

20. POLLEN STRATIGRAPHY AND PALEOECOLOGIC INTERPRETATION OF THE 160-K.Y. RECORD FROM SANTA BARBARA BASIN, HOLE 893A¹

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ABSTRACT

Pollen data (159 samples taken at $\sim\leq 1000$ yr intervals) provide the first continuous, chronologically controlled record of southern California terrestrial environments over the past 160 k.y., a record that is directly correlated with changes in the marine environment inferred from organic and inorganic components of the same sediment samples. In the well-laminated sediments deposited during the last interglacial interval, pollen assemblages are characterized by *Quercus* and other taxa similar to those of present arid coastal biomes (e.g., oak woodland, chaparral, coastal sage scrub, and salt marsh). Pollen assemblages in the massive glacial sediments, dominated by conifers (referable to the Taxodiaceae, Cupressaceae, Taxaceae, and Pinaceae families) imply altitudinal and latitudinal expansion of montane conifer woodland and forest associations (e.g., juniper woodlands and yellow pine forests of the Transverse Ranges). Variable representation of oak woodland and coniferous forests characterizes interstadials and stadials.

During the last glacial maximum on the south coast of California, mean annual temperature and effective precipitation estimates inferred from pollen data in Santa Barbara Basin are $\sim 5^{\circ}\text{C}$ and ~ 1000 mm, respectively. Interglacial temperatures and evapotranspiration were comparable to or possibly higher than at present. High-frequency variability in the pollen/vegetation assemblages from Ocean Drilling Program Hole 893A implies frequent and rapid change between these two climatic endmembers throughout the last 160 k.y. For example, following an abrupt warming at ~ 14 k.y., a brief mesic, cooling event precedes the development of Holocene interglacial conditions.

Systematic variations in the pollen assemblages deposited in Santa Barbara Basin are similar in amplitude and duration to changes reconstructed from oxygen isotopes in the same sediment samples. The apparent synchronicity of the terrestrial (pollen/vegetation of south coastal California) and marine (oxygen isotope) proxy climate signals from Hole 893A concurs with previous results from the North and South Pacific which showed similar rapid responses of terrestrial ecosystems to global climate change during the last glacial cycle.

INTRODUCTION

Ocean Drilling Program (ODP) Hole 893A ($34^{\circ}17.25'\text{N}$, $120^{\circ}02.19'\text{W}$, 576.5 meters below seafloor [mbsf]) was drilled ~ 20 km from the southern California coastline in Santa Barbara Basin (Fig. 1), a small near-shore, silled basin containing rapidly deposited (~ 100 cm/k.y.), upper Quaternary interbedded laminated, nonlaminated, and bioturbated sediment (Shore-based Scientific Party, 1994). Retrieval of a continuous 195-m sedimentary sequence covering the last 161 k.y. provides an opportunity to use pollen analysis to document the nature of coastal southern California vegetation throughout the last glacial cycle, and to determine the response of these terrestrial ecosystems to local and global paleoceanographic and paleoclimatic changes over the past 160 k.y. Previous studies elsewhere in the North and South Pacific, which demonstrated a close relationship between coastal terrestrial environments and ocean/atmospheric forcing, suggest that changes in onshore environments reflected in the pollen assemblages deposited in Santa Barbara Basin would be synchronous with global climate changes (Heusser, L.E., 1978; Heusser and Shackleton, 1979; Heusser and van de Geer, 1994).

Pacific ocean-atmosphere interaction is the major determinant of the character and distribution of the dominant hydrographic features

of Santa Barbara Basin and of onshore climate. Seasonal variations in the California Current system reflect the direction and intensity of the westerlies. Strong northerly winds between April and August enhance flow of the cold California Current toward the equator. Weakening of the northerlies in fall and winter results in intensified flow toward the poles of the warm surface waters of the Davidson Current and inhibits significant upwelling along the margin. Decadal, El Niño-Southern Ocean (ENSO)-related variations in sea-surface temperature are associated with onshore changes in precipitation—warm sea-surface temperatures with high precipitation during El Niño events and cool sea-surface temperatures with dry La Niña conditions (Namias, 1971).

The mild, arid Mediterranean (winter wet, summer dry) climate of coastal southern California is further moderated by fog formed by the passage of warm air over a semipermanent band of cold upwelling water during summer months and by warm offshore waters in winter (Pisias, 1978). Consequently, mean annual temperature is low ($\sim 14^{\circ}\text{C}$) and the annual range of mean monthly temperature onshore is small (January 11°C –July 17°C). Away from the moderating influence of the ocean, ~ 19 km inland, temperatures are $\sim 4^{\circ}$ higher in summer and 1.4° colder in winter (Barbour and Major, 1977). Above the coastal fog at ~ 800 m elevation, summer temperatures rise to 25°C , and on the peaks of the western Transverse Range maximum summer temperatures may exceed those of the lowland (Elford, 1974). Most of the limited and variable precipitation, which annually ranges from ≤ 30 cm on the lowland to ~ 50 – 100 cm on the mountains north of Santa Barbara Basin, is produced in winter by intense, episodic North Pacific frontal storms (Elford, 1974; Peterson, 1980). Subtropical monsoons and local convective storms provide occasional rain in summer.

¹Kennett, J.P., Baldauf, J.G., and Lyle, M. (Eds.), 1995. *Proc. ODP, Sci. Results*, 146 (Pt. 2): College Station, TX (Ocean Drilling Program).

