestrial environments during marine isotope stage 5 (MIS 5) (~125,000 years ago). Our multiproxy record indicates that at the beginning of the last interglacial (MIS 5e), reduction in global ice volume, increase in sea-surface temperature, and warming of air temperature along the central and northern California coast were synchronous within the resolution of our sampling interval. The waters off the coast of northern California (near ODP Site 1020) were strongly influenced by warm central Pacific waters at the beginning of MIS 5e near the maximum interglacial. The strong influence of central Pacific waters resulted in less intense upwelling and more zonal atmospheric circulation than exist under modern conditions. Foraminifer assemblages from ODP Site 1018 are generally sparse and poorly preserved, but the assemblages that are present support interpretations based on assemblages from ODP Site 1020.

Redwood became most abundant on the west coast of North America after the peak interglacial, presumably as coastal upwelling became more organized or persistent and temperature cooled slightly. Variations in pollen records are similar at ODP Sites 1020 and 1018, indicating that our pollen data reflect regional-scale changes.

Variations in physical properties, calcium carbonate content, and diatom assemblages in sediments from ODP Site 1020 appear to be related to changes in the dominance of coastal versus open ocean upwelling. Evidence of upwelling-related cycles of about 8,000 and 5,000 years duration is present throughout much of the MIS 5 record from ODP Site 1020. Two abrupt climatic coolings are identified in MIS 5e, at ~126 ka and at ~119 ka.

INTRODUCTION

Many marine and terrestrial climate studies (for example, Bond and others, 1997; Broecker, 1997) show that millennial-scale cycles and abrupt changes are persistent in records of the last glacial interval and deglaciation. Evidence is less clear for significant and periodic climate variability during the last interglacial (marine isotope stage (MIS) 5e = Eemian of the European continental record (Shackleton, 1969)). Ice cores recovered from Greenland yield conflicting records of climate variation during the last interglacial. The Greenland Ice-core Project (GRIP) core shows a number of abrupt severe cold events during the last interglacial, indicating unstable and highly variable climate conditions (Dansgaard and others, 1993; GRIP Members, 1993). However, analysis of the nearby Greenland Ice Sheet Project 2 (GISP2) ice core showed a different pattern for the early part of the last interglacial, and evidence of major cool events observed in MIS 5e in the GRIP core was not found in GISP 2 (Grootes and others, 1993). The difference in the two records has motivated researchers to evaluate more carefully climate variability of the last interglacial in a variety of environments.

Although many workers now believe that the Eemian record of GRIP is distorted by flow deformation (for example, Grootes and others, 1993; Fuchs and Leuenberger, 1996), studies of the last interglacial in continental and marine settings continue to reveal conflicting records of climate variation. For example, analyses of Eemian pollen sequences preserved in lake sediments from Germany and France show evidence for a number of cold events and

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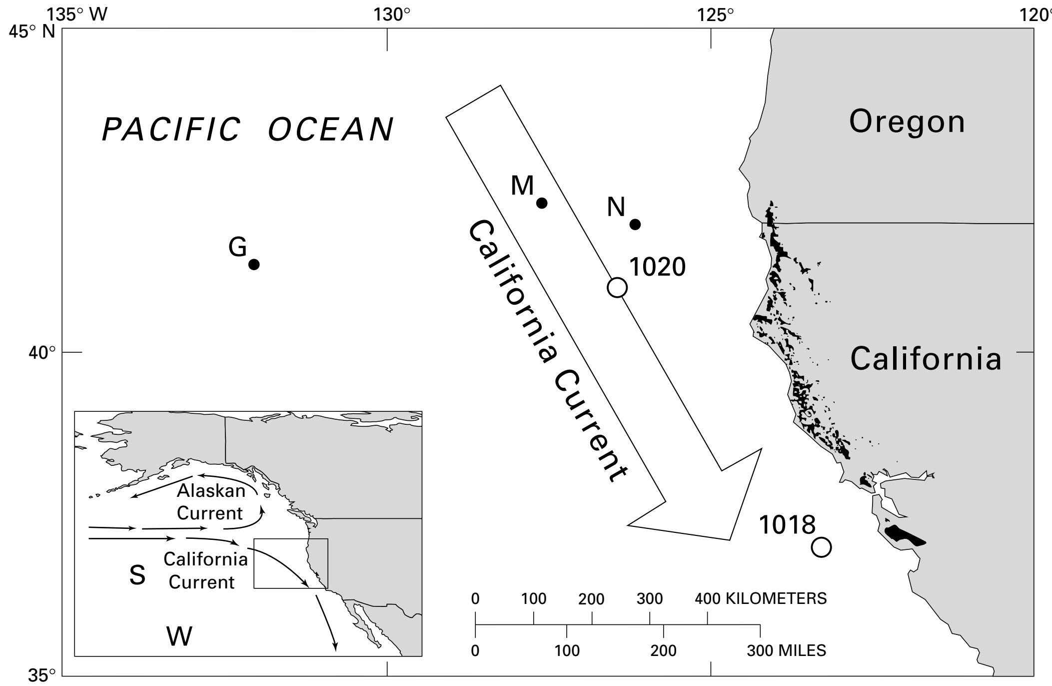

Figure 1. Location of ODP Sites 1018 and 1020 (large open circles) and generalized position of the southward flowing California Current (broad arrow) in the Pacific Ocean off California. Small filled circles show location of MULTITRACERS sediment traps of Lyle and others (1992): N = nearshore site; M = midway site; G = gyre site. Core W8709A–8PC discussed in text was collected near site M. Cores W8709A–13PC and W8709A–9BC discussed in text were collected at site N. Black shading on continental border shows modern distribution of coastal redwood forests (after Powell and others, 1994). Inset map shows generalized locations of North Pacific High in winter (W) and summer (S) and of major surface currents. Figure modified from Sancetta and others (1992).

thus suggest climate instability similar to that indicated by the GRIP record (Field and others, 1994). Records in marine cores from the Norwegian-Greenland Sea suggest variable and unstable conditions, including significant abrupt cold events during MIS 5e (Fronval and Jansen, 1996). However, a detailed pollen sequence from lake sediments in the U.S. Pacific Northwest shows no evidence for strong climate variability during the last interglacial (Whitlock and Bartlein, 1997), and records from marine cores with high accumulation rates from the North Atlantic indicate stable climate conditions during MIS 5e (McManus and others, 1994). Additional information on the character and occurrence of natural climate variability during the last interglacial is needed to resolve these differences.

In this report, we present results of a multiproxy study of the record of the last interglacial contained in sediments recovered at Ocean Drilling Program (ODP) Sites 1018 and 1020 off central and northern California on the west coast of North America. The sites are located within the influence of the southward flowing California Current (fig. 1), which is an eastern boundary current that is sensitive to climate change (Lyle and others, 1992; Sancetta and others, 1992; Gardner and others, 1997).

Upwelling is a major and highly variable feature of the modern California Current. An annual shift in upwelling is controlled by the seasonal migration of the North Pacific High (NPH) (fig. 1). In summer (July–August), the NPH is at its northern extent (lat ~38° N.), and equatorward winds are most favorable for upwelling off northern California, whereas in winter (February), the NPH is at its southern limit (lat ~28° N.), and upwelling conditions are reduced off northern California (for example, Huyer, 1983; Lyle, Koizumi, Richter, and others, 1997). Upwelling can occur off central and southern California at any time of the year when winds are favorable. Most upwelling tends to be concentrated within 25 km of the coast, although open ocean upwelling can occur due to development of jets within the California Current and offshore curl in wind fields (Huyer, 1983; Sancetta and others, 1992). Substantial interannual variability has been documented in the overall pattern of upwelling. During anomalously warm years that are usually associated with El Niño events, southward transport of water in the California Current and upwelling are diminished. Presumably, warmer sea-surface temperature intensifies the Aleutian Low and weakens the NPH, resulting in decreased wind stress (see Pares-Sierra and O'Brien, 1989; Lyle, Koizumi, Richter, and others, 1997, p. 6, fig. 4).

Sediment accumulation rates in the MIS 5 sequences recovered at ODP Sites 1018 and 1020 were rapid enough (≥~10 cm/1,000 years) to resolve millennial-scale variations (Lyle, Koizumi, Richter, and others, 1997; Lyle and others, in press). The sediments along the west coast of North America contain marine microfossils and a significant terrigenous component, including well-preserved pollen assemblages, that allow direct correlation of marine and continental records (Heusser and Balsam, 1977; Gardner and others, 1988; Sancetta and others, 1992). In addition, extensive physical properties measurements available from ODP 1018 and 1020 cores show distinct quasi-periodic variations (Dowsett, 1999). Physical properties, such as magnetic susceptibility and density, can reflect climate variations (Bloemendal and deMenocal, 1989; Thouveny and others, 1994; Rosenbaum and others, 1996; Moros and others, 1997). Thus, the sediments recovered at ODP Sites 1018 and 1020 provide an opportunity to investigate climate variability during the last interglacial and to test the relation of the variations in physical properties records to several traditional climate proxies.

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MATERIALS AND METHODS

Site 1018 of Ocean Drilling Program Leg 167 is at lat 36.99° N., long 123.28° W., ~75 km west of Santa Cruz, Calif., just south of the Guide Seamount in a water depth of 2,477 m (fig. 1). The site is on a sediment drift that is 400 m above the adjacent sea floor. Four holes were cored at Site 1018, recovering a Pliocene to Quaternary sequence of siliciclastic to diatom and nannofossil clays and oozes. Calcium carbonate content is low throughout the sequence, usually ranging between 1 and 5 percent with occasional peaks greater than 10 percent (Lyle and others, in press). Minimum values occur in interglacial deposits. We obtained a series of samples focusing on MIS 5e from Hole 1018C core 3 and Hole 1018D core 3 for foraminifer, isotope, and pollen analyses. Samples from Holes 1018C and 1018D are incorporated into a composite depth scale being used by the ODP 167 scientific party (Lyle and others, in press).

Site 1020 of ODP Leg 167 is at lat 41.00° N., long 126.43° W., on the east flank of the Gorda Ridge ~170 km west of Eureka, Calif., in a water depth of 3,038 m (fig. 1). The site is on a hill that is 50 m above the adjacent sea floor. Four holes were cored at Site 1020, recovering a Pliocene to Quaternary sequence of siliciclastic clay and nannofossil clay with minor amounts of clayey nannofossil ooze. Calcium carbonate content ranges between 1 and 20 percent (Lyle and others, in press). Minimum values occur in interglacial deposits. Several sets of samples were analyzed from ODP Site 1020. One series of samples from Hole 1020D core 2 focusing on MIS 5e was obtained for foraminifer, isotope, and pollen analyses. Pollen data in 1020D core 2 are supplemented by 19 samples used for initial reconnaissance studies (Heusser, in press). A separate set of samples from Hole 1020D core 2 and Hole 1020C core 2 that includes all of MIS 5 was obtained from M. Lyle and analyzed for diatoms. Samples from Holes 1020D and 1020C are incorporated into a composite depth scale (Lyle and others, in press).