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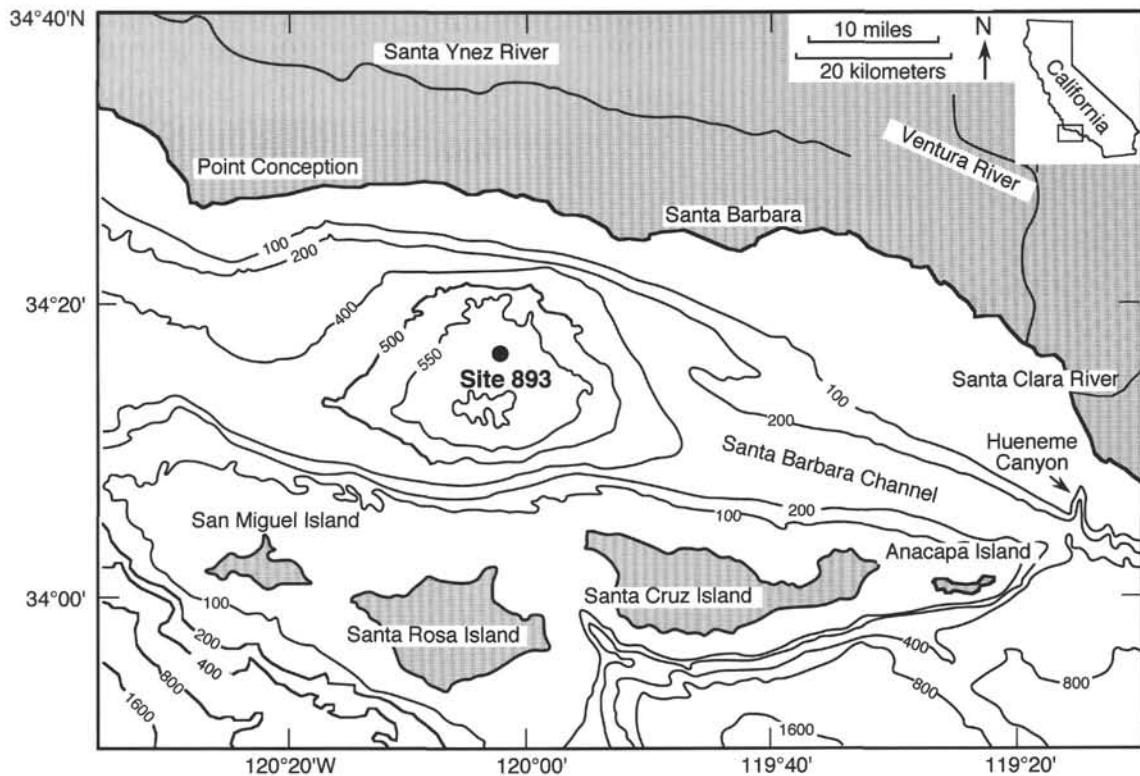


Figure 1. Map of Santa Barbara Channel showing the location of ODP Site 893 in Santa Barbara Basin.

Southern California vegetation around the Santa Barbara Basin is a dynamic landscape mosaic of coastal plant associations that vary with altitude, substrate, topography, and fire history (Barbour and Major, 1977; Barbour and Billings, 1988) (Table 1). The natural vegetation of the narrow coastal plain consists of coastal sage scrub or soft chaparral (including summer deciduous, semi-woody plants such as *Artemisia*, *Salvia*, and *Eriogonum*) that interfingers with chaparral (sclerophyllous shrubs such as *Ceanothus*, *Adenostoma*, *Rhus* and other members of the Anacardiaceae, Rhamnaceae, and Rosaceae), scrub oak (*Quercus dumosa*) and oak (*Q. agrifolia*) woodland savanna (Griffin, 1977; Hanes, 1977; Mooney, 1977; Keeley and Keeley, 1988). Salt marshes are not numerous or extensive around Santa Barbara Basin. Foothill woodlands are dominated by *Q. agrifolia* (live oak).

On the lower slopes of the Transverse Ranges at ~600 m, mixed hardwood (*Q. agrifolia*) forest merges with open pine (*Pinus coulteri* and *P. sabiniana*) woodland in which small stands of incense-cedar (*Libocedrus decurrens*) may occur. These mixed evergreen forests and open, park-like mid-montane conifer forests with yellow pine (*P. ponderosa* and *P. jeffreyi*), incense cedar, and oaks (*Q. kelloggii*) are

found between 800 and 1400 m. The latter extends to 2600 m. In Southern California, mean annual temperature (MAT) and annual precipitation in the mid-montane forests are ~13°C and 850 mm, respectively. Within the forest, MATs decrease to ~11°C and precipitation increases to >1000 mm (Barbour, 1988). Upper montane juniper (*Juniperus occidentalis*) woodland and subalpine coniferous (*P. contorta*) forests occur between 2400 and 2800 m in the higher eastern Transverse Ranges. Although there is little difference in total annual precipitation between the mid and upper montane forests, more precipitation occurs as snow in the higher elevation forests due to the lower MAT (~5°C). The comparatively small area of the Santa Ynez Mountains above 1500 m and the desert slopes of the Transverse Ranges are occupied by piñon pine-juniper woodland (*P. monophylla*, *J. californica*) with understory shrubs such as *Artemisia tridentata* (Thorne, 1977; Callaway and Davis, 1993; Critchfield, 1971).

METHODS

One sample was taken from each section of the 21 cores recovered using the advanced piston corer from Hole 893A for this initial pollen study. A few additional samples were later taken from Cores 146-893A-1H and 3H, yielding a total of 159 samples from the 196.5 m of hemipelagic silty clays recovered from Santa Barbara Basin. Using sample depths adjusted for gas expansion (Rack and Merrill, this volume) and the chronostratigraphy generated by Merrill (this volume) from globally and regionally corrected AMS ¹⁴C dates (Ingram and Kennett, this volume) and oxygen isotope stage (OIS) boundaries (Kennett, this volume), each 2-cm³ pollen sample integrates an average of ~20–30 yr, and sample resolution averages ~1000 yr.

Dried samples (~3–5 g dry-weight sediment [gdws]) were prepared with standard HF and acetolysis treatment, which was preceded and succeeded by screening through 7-μm screens (Heusser and

Table 1. Distribution of major vegetation types of south coastal California in relation to elevation.

Elevation (m)	Vegetation types			
2500	Pine forests		Juniper woodland	
2000		Mid-montane conifer (pine, oak, incense cedar, shrubs)		
1500		Mixed evergreen (pine, oak)		
1000				
500	Chaparral	Sage	Southern oak woodland	
	Pine/cypress		Beach	Salt marsh
	Mesic			Xeric

Stock, 1984). Identification of pollen was frequently hindered by the presence of organic agglomerates (possibly remains of algal mats, Soutar and Crill, 1977) and pyrite. Pollen types were identified to the lowest taxonomic level possible; for instance, *Sarcobatus* was differentiated from the Chenopodiaceae (which is indistinguishable from the Amaranthaceae), and *Artemisia* was tallied separately from other Compositae. In California, the inaperturate pollen grains of the Taxodiaceae, Cupressaceae, and Taxaceae—families that cannot be satisfactorily separated using light microscopy—are customarily referred to as TCT (an acronym formed from the first letter of the three families from which the pollen might be derived (Adam, 1988; Mensing, 1993). Possible sources of pollen from these three families in Santa Barbara Basin include *Juniperus californica*, *J. occidentalis*, *Torreya californica*, *Cupressus macrocarpa*, *C. sargentii*, and *Libocedrus decurrens*. *J. californica* is widely distributed, occurring in isolated groves or as an emergent in coastal sage scrub, chaparral and in canyon washes. *J. occidentalis* is found in montane-juniper woodlands in the Transverse Ranges (Barbour and Major, 1977). *L. decurrens* occurs in chaparral, mid-montane conifer forest, and lower montane woodlands; relict stands of *C. sargentii* are scattered along the coast. Regional Rosaceae, Rhamnaceae, and Anacardiaceae pollen grains, also difficult to separate using light microscopy, are also referred to by an acronym (RRA) derived from the initials of the three families).

In this preliminary survey, pollen percentages were calculated using the sum of terrestrial pollen, which was limited to ≥ 200 pollen grains. Spores were not included in the pollen sum. (Final counts of ~ 300 pollen grains for each of the 159 samples analyzed for this study, as well as final counts from ~ 400 additional samples, were incorporated into the ODP database in 1995). To reduce the number of variables to a few independent, ecologically meaningful groups, pollen data were synthesized using Q-mode factor analysis. Mass-accumulation rates of pollen (PAR) were calculated using the number of pollen grains/gdws and bulk mass-accumulation rates (MAR) (Gardner and Dartnell, this volume).

RESULTS

Pollen is well preserved and abundant in Santa Barbara Basin sediment. Pollen concentration (pollen grains/gdws) is variable, ranging from $\sim 1,000$ /gdws to $180,000$ /gdws, with an average concentration of $\sim 34,000$ /gdws (Fig. 2). Pollen concentrations in the intermittently laminated sediments (lithologic Subunits 1C, 37–131 mbsf, and 1F, 160.5–196.5 mbsf), vary between the lowest values ($\sim 1,000$ /gdws) in laminated sediment (lithologic Subunit 1A, 0–24.25 mbsf, and Subunit 1D, 131–145.5 mbsf) to high values ($180,000$ /gdws) found in the nonlaminated sediment (lithologic Subunit 1B, 24.3–37 mbsf, and 1E, 145.5–160.5 mbsf). When plotted vs. age (Fig. 3, left), pollen concentration does not appear to follow clearly a glacial-interglacial pattern. Although pollen concentrations are low during or close to interglacial intervals (e.g., OIS-1 and -5e) and high during glacial intervals (OIS-2 and -6), they are not high during OIS-4. Smoothed with a 3-point moving average, pollen concentrations do appear to vary systematically at ~ 20 -k.y. intervals (Fig. 3, right), close to precessional periodicity of 23 k.y./cycle. When corrected for annual sedimentation rates, however, accumulation rates of pollen (pollen grains/cm²/yr = PAR) (Fig. 4) are noisy, and spectral analysis of PARs showed no power in the 10- and 20-k.y. frequencies. This may reflect the large statistical uncertainties affecting pollen accumulation rates (Davis et al., 1984).

In recent sediment samples from Santa Barbara Basin, pollen composition reflects the composition of major plant associations growing nearby (Table 1). Pollen assemblages in sediment deposited over the last 20 yr (e.g., the uppermost sample from Hole 893A: Sample 146-893A-1H-1, 4–6 cm; 0.04 mbsf) (Fig. 5) and samples from box Core SBB 11-19-89 (34°14.0'N, 120°01'W, 587 m water depth)

Pollen concentration

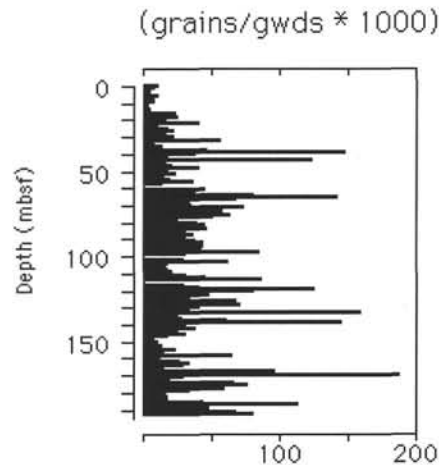


Figure 2. Depth plot of pollen concentration in Hole 893A.

are composed of *Quercus*, shrub, and herb taxa representative of the present mosaic oak woodland/chaparral/sage scrub communities on shore (L.E. Heusser, unpubl. data). In addition to these, regional taxa that periodically appear in lesser amounts include: *Ephedra*, *Salix*, *Juglans*, *Fraxinus*, *Myrica*, *Platanus*, *Sarcobatus*, *Eriogonum*, *Pseudotsuga*, *Abies*, *Umbelliferae*, *Cyperaceae*, fern spores, *Selaginella*, *Isoetes*, and *Sphagnum*.