Samples for foraminifer, pollen, and isotope analyses were dried at <50°C, disaggregated in deionized water, and wet sieved at 63 µm. The <63-µm fraction from initial wet sieving was retained and used for pollen analyses. The use of the <63-µm fraction for pollen census eliminates large pollen grains (primarily conifers) from our census. However, the other microfossils are so sparse that we adopted this procedure to maximize use of our samples and also provide multiple proxies from single samples. All pollen samples were processsed by using standard chemical procedures, including the addition of known amounts of an exotic tracer to calculate pollen concentration.

Taxonomic identification of pollen was based on the use of modern pollen reference collections from western North America. Pollen grains were identified to species level when possible; otherwise, pollen and spores were assigned to genera or higher rank (see Poore and others, 1999, for taxonomic categories used). Floral (terrestrial pollen grains) counts average ≥130 specimens per sample.

The >63-µm fraction was dried and then sieved into two fractions: 63–150 µm and >150 µm. Samples with abundant planktic foraminifers were mechanically split to obtain subsamples of ~300 planktic specimens >150 µm for faunal census. The entire >150-µm fraction was used for the foraminifer census if <300 planktic foraminifers were present. Sea-surface temperatures (SST's) based on planktic foraminifer assemblages were estimated by using the modern analog technique (MAT) that incorporated a revised modern core-top calibration data set that includes core-top samples from the U.S. Pacific margin (Dowsett and Poore, 1999).

Oxygen-isotope analyses were done on the benthic foraminifers *Fontbotia wuellerstorfi* and *Uvigerina* spp. In general, three specimens of *F. wuellerstorfi* and five specimens of *Uvigerina* were used in each analysis. Isotopic

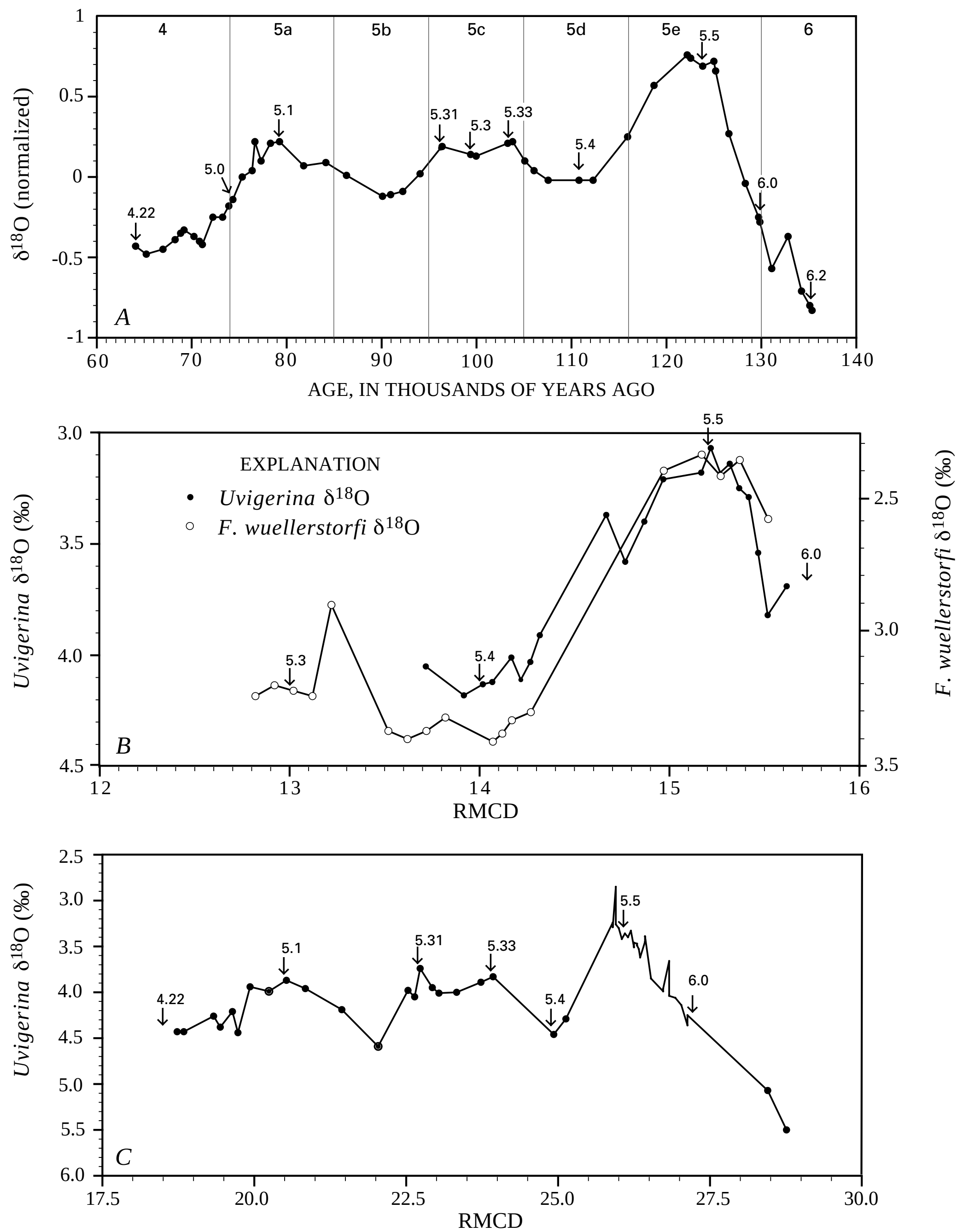


Figure 2. Oxygen-isotope records and chronology. *A,* Normalized oxygen-isotope record and time scale for marine isotope stage (MIS) 5 (Martinson and others, 1987). Stage 6/Stage 5 boundary (Termination II) and Stage 5/Stage 4 boundary are from Martinson and others (1987). Boundaries between substages within MIS 5 are from this study (see text for discussion). *B,* Oxygen-isotope measurements on the benthic foraminifers *Uvigerina* and *Fontbotia wuellerstorfi* from this study of ODP Site 1020 plotted against revised mean composite depth (RMCD) in meters (Lyle and others, in press). Arrows mark points on the isotope record that were correlated to the normalized record of Martinson and others (1987) and that were used to construct the age model for this study. Event 5.0 (not shown in *B* above; see table 1) was established from the Site 1020 oxygen-isotope record of Lyle and others (in press, fig. 6). *C,* Oxygen-isotope measurements on *Uvigerina* from ODP Site 1018. Arrows mark points on the isotope record used to construct the age model for this study. Data from 24 to 27 m RMCD are from this study. Data from above 24 m RMCD and below 27.5 m RMCD are from Andreasen and others (in press). Ages and depths used for the age models are listed in table 1; see text for discussion.

analyses of samples from Site 1018 were conducted on a PRISM micromass mass spectrometer at the University of California, Santa Cruz (UCSC). Analytical precision is ±0.08‰ for oxygen standards. Analyses of samples from Site 1020 were conducted at Oregon State University (OSU) on a Finnigan MAT–251 stable isotope mass spectrometer. Analytical precision based on replicate analyses of local calcite standards is ±0.08‰ for oxygen standards. Additional details of analytical procedures were discussed in Poore and others (1999). Isotopic values were calibrated via National Institute of Standards and Technology (NIST) isotopic reference material NBS–18 and NBS–19 (UCSC) and NBS–19 and NBS–20 (OSU) to the Pee Dee Belemnite scale maintained by the International Atomic Energy Agency in Vienna (VPDB). Values are reported relative to the VPDB standard in delta notation and expressed in per mil.

Diatom samples (0.5–1 cm^3) were processed in hydrogen peroxide and hydrochloric acid. Strewn slides of the residues were prepared. Except where preservation was poor, at least 300 diatoms per slide were counted at a magnification of × 1,250 during random traverses of the slides by using the counting techniques of Schrader and Gersonde (1978). Note that percentages of *Chaetoceros* spores are calculated as percent of the total diatom assemblages whereas percentages of all other taxa are calculated on a *Chaetoceros*-free basis. This is done because *Chaetoceros* spores dominate the diatom assemblages in all samples. Isotopic results, discussion of taxonomic categories used for faunal and floral census, and tables giving pollen, foraminifer, and diatom census data were provided by Poore and others (1999).

Bulk density, magnetic susceptibility, and color reflectance records were examined for this study. Bulk density and magnetic susceptibility were measured onboard ship at 4-cm intervals by using the multisensor track (MST) on whole core sections. Reflectance was measured by the Oregon State University spectral reflectometer on split core surfaces. Methods and instruments used to obtain these data are outlined in Lyle and others (1997). Tables of physical property measurements are provided with the Initial Cruise Report on CD-ROM (Lyle, Koizumi, Richter, and others, 1997).

CHRONOLOGY

We used the normalized oxygen-isotope record and chronology of Martinson and others (1987) as the basis for developing a time scale for this study. Dated features of the normalized oxygen-isotope age model of Martinson and others (1987) identified in our isotope records (fig. 2) were used to create an age model and assign ages to individual samples by assuming constant sediment accumulation rates between control points (table 1). Our isotope data were supplemented by isotope and carbonate data from Sites 1018 and 1020 (Lyle and others, in press), which were used to help locate the MIS 6/MIS 5 boundaries at both sites. The MIS 5/MIS 4 boundary (event 5.0) was derived from the oxygen-isotope record for Site 1020 of Lyle and others (in press, fig. 6). In order to facilitate discussion of our results, we found it convenient to define the boundaries between substages of MIS 5. Following the suggestion of Shackleton (1969) for recognizing the boundary between substages 5e and 5d, we place boundaries between substages of MIS 5 at the midpoint of the transition between them (see fig. 2). According to our definition and the time scale of Martinson and others (1987), the total duration of MIS 5e is 14,000 years. The interval of warmest conditions (normalized $\delta^{18}O$ ≥0.5 in fig. 2) is ~9,000 years.

Table 1. Calibration points used for age models.