Percentages of *Quercus* and Compositae, excluding *Artemisia*, (taxa which dominate the upper 23.5 m of Hole 893A) fluctuate substantially downcore. Major changes in their relative abundance and in that of the other pollen types shown in Figure 5 were used as the basis for defining pollen zones (Table 2). *Quercus* maxima, accompanied initially by small but significant amounts of *Alnus*, characterize pollen assemblage zones (PAZs) 9, 5, and 1—and, to a lesser degree, PAZs 5 and 3c. The relative abundance of the Rhamnaceae, Rosaceae, and Anacardiaceae (RRA), Compositae, and Chenopodiaceae display a similar pattern. Beginning with PAZ 9, percentages of *Quercus*, Compositae, and Chenopodiaceae show an overall upward decrease to PAZ 3a. Peaks of *Quercus*, Compositae, and Chenopodiaceae, together with abundant TCT, characterize PAZs 5 and 3c.

Conifers (TCT and *Pinus*) with varying amounts of *Artemisia* characterize all the other pollen zones (PAZs 10, 8, 6, 4, 3, and 2). In fact, TCT-type pollen dominates most of the record from Hole 893A. *Pinus*, which is more important in the upper half of the pollen diagram, peaks in PAZs 4, 3b, and 2, and large contributions of *Artemisia* identify subzones PAZ 10b and PAZ 3c.

When plotted vs. age on the Y-axis (Fig. 6), variations in percentages of *Quercus*, RRA, Compositae, and Chenopodiaceae clearly mirror the classic glacial/interglacial pattern of the last 160 k.y., which is also seen in the $\delta^{18}\text{O}$ variations plotted from comparable sample depths in Hole 893A (Kennett, this volume). OIS-1 and -3 and the substages of OIS-5 (5a, 5c, and 5e) are delineated by maxima in these three pollen groups. Minimal amounts of *Quercus*, RRA, Compositae, and Chenopodiaceae occur in OIS-2, -4, and -6. The nature and timing of changes in *Quercus* pollen and in the benthic $\delta^{18}\text{O}$ values are remarkably similar. For example, the abrupt increase in both these variables occurs at exactly the same depth at the beginning of OIS-1 and -5e (Fig. 7). The major difference between the pollen and oxygen isotope curves in Figure 7 is the *Quercus* spike at ~ 108 k.y.

Prior to 14 k.y., except for brief intervals (centered at ~ 52 , 80, 108, and 125 k.y.) TCT pollen types dominate the pollen record from Hole 893A, although the younger glacial intervals (OIS -2 and -4, as well as stadials of OIS-3), unlike those >70 k.y. (OIS-5b, -5d, and

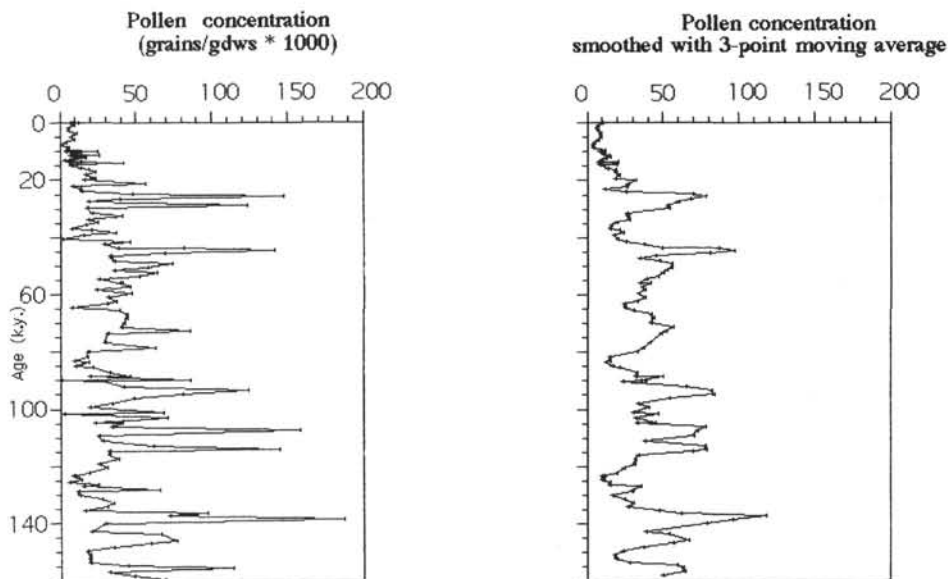


Figure 3. Times series of pollen concentration in Hole 893A. Data on the right were smoothed with a 3-point moving average.

-6), are characterized by substantial amounts of *Pinus* (Fig. 6). Other conifers present periodically are *Tsuga mertensiana* (mountain hemlock), *Picea*, *Abies*, *T. heterophylla*, *Pseudotsuga*, and *Sequoia* (presumably *S. sempervirens*, coastal redwood).

Because of the length and complexity of the pollen record from Santa Barbara Basin, it is instructive to examine some segments in

greater detail. The last 30 k.y. documents the replacement of gymnosperms, which dominate glacial sediments, by angiosperms (Fig. 8). Between ~30 and 14 k.y., conifers totally dominate. TCT, accompanied by lesser amounts of *Pinus*, *Artemisia*, and Compositae between 30 and 26 k.y. increases to ~80% at 25 ka, and then decreases to <10% until 14 ka when a brief 2-k.y. re-expansion occurs. *Artemisia* and Compositae reach maximum glacial levels at ~18 ka. The record of *Pinus* is quite different. At the end of the last glacial, *Pinus* rises gradually to peak levels (~60%) at ~15 ka, abruptly drops to ~10% at 14 ka, and then fluctuates between <10% to 40% for the next 4 k.y. Significant changes in other taxa also occur between 14 and 10 k.y., of which the rise in *Quercus* from <5% to ~40% is perhaps the most obvious. Lesser increases occur in the Chenopodiaceae and RRA. The rapid shift from *Pinus* to *Quercus* prominence at 14 ka, followed by a resurgence in TCT pollen types and secondarily of *Pinus*, is accompanied by a unique increase in *Alnus*. The timing of these deglacial fluctuations may be correlative with such brief events as the European Younger Dryas. It is interesting to note, however, that the evidence of apparent climatic reversal in the pollen data is not completely synchronous with lithologic changes interpreted as evidence of climatic reversal (Shore-based Scientific Party, 1994).

Between 30 and 70 k.y., the pollen assemblage is dominated by inaperturate conifers (TCT values average 54%) (Fig. 9). *Pinus*, which is most abundant between ~44 and 30 k.y., exhibits a brief expansion centered at ~60 ka. This precedes small increases in *Quercus* (to <10%) between ~58 and 50 k.y. The beginning of OIS-3 is also marked by higher values of shrubs and herbs (RRA, Compositae, *Artemisia*, and Chenopodiaceae). *Alnus* is absent, except for two samples where it is present in trace amounts.

OIS-5 is characterized by large amounts of *Quercus*, which reach Holocene values at ~124 ka and again between ~106 and ~108 ka. A minor increase occurs ~84 ka (Fig. 10). The *Quercus* assemblages include small but consistent amounts of *Alnus* that are highest at the base of OIS-5 (substage 5e). As in the Holocene, *Pinus*, which increases prior to *Quercus*, is minimal during the last interglacial. The replacement of gymnosperms by angiosperms at the beginning of the last interglacial appears to be less abrupt than at the beginning of the Holocene; however, this may be an artifact of our sampling interval and time scale. The last interglacial (OIS-5e) also differs subtly from the Holocene with higher TCT percentages and with slightly lower percentages of *Alnus* and *Artemisia*.

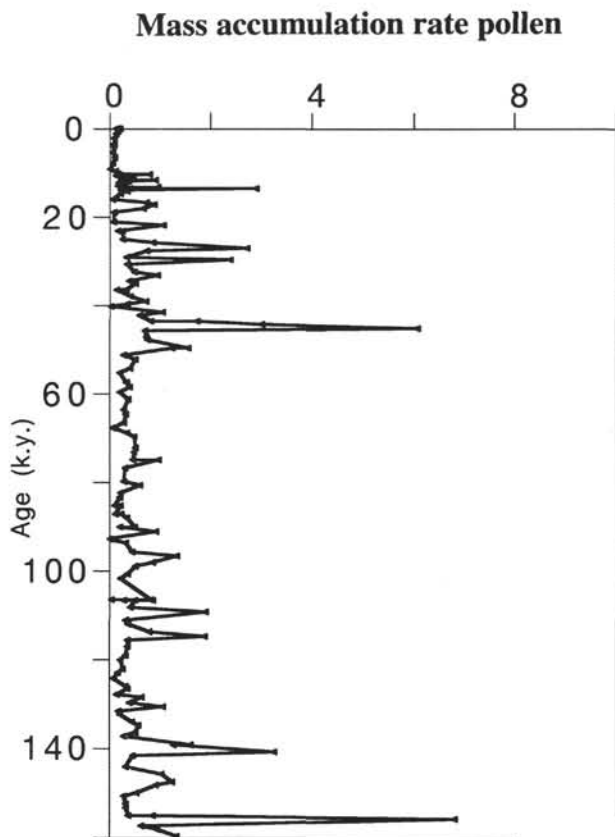


Figure 4. Time series of pollen mass-accumulation rate in Hole 893A.

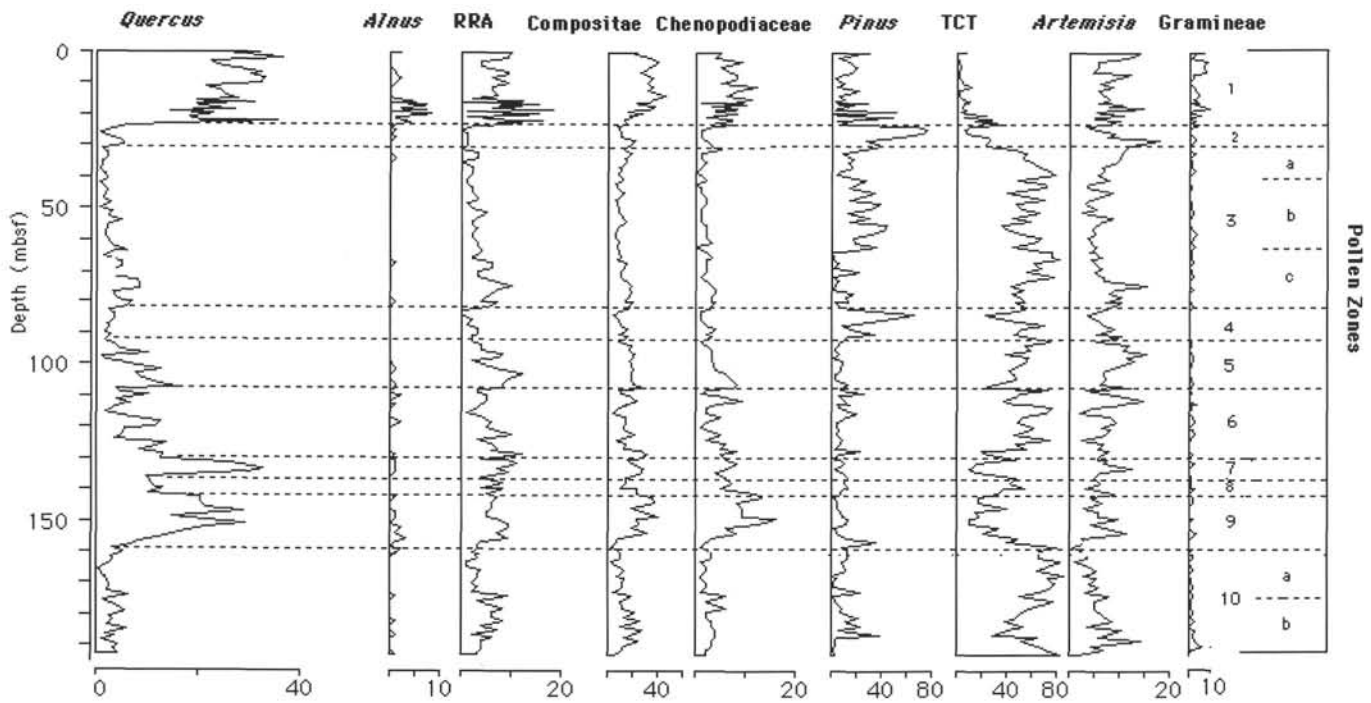


Figure 5. Depth plot of the relative abundance (%) of selected pollen types from Hole 893A. Pollen zones (Table 2) are shown on the right.