[RMCD, revised mean composite depth in meters; ka, thousand years ago]

Event[1]	Depth (RMCD)	Age[1] (ka)
Ocean Drilling Program Site 1018		
4.22	18.49	64.09
5.1	20.49	79.25
5.31	22.69	96.21
5.33	23.89	103.29
5.4	24.89	110.79
5.5	26.05	123.82
6.0	27.20	129.84
Ocean Drilling Program Site 1020		
5.0	9.85	73.91
5.3	13.00	99.38
5.4	14.00	110.79
5.5	15.20	123.82
6.0	15.73	129.84
6.2	16.17	135.10

[1]Event terminology and ages from Martinson and others (1987).

RESULTS

ODP SITE 1020

All samples we examined from ODP Site 1020 yielded relatively well preserved pollen assemblages. Occurrence and preservation of foraminifer and diatom assemblages are variable. Sample resolution within MIS 5e is ~1,000 years. Distributions of common pollen types are shown in figure 3. Pine (*Pinus*), the most common pollen type in the assemblages, decreases in abundance from MIS 6 into MIS 5e deposits to low but still significant values, and then increases upsection into MIS 5d deposits. The highest amounts of alder (*Alnus*), oak (*Quercus*), and coastal redwood (*Sequoia sempervirens*) occur in MIS 5e

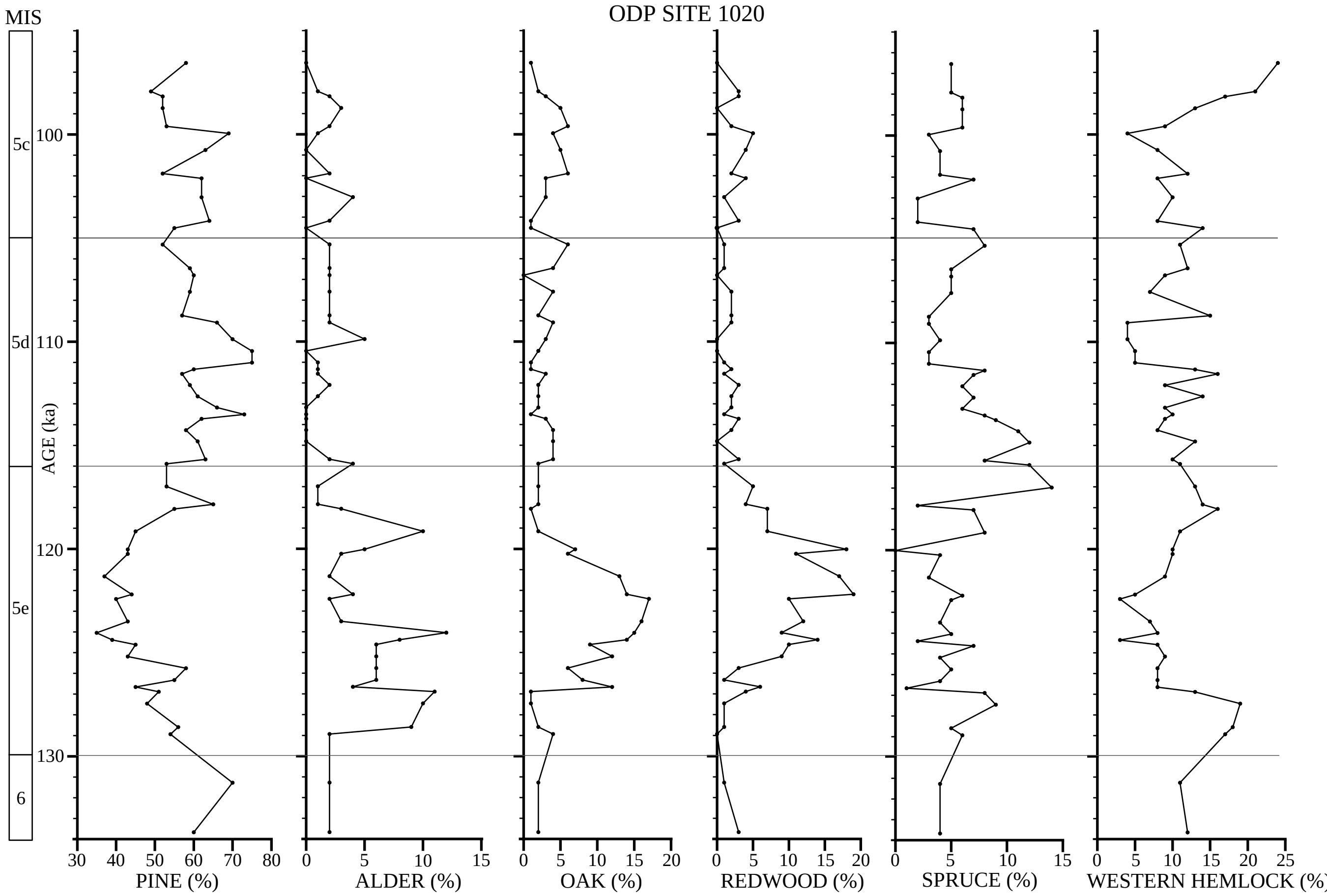


Figure 3. Age and marine isotope stage plotted against abundances (in percent) of selected pollen taxa in samples from ODP Site 1020.

deposits. Percentages of spruce (*Picea*) and western hemlock (*Tsuga heterophylla*) vary throughout the sequence. Oak and redwood show a distinct increase within MIS 5e deposits to a broad abundance peak and then decrease dramatically into 5d deposits. Oak and redwood are present throughout MIS 5d deposits in low abundances and then increase slightly in MIS 5c sediments. There is a distinct lag in the oak and redwood abundance peaks, with redwood peaking later in MIS 5e at the point where pine begins to increase.

Planktic foraminifers are moderately well preserved in many of our ODP Site 1020 samples but are usually few in number, and most assemblages show effects of dissolution. Distributions of common taxa of planktic foraminifers are shown in figure 4. Left-coiling *Neogloboquadrina pachyderma* has minimum values within MIS 5e deposits and then increases to maximum values in MIS 5d sediments. Left-coiling *N. pachyderma* and right-coiling *N. pachyderma* s.l. (includes gradational forms between right-coiling *N. pachyderma* and *N. dutertrei*) are inversely related. Assemblages from MIS 5e include right-coiling *N. pachyderma* s.l. along with significant amounts of *Globorotalia inflata* (lower part) and *N. dutertrei* (upper part) and varying amounts of *Globigerina bulloides*. In contrast, the assemblages of MIS 5c consist almost exclusively of various amounts of left- and right-coiling *N. pachyderma* with *G. bulloides. Neogloboquadrina dutertrei* and *G. inflata* are essentially absent.

Sea-surface-temperature (SST) estimates for winter and summer seasons derived from planktic foraminifer assemblages are also shown in figure 4. The warmest SST estimates derive from MIS 5e samples at levels containing the warm-water taxa *G. inflata* and *Globigerinoides ruber* and minimum values of the polar form left-coiling *N. pachyderma*. Assemblages are sparse and poorly preserved in samples dated at ~124 to 119 ka, and only a few quantitative SST estimates were possible over that interval. The maximum summer SST estimates for MIS 5e at Site 1020 are as much as 4°C warmer than our modern core-top calibration values, whereas winter maximum SST estimates for MIS 5e are near modern values (see Dowsett and Poore, 1999). Our planktic foraminifer SST estimates compare well with alkenone-based paleotemperature estimates for MIS 5e at Site 1020. The alkenone results indicate that average SST's during the maximum interglacial were about 2°C above modern values (Kreitz and others, in press). The maximum winter SST estimates for MIS 5e at ODP Site 1020 are similar to Holocene winter SST estimates derived from alkenone and radiolarian data from piston core W8709A–8PC (Prahl and others, 1995) collected nearby (fig. 1).

The foraminifer SST estimates indicate that winter temperatures during MIS 5d were ~8°C–10°C colder than the modern winter temperature. Alkenone and radiolarian data from core W8709A–8PC suggest that winter SST's during the last glacial maximum were 4°C–5°C below modern temperatures (Prahl and others, 1995). It seems unlikely that winter SST's off northern California during MIS 5d would be colder than winter SST's during the last glacial maximum. Additional work is required to resolve the apparent discrepancy between our MIS 5d winter SST estimates and the last glacial maximum SST estimates of Prahl and others (1995). The few samples yielding enough foraminifers to provide SST estimates for MIS 5c indicate temperatures several degrees warmer than MIS 5d temperatures but below peak temperatures of MIS 5e.

Diatom abundance and preservation are highly variable in MIS 5 sediments of ODP Site 1020 (fig. 5). Assemblage data are reported only for samples containing ≥10 diatoms per traverse. The abundance of the *Chaetoceros* spores is calculated for the entire diatom assemblage, whereas the abundances of the other taxa are calculated on a *Chaetoceros*-free basis. *Chaetoceros* spores are always common to abundant. On a *Chaetoceros*-free basis, *Thalassionema nitzschioides* and *Stephanopyxis* spp. are the most common taxa. Inspection of figure 5 reveals that *Chaetoceros* and *T. nitzschioides* vary inversely throughout the record and show distinct cycles in deposits of MIS 5b and MIS 5a and parts of MIS 5d. The relation between these two taxa is less clear in MIS 5e. *Chaetoceros* spores first appear in MIS 5e sediments at relatively low abundances and then increase in abundance towards MIS 5d deposits.

Stephanopyxis spp. increases in abundance from MIS 5e into MIS 5d sediments and shows distinct abundance cycles in MIS 5b and 5a and the lower part of MIS 4. The *Stephanopyxis* minima in MIS 5b and MIS 5a coincide with intervals of high diatom abundance as measured by the diatoms/traverse index and peaks in *T. nitzschioides*. S*tephanopyxis* is a shelf indicator, and its abundance variations in deepwater sediments are sometimes interpreted as an off-shelf transport index. Gardner and others (1988) studied cores off northern California and related increased abundance of *Stephanopyxis* spp. in glacial deposits to enhanced downslope transport during glacial periods. Hemphill-Haley and Fourtanier (1995) suggested that increased numbers of *Stephanopyxis* spp. at ODP Site 893 in the Santa Barbara Basin were due to selective dissolution of more delicate diatoms. However, they also observed a correspondence between increased *Stephanopyxis* spp. and increased benthic and reworked diatoms in glacial deposits, which suggests enhanced downslope transport.