Table 2. Preliminary pollen zones from Hole 893A.

Pollen zone	Depth (mbsf)	Age (k.y.)
1	<i>Quercus</i> 0–23.5	0–14.9
2	<i>Pinus</i> 23.5–31	14.9–20
3	TCT 31–81	20–56
3a	TCT- <i>Artemisia</i> 31–40	20–26
3b	TCT- <i>Pinus</i> 40–64	26–44
3c	TCT- <i>Quercus</i> 64–81	44–56
4	<i>Pinus</i> -TCT 81–95	56–70
5	<i>Quercus</i> 95–109	70–84
6	TCT 109–130	84–104
7	<i>Quercus</i> 130–136	104–110
8	<i>Quercus</i> -TCT 136–141	110–116
9	<i>Quercus</i> 141–160	116–128
10	TCT 160–194	128–161
10a	TCT 160–183	128–144
10b	TCT- <i>Artemisia</i> 183–194	144–161

Q-mode factor analysis of the pollen data from Hole 893A (17 taxa, 159 samples) provides added insight into the structure of the data. Five factors, identified by the names of the diagnostic taxa in each assemblage, capture 99% of the variability in the raw pollen counts (Appendixes A and B; Fig. 11). In the TCT factor, TCT pollen with RRA, *Artemisia*, *Chenopodiaceae*, and *Compositae* of secondary importance, is segregated from other taxa. One source of TCT pollen in this factor is probably *Juniperus*. *Juniper*, which also occurs in small, widely separated stands in oak woodland and chaparral of the Coast Range (Griffin, 1977; Hanes, 1977), is present on lower mountain slopes in western Santa Barbara County (Vasek and Thorne, 1977) and is widely distributed to the east. It is possible that this factor represents *Juniperus* communities not unlike those now distributed in the Great Basin (Anderson and Davis, 1988; Hevly et al., 1965; Leopold, 1967; Solomon and Silkworth, 1986). This factor may also represent the expansion of cypress, which now occurs in small, disjunct communities scattered along the California coast. One of the most widely distributed, *C. sargentii*, is found on Zaca Peak in Santa

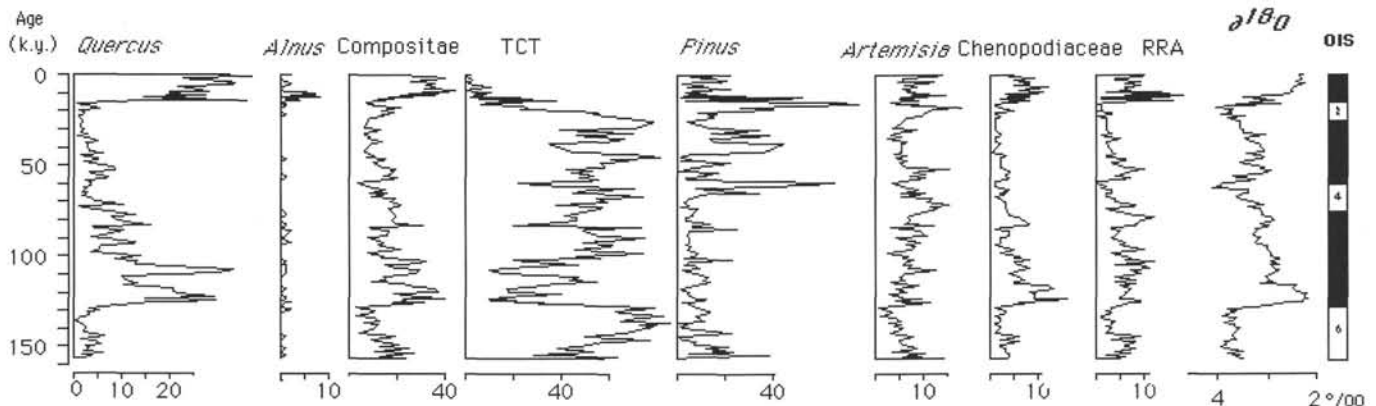


Figure 6. Time series of the relative abundance (%) of selected pollen types from Hole 893A. The $\delta^{18}O$ record and oxygen isotope stage (OIS) zonation shown on the right are from Kennett (this volume).

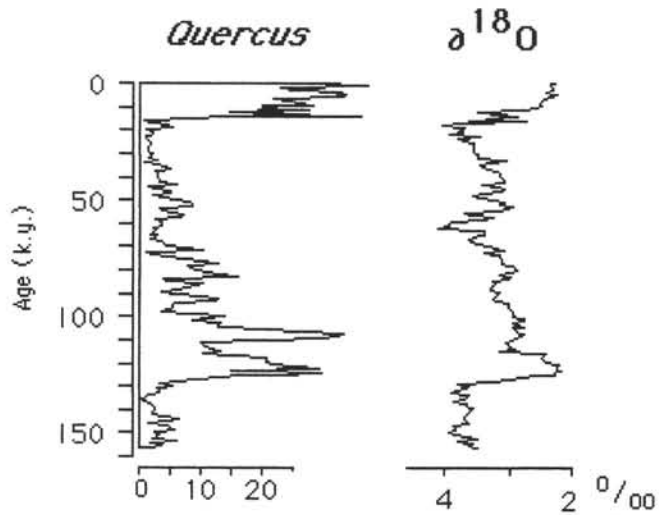


Figure 7. Time series of the relative abundance (%) of *Quercus* (oak) from Hole 893A plotted with the $\delta^{18}O$ record from the same sample intervals on the right (Kennett, this volume).