Pseudoeunotia doliolus, which is a warm-water taxon indicative of the central Pacific water mass, occurs in significant amounts only in the lower diatom-bearing samples of MIS 5e. *Roperia tesselata*, which is a temperate form, becomes an important component of the assemblages deposited during MIS 5a. *Thalassiosira pacifica*, which is a cooler water subpolar form, occurs in MIS 5d deposits and is common to abundant in MIS 5b deposits and portions of the MIS 5a record. Note that *R. tesselata* and *T. pacifica* show alternating abundance peaks in sediments deposited in the MIS 5b to 5a interval, suggesting cycles on the order of 5,000 years long. The temperature record of MIS 5 suggested by the diatom assemblages is consistent with the temperatures indicated by foraminifer assemblages and isotope data. Warmest SST's are indicated within early MIS 5e. Cooler SST's in late MIS 5e and much cooler SST's in MIS 5d were followed by increasing SST's in MIS 5c that were not as warm as SST's in MIS 5e, as evidenced by the lack of *P. doliolus* in the assemblages. Cooler SST's prevailed in MIS 5b, and SST's were variable during MIS 5a.

For ODP Site 1020, magnetic susceptibility and reflectance values show similar structure for sediments deposited in MIS 5e to 5c, but very large changes in susceptibility values for sediments deposited near the end and beginning of MIS 5 tend to obscure the correlation (see Dowsett, 1999). The wet-bulk density of the sediments as measured by the Gamma Ray Attenuation Porosity Evaluator (GRAPE) system also shows high-frequency variations, but the variations are not systematically related to the other physical properties. The reflectance record shows the clearest pattern of variation, with well-defined cycles having a period of ~8,000 years (fig. 6). Cycles of ~5,000 years are evident over some intervals (MIS 5e to 5d and MIS 5a to MIS 4). Spectral analyses show higher frequency variations at 3,000 and 2,200 years (fig. 6). Several prominent maxima in carbonate content coincide with reflectance peaks; for example, see the carbonate peaks in figure 6 centered at ~81 ka and 112 ka. Minor carbonate peaks at ~94 ka and 102 ka also match reflection maxima. However, a peak in reflectance within MIS 5e corresponds to a carbonate low.

The abundance of the foraminifer *Globigerina bulloides* shows a negative correlation with the reflectance record (note that the scale for *G. bulloides* in fig. 6 increases to the left). *Globigerina bulloides* is typically a species of transitional to subpolar water masses (Kipp, 1976); it is also an indicator of upwelling in many areas (for example, Prell and Curry, 1981; Sautter and Thunell, 1991; Hui-Ling and others, 1997). We infer that some of the *G. bulloides* abundance fluctuations are related to the intensity of offshore upwelling and that, at ODP Site 1020, the 8,000- and 5,000-year cycles in reflectance during MIS 5 contain an

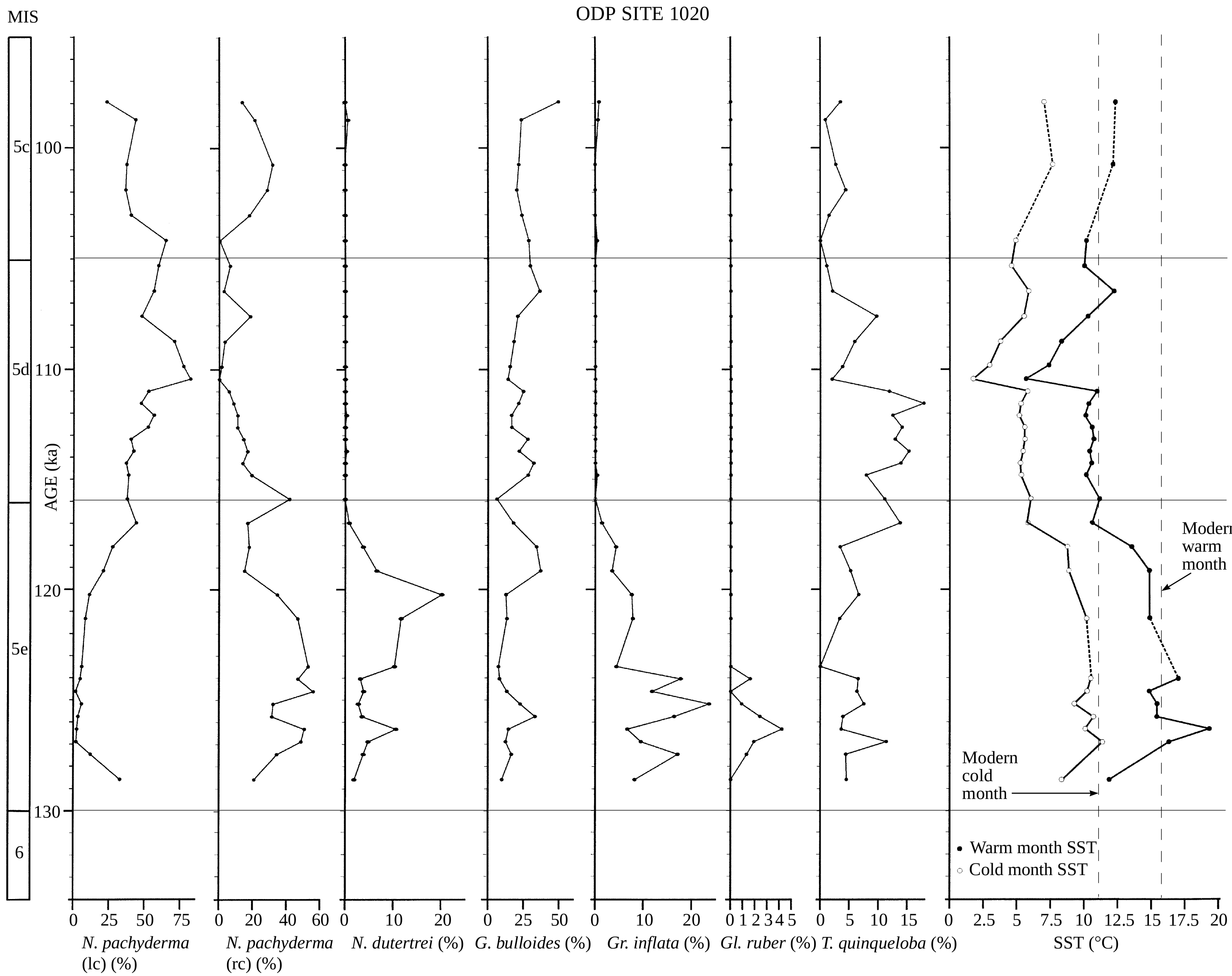


Figure 4. Age and marine isotope stage plotted against (1) abundances (in percent) of selected planktic foraminifer taxa in samples from ODP Site 1020 and (2) sea-surface-temperature (SST) estimates based on the modern analog technique (MAT) for Site 1020 samples. *N. pachyderma* (lc) = left-coiling *Neogloboquadrina pachyderma*. *N. pachyderma* (rc) = right-coiling *N. pachyderma* and transitional forms between right-coiling *N. pachyderma* and *N. dutertrei*. *G. bulloides* = *Globigerina bulloides*. *Gr. inflata* = *Globorotalia inflata*. *Gl. ruber* = *Globigerinoides ruber*. *T. quinqueloba* = *Turborotalita quinqueloba*. Modern warm month and cold month SST's are shown by vertical dashed lines on the SST plot. The SST estimate lines are dashed where samples are sparse.

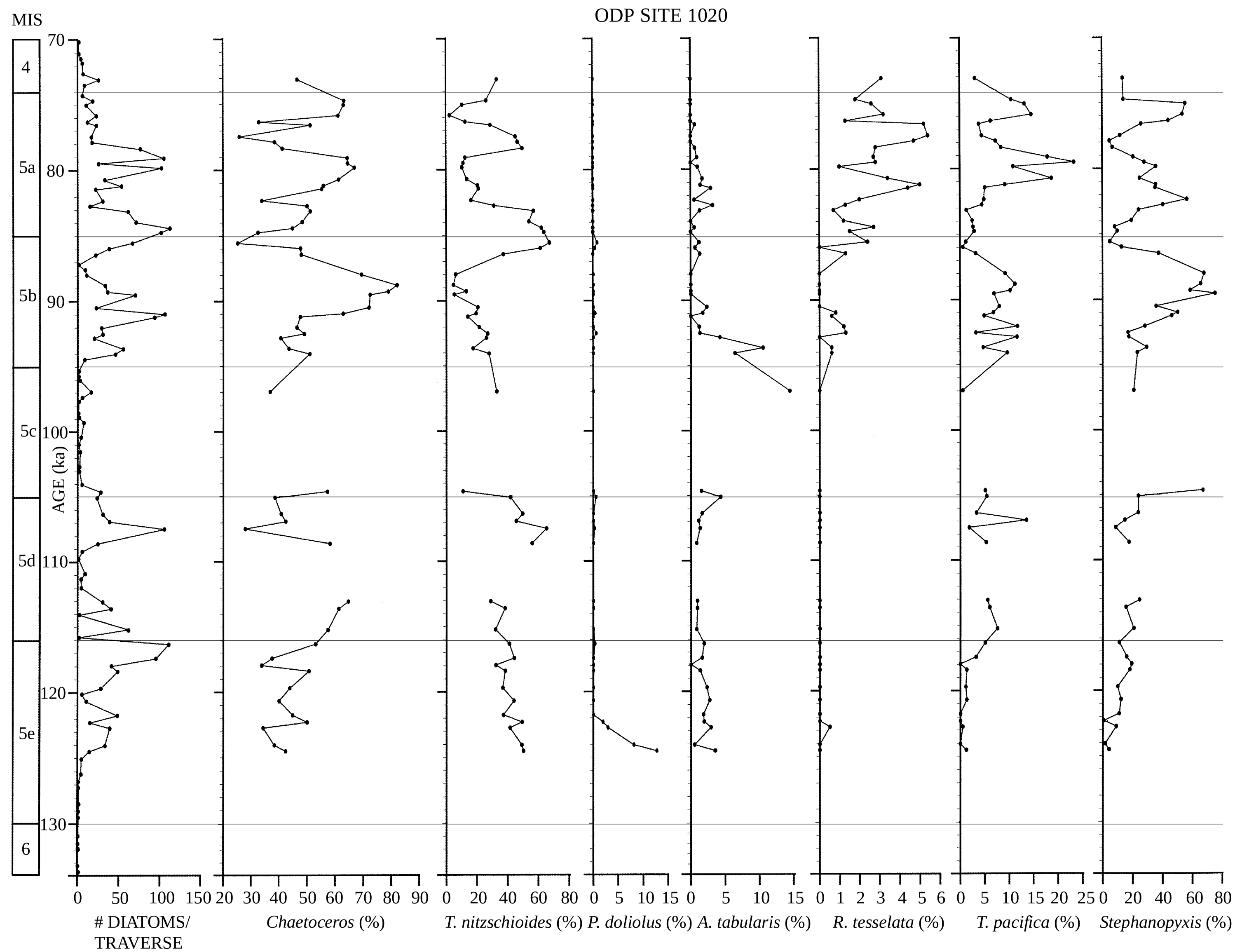
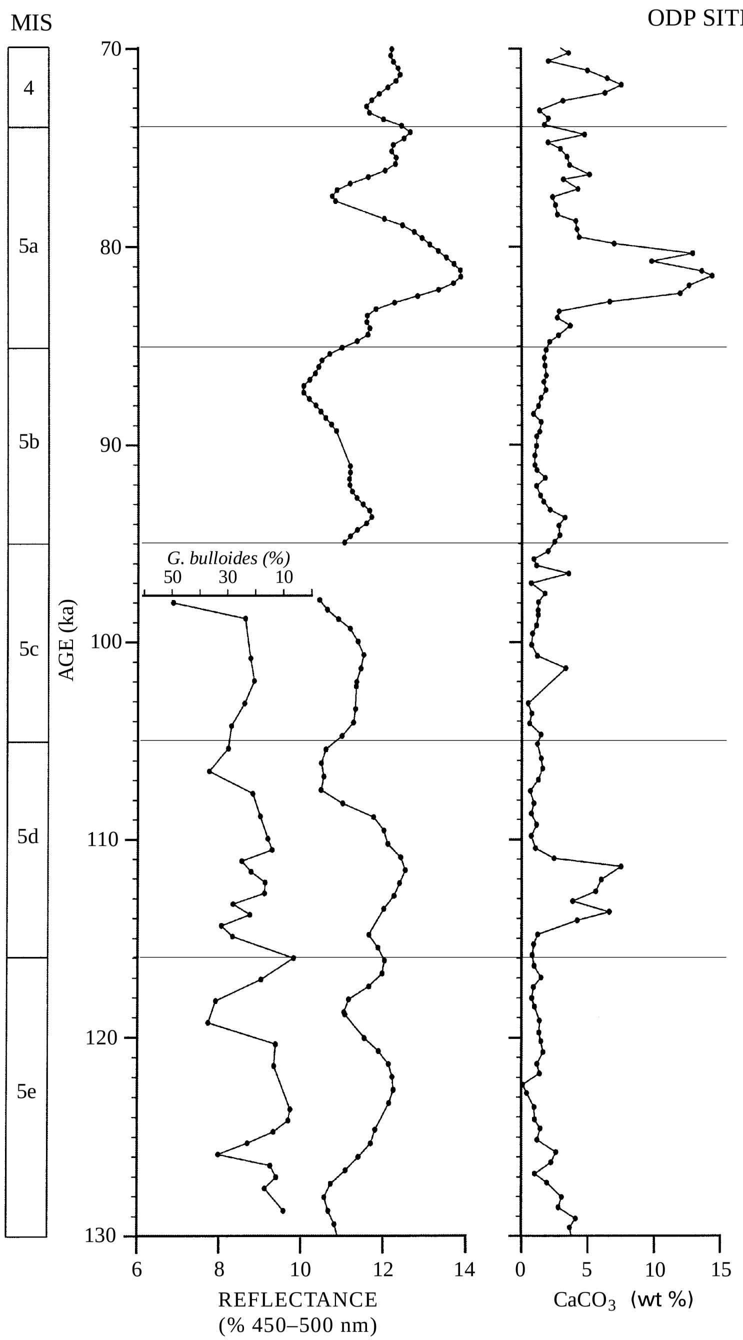


Figure 5. Age and marine isotope stage plotted against (1) the number of diatoms per traverse and (2) abundances (in percent) of selected diatom taxa in samples from ODP Site 1020. Abundances of diatom taxa are plotted only for samples having ≥10 specimens per traverse (at magnification of × 1,250). The abundance of the *Chaetoceros* spores is calculated for the entire diatom assemblage, whereas the abundances of the other taxa are calculated on a *Chaetoceros*-free basis. *Chaetoceros* = *Chaetoceros* spores. *T. nitzschioides* = *Thalassionema nitzschioides*. *P. doliolus* = *Pseudoeunotia doliolus*. *A. tabularis* = *Azpeitia tabularis*. *R. tesselata* = *Roperia tesselata*. *T. pacifica* = *Thalassiosira pacifica*.



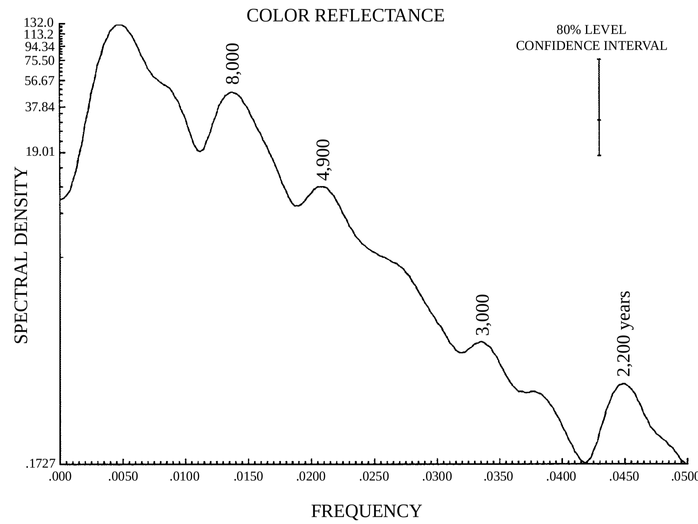


Figure 6. Age and marine isotope stage plotted against (1) *Globigerina bulloides* abundance (in percent), (2) reflectance, and (3) calcium carbonate ($CaCO_3$) content (in weight percent) in samples from ODP Site 1020 plus spectral analyses of reflectance data. Note that the scale for the abundance of *G. bulloides* increases to the left. Calcium carbonate measurements are from Lyle and others (in press). Reflectance data are from Lyle, Koizumi, Richter, and others (1997). Reflectance values are reported in percentage of reflected light from 450 to 500 nm. The power spectrum shows color reflectance data in the frequency domain. The spectrum was calculated by using the Blackman-Tukey method (Jenkins and Watts, 1968) on a linearly detrended sequence sampled every 300 years. Peaks in spectral density occur at 2,200, 3,000, 4,900, and 8,000 years.

upwelling signal. High values of reflectance generally indicate dominance of coastal upwelling and increased carbonate content of the sediments, whereas low values of reflectance indicate dominance of offshore upwelling and decreased carbonate content of sediments. Our interpretations are consistent with the conclusion of Lyle and others (in press) that millennial-scale cycles in calcium carbonate content in cores from the California margin reflect changes in calcium carbonate production by plankton, not dissolution. Thus, the physical properties of ODP Site 1020 sediments contain a climatic signal, but the signal is not a simple glacial-interglacial signal.

ODP SITE 1018

Sediments deposited near the beginning of MIS 5e through MIS 5c were examined from ODP Site 1018; sample resolution within MIS 5e ranges from ~300 to 600 years. Pollen assemblages are relatively well preserved (fig. 7). Pine decreases from >50 percent of the pollen assemblage at the base of MIS 5e deposits to values <30 percent within MIS 5e and then increases upsection into MIS 5d deposits. Pine is usually dominant in the remainder of the pollen assemblages except for an interval deposited within MIS 5c. Spruce occurs in trace amounts except in the lower deposits of MIS 5e. Alder is present only in trace abundances in MIS 5e sediments (Poore and others, 1999). Oak is consistently present in our Site 1018 samples with a distinct short maximum in MIS 5e and broad maxima in MIS 5d and MIS 5c. In general, the oak increases in MIS 5d and 5c correspond to decreases in pine (fig. 7). Redwood is abundant only in MIS 5e sediments and shows a well-defined maximum just above the short oak abundance peak. Thus, the sequence of oak maxima followed by redwood maxima in MIS 5e observed at ODP Site 1020 is present in the record from ODP Site 1018.

Planktic foraminifers were generally sparse and poorly preserved in MIS 5 samples from ODP Site 1018. Only a few samples had ≥50 specimens in the >150-µm fraction, and most were barren or nearly barren of foraminifers. Although foraminifer assemblages are sparse, a few of the assemblages in the sequence provided SST estimates within acceptable statistical parameters (see Dowsett and Poore, 1999), and samples from the lower part of the section contained sufficient numbers of the benthic foraminifer *Uvigerina* for isotopic analyses (figs. 2, 7). The distribution of common taxa in samples containing at least 50 specimens was presented by Poore and others (1999). In general, foraminifer assemblages from samples at the base of MIS 5e deposits are dominated by left-coiling *Neogloboquadrina pachyderma*, whereas the few assemblages higher in the MIS 5e record are dominated by right-coiling *N. pachyderma* with important contributions from *N. dutertrei*, *Globigerina bulloides*, and *Globorotalia inflata*.

The warmest SST estimates for MIS 5e at Site 1018 are from samples that are dated at about 125 ka and that have $\delta^{18}O$ values for *Uvigerina* spp. that approach but do not reach the minimum values seen for MIS 5e (fig. 7). The summer SST estimates are about 2°C warmer than our modern core-top calibration values (see Dowsett and Poore, 1999) and are consistent with, but are about 2°C below, the warmest SST estimates for MIS 5e samples from ODP Site 1020. Planktic foraminifer assemblages at younger MIS 5e levels with minimum *Uvigerina* $\delta^{18}O$ values are sparse and highly dissolved. Thus, SST estimates derived from these samples probably underestimate the maximum SST temperatures during MIS 5e at ODP Site 1018.

Variations in the reflectance and magnetic susceptibility records from ODP Site 1018 closely correspond (fig. 8). Inspection of figure 8 shows cycles on the order of 10,000 years and 5,000 years, and spectral analyses reveal higher frequency cycles of 3,300, 2,500, 2,200, and 1,900 years. However, the cycles do not show a clear relation to carbonate content of the sediments. The most prominent peak in carbonate content is centered at ~116 ka and corresponds to a low in the reflectance record. It is likely that carbonate values from ODP Site 1018 are too low to strongly influence the physical properties of the sediments.

Alternatively, the carbonate signal could indicate differences between conditions and processes at ODP Sites 1020 and 1018. Note that prominent carbonate peaks for samples from Sites 1020 and 1018 do not coincide (compare figs. 6 and 8). We cannot interpret the environmental significance of the reflectance and magnetic susceptibility data from ODP Site 1018 at this time. However, comparison of figures 6 and 8 demonstrates that care must be taken in inferring environmental conditions from physical properties records. Relations between proxy data and environmental conditions obtained in a specific core or depositional system may not necessarily be valid in other cores or systems.