Barbara County, ~1323 m above sea level (Thorne, 1977; Vogl et al., 1977; Mensing, 1993). The negative association between inaperturate conifer pollen (TCT) and *Pinus*, however, suggests that this factor may not represent communities like southern California closed-cone pine and cypress stands, upper montane and subalpine conifer forests, piñon-juniper woodland, or any plant community in which

Juniperus, *Libocedrus*, or *Cupressus* is associated with *Pinus* (Heusser, 1960; Leopold, 1967; Thorne, 1977).

The *Quercus*-Compositae factor groups oak with all pollen types except TCT and *Abies*. This factor is interpreted as representative of present-day southern California oak associations, such as lowland oak woodlands, oak-dominated chaparral, oak woodland and grassland, as well as lower and mid-montane woodlands in which oak is prominent (Barbour and Major, 1977). These first two factors account for 86% of the original variability.

In the third factor, which accounts for 12% of the total variance, *Pinus* is positively associated with conifers (TCT, *Picea*, *Tsuga*, and *Abies*), shrubs and herbs (*Artemisia*, *Ephedra*, Gramineae) and is negatively related to *Quercus*, *Alnus*, RRA, Compositae, and Chenopodiaceae. This factor is interpreted as representing pine-conifer forests in which oak is absent and herbs are not well developed—southern California communities such as the upper montane and subalpine coniferous forests of the eastern Transverse Ranges, or possibly coastal closed-cone pine and cypress (Thorne, 1977; Vogl et al., 1977). In this factor, as in the TCT factor, the negative relation between *Quercus* and *Pinus* precludes interpreting this component as a pine oak woodland, or as piñon-juniper foothill woodland of Baja, California, in which oak is present (Leopold, 1950). The minimal representation of *Picea*, *Abies*, and *Tsuga*, and the absence of *Sequoia* suggest that this factor is in no way analogous with present-day mesic lowland conifer forests to the north (e.g., Pacific Coastal Forest of the north California and Oregon coast (Barbour and Major, 1977).

Although the remaining two factors account for less than 1% of the variability, they are of interest because they isolate three ecologically interesting communities: riparian, sage scrub/chaparral, and halophytic associations. In the *Alnus* factor, *Alnus*, along with *Picea*,

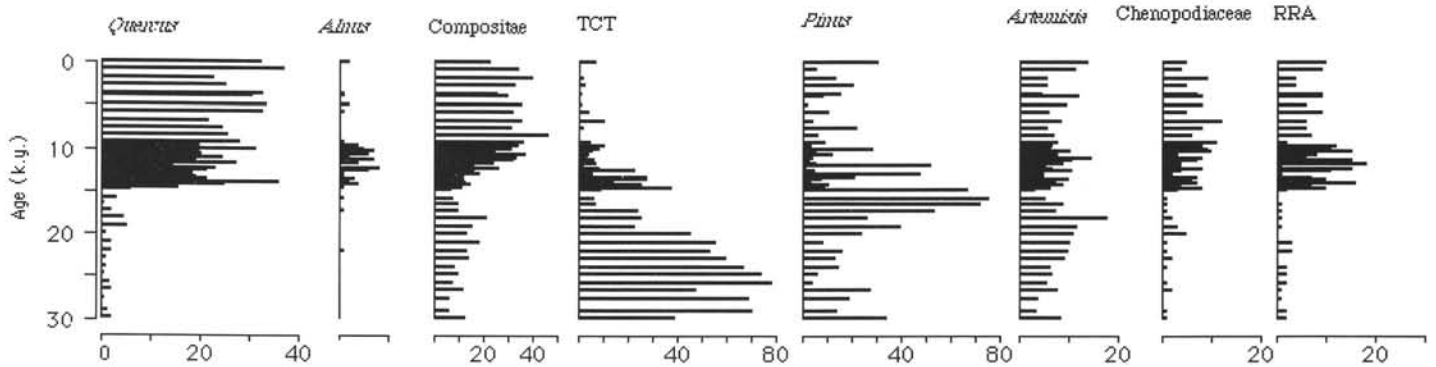


Figure 8. Plot of the relative abundance (%) of selected pollen types from upper 30 k.y. of record from Hole 893A. The darker plot reflects denser sampling between ~10 and 15 k.y.

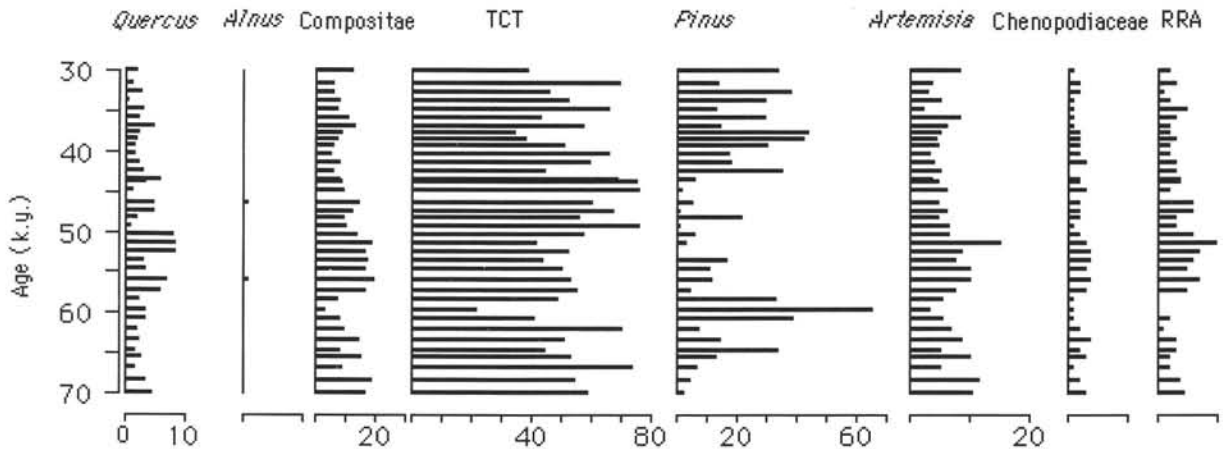


Figure 9. Plot of the relative abundance (%) of selected pollen types from Hole 893A during the last full glacial interval between 30 and 70 k.y.