DISCUSSION

The data from ODP Sites 1018 and 1020 show strong links between the marine and terrestrial environments. Previous studies demonstrated that the pollen in marine sediments along the U.S. Pacific margin reflects vegetation of the adjacent coastal areas (for example, Heusser and Balsam, 1977; Gardner and others, 1988; Sancetta and others, 1992; Heusser, 1998). Redwood-dominated coniferous forests with spruce and hemlock distinguish the present-day natural coastal vegetation of northern California. Inland in drier settings, oak woodland and grassland occur and, at higher elevations in the Coast Range, montane forests are present with pine, evergreen oaks, fir (*Abies*), Douglas fir (*Pseudotsuga menziesii*), and mountain hemlock (*Tsuga mertensiana*) (Barbour and Major, 1977). Thus, in areas off central and northern California, pine is generally an indicator of cooler or glacial conditions, and

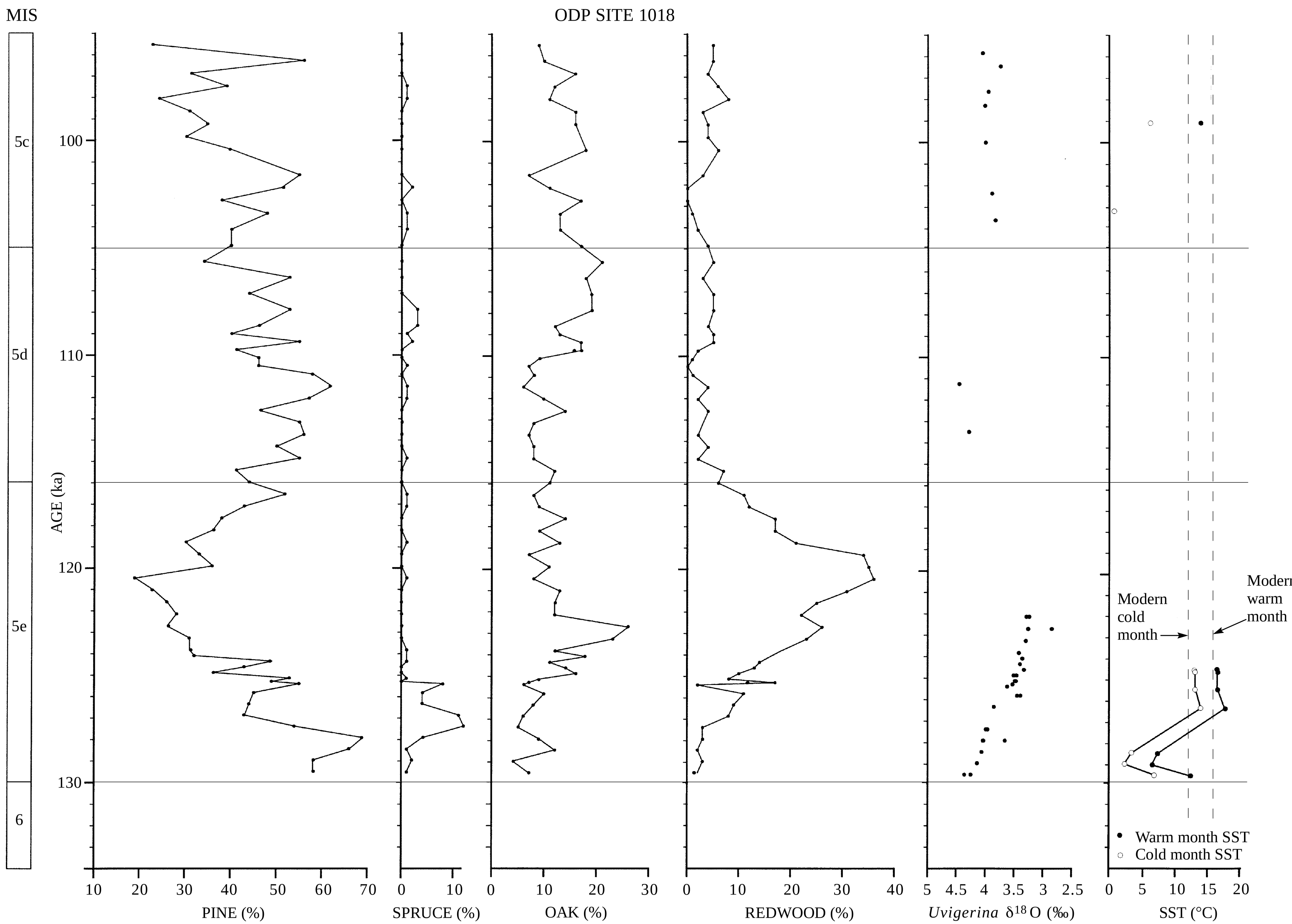
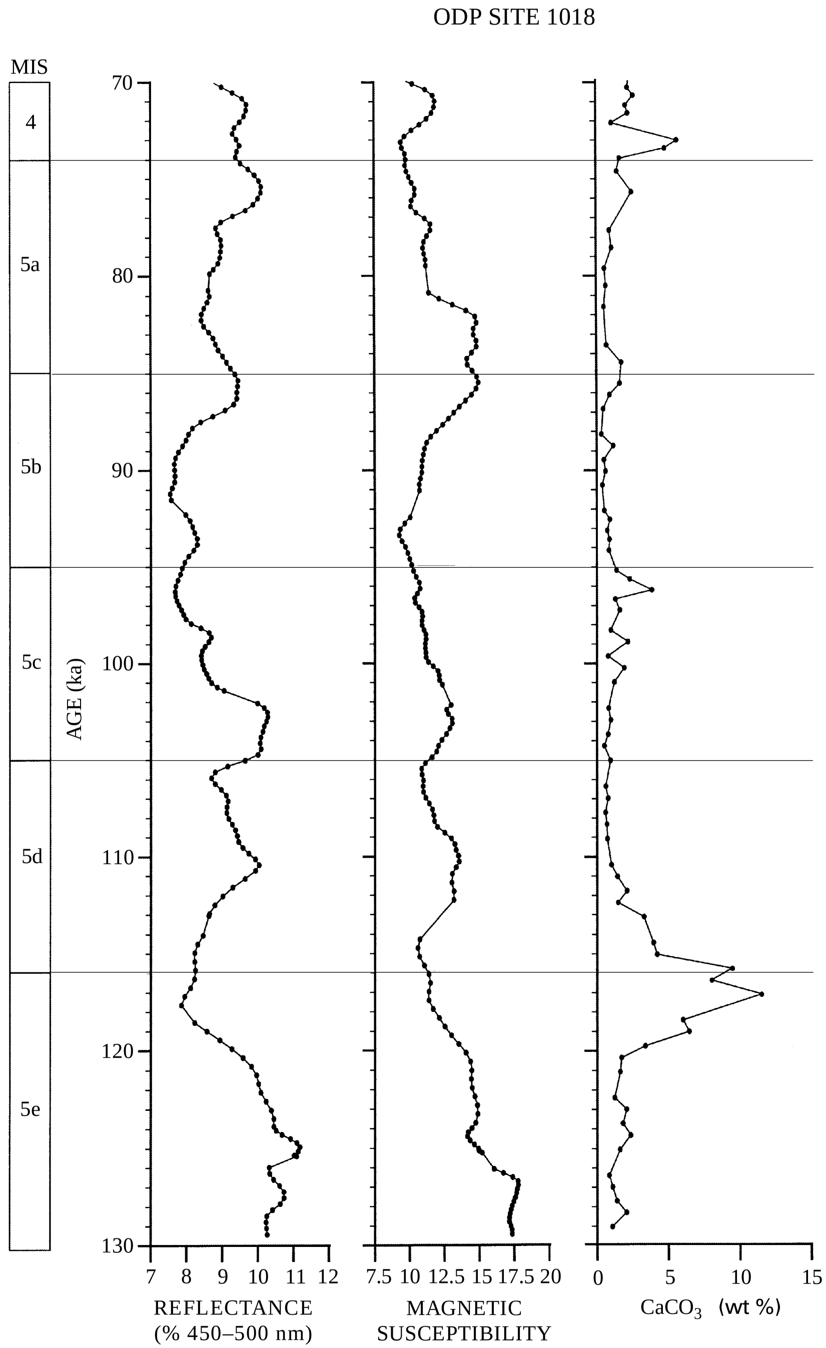


Figure 7. Age and marine isotope stage plotted against (1) abundances (in percent) of selected pollen taxa in samples from ODP Site 1018, (2) oxygen-isotope results from *Uvigerina*, and (3) sea-surface-temperature (SST) estimates based on the modern analog technique (MAT) for samples from ODP Site 1018. Modern warm month and cold month SST's are shown by vertical dashed lines on the SST plot.



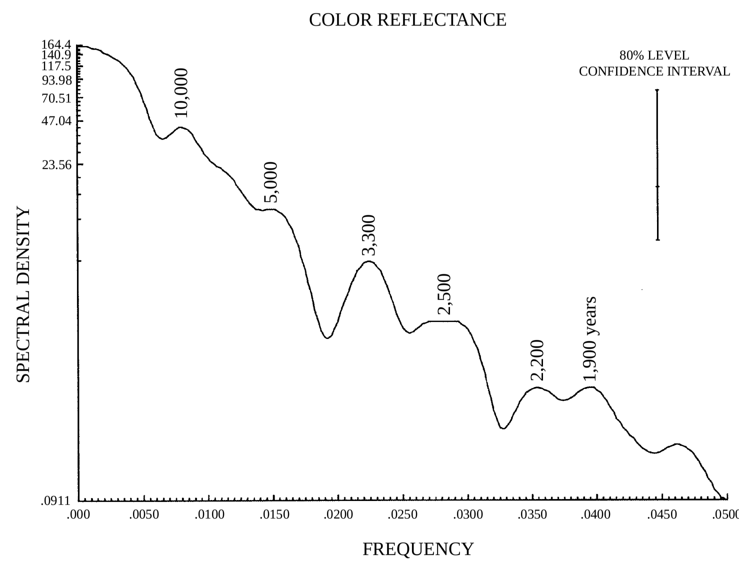


Figure 8. Age and marine isotope stage plotted against (1) reflectance, (2) magnetic susceptibility, and (3) calcium carbonate ($CaCO_3$) content (in weight percent) in samples from ODP Site 1018 plus spectral analyses of reflectance data. Reflectance and magnetic susceptibility data are from Lyle, Koizumi, Richter, and others (1997). Reflectance values are reported in percentage of reflected light from 450 to 500 nm. Calcium carbonate measurements are from Lyle and others (in press). The power spectrum shows color reflectance data in the frequency domain. The spectrum was calculated by using the Blackman-Tukey method (Jenkins and Watts, 1968) on a linearly detrended sequence sampled every 400 years. Peaks in spectral density occur at 1,900, 2,200, 2,500, 3,300, 5,000, and 10,000 years.

oak is an indicator of warm conditions. Redwood is an indicator of increased moisture and moderated summer coastal temperature related to coastal fog, which is, in turn, related to coastal upwelling (Sancetta and others, 1992; Heusser, 1998).

The data from marine and terrestrial proxies at ODP Site 1020 show clear evidence for rapid warming at the beginning of MIS 5 (fig. 9). Warming of coastal air temperatures is indicated by the decrease in pine and increase in oak pollen. The foraminifer MAT SST values show warming at the same time that oak pollen increases. Reduction in global ice volume is indicated by the decreasing $\delta^{18}O$ values for benthic foraminifers. Plots of $\delta^{18}O$ values for *Uvigerina* spp. and *F. wuellerstorfi* show the same structure, and either can be used to identify MIS 5e and 5d (fig. 9). The $\delta^{18}O$ scales in figure 9 have been adjusted so that the smallest values from the two taxa coincide. Note that the values become offset by about 0.25‰ at the larger values in MIS 5d, suggesting that fractionation between *Uvigerina* spp. and *F. wuellerstorfi* may be nonlinear.

Maximum values for oak coincide with minimum values for pine and benthic $\delta^{18}O$. We assume that values of $\delta^{18}O$ for benthic foraminifers from Site 1020 largely reflect global ice volume; therefore, the sequence deposited in MIS 5e indicates that reduction in global ice volume, increases in SST's, and warming of air temperatures along the coast were all synchronous within the resolution of our sampling interval. Minima in $\delta^{18}O$ and maxima in SST's and coastal air temperatures coincide.

In MIS 5e deposits of Site 1020, the maximum in oak pollen is followed by a maximum in redwood pollen. The redwood maximum occurs as isotope and pine values are beginning to increase and as SST's are beginning to decrease. Following results from studies of modern surface sediment samples and sediment traps, we infer that the variations in pollen abundance in our marine samples reflect variations in abundance of vegetation on the adjacent coastal regions (Heusser and Balsam, 1977; Gardner and others, 1988; Sancetta and others, 1992; Heusser, 1998). Thus, maximum development of redwood forests occurred after the peak interglacial as temperatures cooled slightly and presumably as coastal upwelling became more organized or persistent (see discussion below).

The data from ODP Site 1018 are less complete but show a similar pattern (see fig. 7). Pine abundance and benthic isotope values decrease upsection in the MIS 5e record. Within 5e deposits, an oak maximum is followed by a redwood maximum. The oak maximum coincides with the minimum values in pine and benthic $\delta^{18}O$. The few SST estimates available indicate that an increase in oak and warming of surface waters coincide. The redwood maximum clearly follows the maximum in oak and corresponds to the beginning of the increase in pine abundance. At Sites 1020 and 1018, the lag between oak and redwood maxima is ~2,000–3,000 years.

The sequence and timing of pollen and marine proxy events at ODP Site 1018 match those of the correlative events at ODP Site 1020. Thus, while conditions along the California margin have been highly variable in detail during glacial-interglacial transitions (Gardner and others, 1997), it appears that during the last interglacial, the major terrestrial vegetation changes and links between marine and terrestrial temperature changes along the northern and central California coastal area were in phase. A similar sequence of oak pollen maximum followed by redwood pollen maximum has been documented for the Holocene marine sediments off northern California (Sancetta and others, 1992) and for marine sediments from older Pleistocene interglacials recorded at Sites 1018 and 1020 (Heusser, in press; Heusser and others, in press). Thus, the lag between oak and redwood maxima observed in the MIS 5e sections from ODP Sites 1020 and 1018 appears to be typical of late Pleistocene interglacial records in this area.

In general, the transition from glacial to interglacial conditions should favor increased upwelling intensity along the coast of central and northern California. During glacials, the large ice sheet on the North American continent results in a high-pressure cell over the continent that deflects the jet stream to the south and also causes the summer North Pacific High to be weaker and move south and west of its modern position (COHMAP, 1988; Lyle and others, 1992; Bartlein and others, 1998). These changes reduce or eliminate the northerly winds that drive upwelling along the coast (for example, Lyle and others, 1992, fig. 15). During deglaciation, the melting of the ice sheet allows a progressive change back to the modern configuration, and upwelling should increase.

Our results indicate that development of upwelling during deglaciation is more complex in detail. Figure 9 shows that the microfossil assemblages deposited in the warmest part of MIS 5e at ODP Site 1020 contain *Globorotalia inflata* along with the diatom *Pseudoeunotia doliolus*. Both of these taxa decline rapidly in the upper part of the MIS 5e record, as does the warm-water foraminifer *Globigerinoides ruber* (fig. 4). *Globorotalia inflata* is typical of Pleistocene interglacial assemblages of the central Pacific water mass (Poore, 1999), as is *P. doliolus* (Sancetta and others, 1992). In addition, diatoms are sparse in sediments deposited during the earliest part of MIS 5e. When diatoms first occur in MIS 5e deposits, the assemblages with *P. doliolus* have relatively low values of the coastal upwelling indicator *Chaetoceros* and relatively high values of the offshore upwelling indicator *Thalassionema nitzschioides* (fig. 5). Diatoms are better preserved and *Chaetoceros* becomes more abundant in sediments deposited toward the end of MIS 5e, indicating increased influence of upwelling (fig. 9). The diatom and planktic foraminifer assemblages indicate strong influence of warm central Pacific waters at ODP Site 1020 during the warmest part of MIS 5e, and they probably indicate

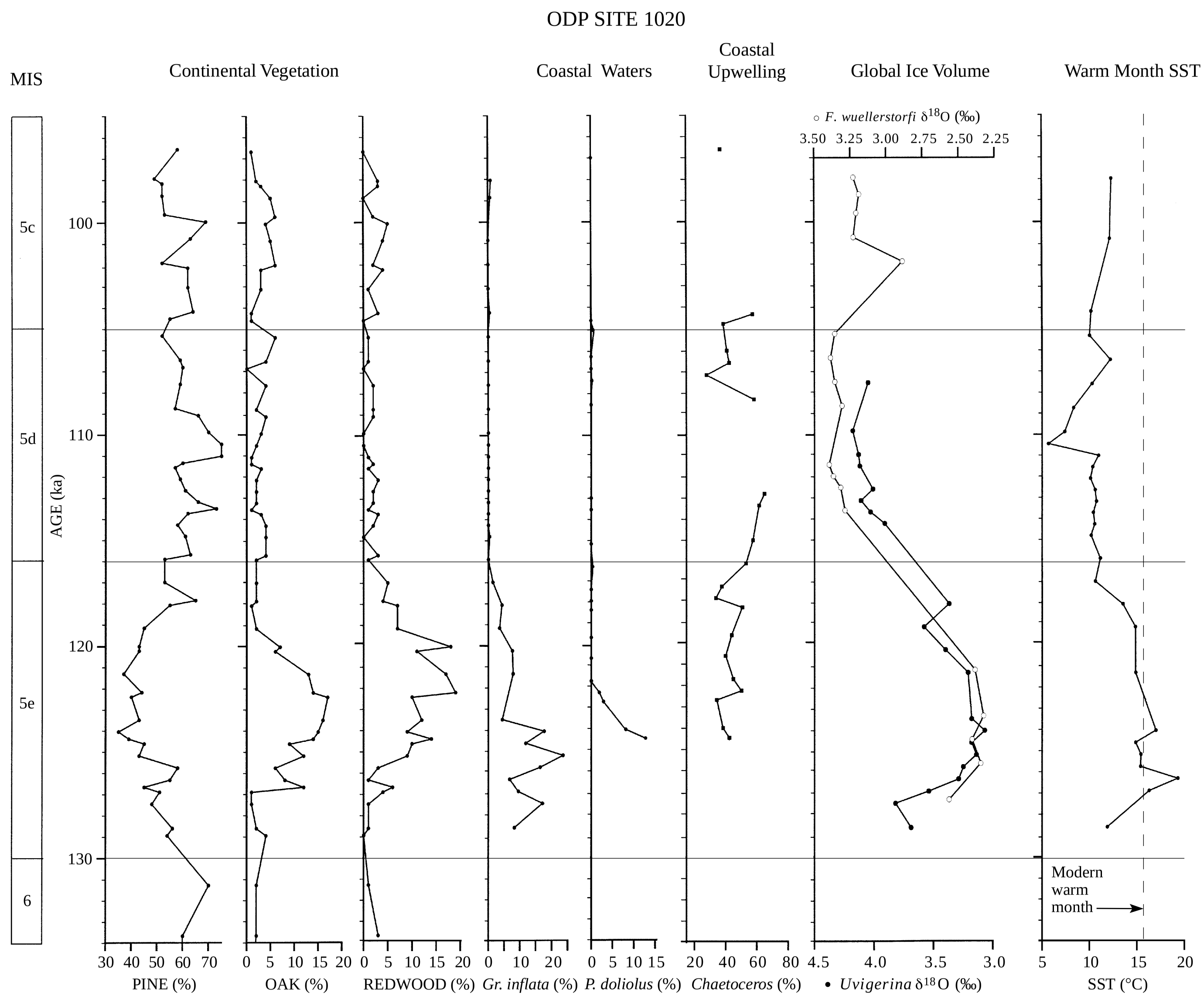


Figure 9. Age and marine isotope stage plotted against key environmental proxies from ODP Site 1020, core 1020D. Continental vegetation: pollen data are from figure 3. Coastal waters: planktic foraminifer data are from figure 4 (*Gr. inflata* = *Globorotalia inflata*), and diatom data are from figure 5 (*P. doliolus* = *Pseudoeunotia doliolus*). Coastal upwelling: diatom data are from figure 5 (*Chaetoceros* = *Chaetoceros* spores). Global ice volume: oxygen-isotope data for benthic foraminifers *Uvigerina* and *Fontbotia wuellerstorfi* are from figure 2; the $\delta^{18}O$ scales in figure 9 have been adjusted so that the smallest values from the two taxa coincide. Warm month sea-surface-temperature (SST) estimates: the SST estimates are from figure 4.

that atmospheric circulation was more zonal than it is today. A more modern circulation pattern with stronger or more persistent coastal upwelling and maximum development of redwood forests did not develop until later in the interglacial, at ~121 ka.

The record of the last deglaciation in piston cores off of southern Oregon shows a similar pattern. Sancetta and others (1992) found that in cores W8709–9BC and W8709A–13PC (fig. 1), *P. doliolus* reached maximum values in Holocene sediments dated at between 10 and 7 ka. *Chaetoceros* was common in the early Holocene and continued to increase into the late Holocene, reaching maximum values after *P. doliolus* declined in abundance. Sancetta and others (1992) concluded that the abundance of *P. doliolus*, combined with the relatively low abundance of *Chaetoceros* in the early part of the Holocene, reflects warmer waters and reduced upwelling compared to modern or late Holocene conditions.

Model simulations (COHMAP, 1988; Bartlein and others, 1998) of the last deglaciation suggest development of strong summer northerly winds and thus upwelling along the U.S. northwest Pacific coast during the deglacial-glacial transition and into the early part of the interglacial. Our results from MIS 5e and the record of Sancetta and others (1992) show that strong upwelling off the U.S. northwest Pacific coast develops in the middle to late part of interglacials, not in the early part as suggested by the model simulation.

In the modern ocean, El Niño events result in warmer surface waters along the coast of California. The warmer temperatures coincide with diminished southward oceanic transport and reduced upwelling along the California margin, presumably due to weakening of the North Pacific High (see Pares-Sierra and O'Brien, 1989; Lyle, Koizumi, Richter, and others, 1997, fig. 4). Coastal upwelling and associated high productivity off central California are reduced during El Niño events (Chavez, 1996). Our results suggest that the response of the California Current to maximum interglacial warming and El Niño events is similar. Warming of surface waters above modern values results in reduced or less persistent coastal upwelling and lower productivity compared to modern conditions.

The diatom assemblages from ODP Site 1020 suggest a complex and variable history of upwelling throughout all of MIS 5. As noted above, abundant *Chaetoceros* spores are indicative of summer coastal upwelling, and *Thalassionema nitzschioides* is a proxy for upwelling at the edge of the coastal zone and the central water mass (offshore upwelling) (Sancetta and others, 1992). These two taxa are common in all our samples from Site 1020 that have diatoms. *Chaetoceros* spores show an increase in abundance from MIS 5e deposits into MIS 5d deposits and *T. nitzschioides* shows a decrease through the same interval (fig. 5), indicating an overall trend towards increasing coastal upwelling from the latter part of MIS 5e into MIS 5d.

These taxa show an inverse correlation and distinct cycles over much of the rest of MIS 5. For example, abundance variations between 95 and 87 ka have a simple correlation coefficient (r^2) of –0.64. Inspection of figure 5 indicates that cycles of about 5,000 years are especially well developed in MIS 5a and 5b and are possible in MIS 5d. We interpret these cycles as changes in the influence of coastal versus offshore upwelling at Site 1020 through time. Offshore upwelling tends to be strongest during transitions between substages. Above the middle part of MIS 5c (~100 ka), there is a strong inverse correlation between percent *Thalassionema nitzschioides* and percent *Stephanopyxis* spp. (r^2 between 95 ka and 74 ka = –0.76). This relation is interpreted to reflect variations in the amount of pelagic diatom deposition (*T. nitzschioides*) versus downslope transport of slope species (*Stephanopyxis* spp.). In general, during MIS 5b and 5a, trends in percent *Chaetoceros* closely parallel those of *Stephanopyxis* spp., suggesting that downslope transport may have played an important role in the deposition of *Chaetoceros* during the early part of MIS 5.

COASTAL REDWOOD AND UPWELLING

Summer upwelling, because of its influence on the generation of coastal fog, is required for the development of extensive coastal redwood forests. The abundance of *Chaetoceros* in the record from ODP Site 1020 indicates that coastal upwelling was well developed in parts of MIS 5e, 5d, 5b, and 5a. We have limited data from MIS 5c, but we infer that coastal upwelling occurred during some or all of MIS 5c because upwelling was clearly developed during parts of MIS 5e and 5a. However, redwood pollen remains at very low levels in our samples from MIS 5d and 5c deposits at Site 1020 (fig. 9). The low abundance of oak and high abundance of pine in our assemblages in MIS 5d and 5c deposits from Site 1020 indicate that the climate was too cold for redwood forests to re-occupy large areas along the northern California coast during MIS 5c. This interpretation is consistent with our maximum SST estimates for MIS 5c that are several degrees cooler than Holocene or MIS 5e temperatures.

The record from ODP Site 1018 is more complicated. At Site 1018 (fig. 7), oak pollen shows broad abundance increases in sediments deposited during MIS 5d and MIS 5c that approach peak MIS 5e values. In addition, pine abundance declines to near MIS 5e levels in a number of samples from MIS 5c deposits. The pollen data suggest that warm coastal air temperatures occurred during parts of MIS 5d and 5c and that temperatures during MIS 5c approached MIS 5e conditions. We also infer that coastal upwelling must have been active during parts of MIS 5d and 5c because we have evidence for coastal upwelling from ODP Site 1020. However, redwood pollen remains at very low background levels throughout our MIS 5d and

MIS 5c assemblages. We conclude that extensive redwood forests developed along the coast of northern and central California only during short intervals following interglacial maxima when optimal temperature and upwelling conditions for their growth developed. Coastal redwood forests declined during cooler or warmer climatic conditions.

MILLENNIAL-SCALE CYCLES

Inspection of the physical properties records and spectral analyses establishes the presence of strong cycles having frequencies of ~8,000 and 5,000 years in sediments from ODP Site 1020 and 10,000 and 5,000 years in sediments from ODP Site 1018 (figs. 6 and 8). In addition, spectral analyses reveal several higher frequency cycles, including cycles of ~3,000 years and ~2,200 years in both records. Our data, however, do not show clear evidence for the ~1,500-year cycle that is persistent in Holocene and glacial intervals of the North Atlantic (Bond and others, 1997).

We conclude, however, that our study cannot be used to rule out the presence of the ~1,500-year cycle in MIS 5 records of the California margin. The persistent North Atlantic cycles are greatly subdued in the Holocene record compared to cycles in deposits from glacial intervals and, in addition, the North Atlantic cycles were not observed in all proxies (Bond and others, 1997). The Holocene cycles of ~1,500±500 years in the North Atlantic are best developed in ice-rafting indices based on type and abundance of lithic grains and are not reflected in planktic foraminifer isotope records nor are they convincing in abundance variations of foraminifers such as left-coiling *N. pachyderma* that are typically used as paleoceanographic indicators. We conclude that the poor preservation of microfossils in our samples, especially in the high-accumulation-rate sequence of ODP Site 1018, and the lower accumulation rate of the better preserved record at ODP Site 1020 preclude recognition of cycles with frequences less than ~2,000 years.

ABRUPT EVENTS

We see evidence for two abrupt cooling events in MIS 5e. One event occurred at ~126 ka and is marked best by the rebound in pine pollen abundance that is superimposed on an overall trend of declining pine abundance at ODP Sites 1020 and 1018 (figs. 3 and 7). The rebound to higher pine abundance is seen in more than one sample in both cores, and oak and redwood show a corresponding reversal in their trend towards increasing values at the same levels. The foraminifer assemblages and resulting SST estimates for ODP Site 1020 also show a brief cooling event associated with the pine rebound. The summer SST estimates show a sharp decline of 5°C (fig. 4).

The second abrupt cooling occurred near the end of MIS 5e at ~119 ka. The event is expressed in the pollen record from ODP Site 1020 by the drop in oak and redwood abundances from near peak interglacial levels down to background levels within 1,000 to 2,000 years (fig. 3). Foraminifer assemblages also show indications of cooling at this level with SST estimates dropping by 3°C between samples dated at 118 and 117 ka (fig. 4). Redwood pollen from Site 1018 shows a decline from 30 percent of the assemblage to 15 percent of the assemblage between 119 and 118 ka (fig. 7).

The pollen records from these cores are noisy, but we consider the cooling events at ~126 ka and ~119 ka to be reliable signals and not spurious events. Pollen evidence for the events occurs at the same levels in both cores, and, at ODP Site 1020, the cooling is also indicated by the foraminifer data. Thus, it is unlikely that the events can be explained by counting errors, burrowing, or some other type of reworking (Crowley, 1999). The event at ~119 ka represents a rapid cooling associated with the end of MIS 5e and the start of the transition to MIS 5d. The event at 126 ka occurred early in MIS 5e and appears to have been a brief cool pulse just prior to maximum interglacial conditions. The event at 126 ka is thus similar in timing to the brief cooling event at 8 ka in the early part of the Holocene (Alley and others, 1997).

SUMMARY AND CONCLUSIONS

Analysis of several marine climate proxies and pollen in cores from ODP Sites 1018 and 1020 reveals a close linkage between marine and terrestrial climate change during the last interglacial. Changes in global ice volume, coastal SST's, and coastal air temperature as indicated by benthic foraminifer isotope values, planktic foraminifer assemblages, and pollen assemblages from the same samples coincide. During the early warming of MIS 5e, warm central Pacific waters moved closer to the California margin, atmospheric circulation was more zonal, and coastal upwelling was reduced. Optimum conditions for development of redwood forests along the central and northern California coast were confined to a short interval just after the maximum warming of MIS 5e when coastal upwelling became well organized or persistent and ocean and atmospheric temperatures were still warm but below maximum interglacial levels. Substantial redwood forests were not reestablished along the coast during MIS 5c or MIS 5a even though coastal upwelling was present. Reflectance values for sediments from ODP Site 1020 generally correlate with calcium carbonate contents and show cycles of about 8,000 to 5,000 years that are linked to variations in upwelling. High values of reflectance represent dominance of coastal upwelling and increased carbonate content of the sediments, whereas low values of reflectance represent dominance of offshore upwelling and decreased carbonate content of sediments. Reflectance values for sediments from ODP Site 1018 are not clearly correlated with sediment carbonate variations. The relation between physical properties and climate proxies is complicated and likely varies depending on the depositional setting.

The poor preservation of microfossils in these cores precludes recognition of the cycles having frequences less than ~2,000 years recorded in Holocene sediments of the North Atlantic. Pollen records from ODP Sites 1020 and 1018 are supported by foraminifer assemblages from Site 1020 and indicate two abrupt cooling events at about 126 ka and 119 ka within MIS 5e.

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