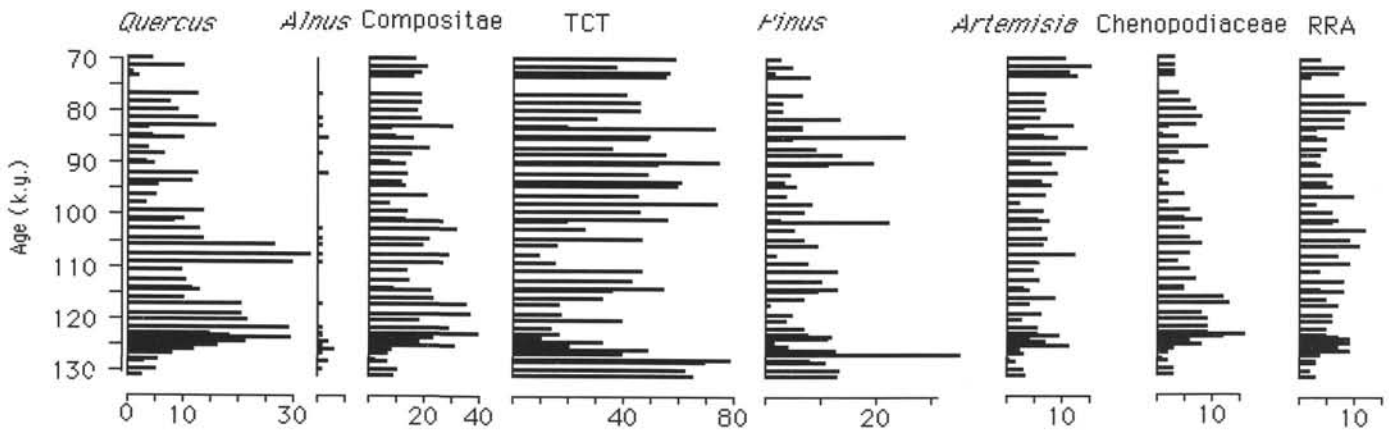


Figure 10. Plot of the relative abundance (%) of selected pollen types from Hole 893A between 70 and 130 k.y.

Tsuga, *Pinus*, and RRA, is negatively related to *Quercus* and TCT pollen types. The association of alder (presumably *A. rhombifolia* which now grows along streams in southern California) with more mesic types such as *Picea*, *Tsuga*, and *Pinus*, suggests that this factor might be an indicator of precipitation/runoff. The composition of the *Alnus* factor resembles present-day surface samples from areas with greater rainfall than southern California (e.g., western Oregon; Heusser, C.J., 1978) or northern California coastal forests in which *Sequoia* is not present (Heusser, 1988). The latter possibility suggests that the *Alnus* assemblage, or any of the fossil pollen assemblages from Hole 893A for that matter, may not have exact modern pollen or vegetation analogues.

The fifth factor separates Chenopodiaceae pollen, which is positively associated with *Pinus*, *Quercus*, and TCT, from *Artemisia* and *Ephedra*. This factor identifies a dichotomy between coastal southern California communities—halophytic communities in which chenopods are well developed (e.g., salt marshes and beach strands) and communities in which *Artemisia* (sage) is prominent and *Pinus*, *Quercus*, and *Juniperus* are absent (possibly extensive chaparral and/or coastal sage scrub far from any trees) (Mooney, 1977; Mudie and Byrne, 1980).

DISCUSSION

Pollen concentration in Santa Barbara Basin is up to four times as high as in a basin farther offshore (Tanner Basin, 32°54.92'N, 119°44.23'W; 1475 mbsf), and about 10 times the pollen concentration of marine sediments deposited elsewhere along the northeast Pacific coast (Cross et al., 1966; Heusser and Balsam, 1977; L.E. Heusser, unpubl. data). The large quantity of pollen in sediments of Santa Barbara Basin, amounts that are comparable to the highest marine pollen concentrations reported elsewhere in the world (e.g., the Black Sea and modern and fossil deltaic environments; Traverse, 1988), is related to the proximity of the source areas of pollen, the unusually high terrigenous (including pollen) sedimentation rates, and the excellent pollen preservation in sediments deposited under the anoxic to suboxic bottom waters of Santa Barbara Basin.

The relative importance of fluvial pollen transport in marine pollen sedimentation elsewhere on the Pacific coast of North America (Heusser and Balsam, 1977) implies that rivers are a primary factor in pollen sedimentation in Santa Barbara Basin. Previous analyses showed that the Santa Clara and Ventura rivers carried surprisingly large amounts of pollen (Heusser, L.E., 1978), and pollen analysis of monthly samples from sediment traps off northern California and southern Oregon showed that seasonal variations in pollen concentration correlated more with seasonal variations in precipitation/runoff than with pollen production and initial aeolian dispersal (Heusser, 1988). Therefore, the large amounts of pollen in Santa Barbara Basin

are assumed to be related to the extremely high flux of pollen-bearing terrigenous sediment delivered by winter runoff from the Ventura, Santa Clara, and possibly the Santa Ynez Rivers (Soutar and Crill, 1977; Gardner and Dartnell, this volume). This interpretation is supported by the comparatively high percentages of riparian taxa (principally *Alnus*) in nonlaminated sediments of Hole 893A (Fig. 8) that are attributed to increased precipitation/runoff (Rack et al., this volume), and by the increased importance of the *Alnus* factor between ~14 and 10 ka (Fig. 11), a time when flow rates of the Santa Ynez River were higher than present (Morgan et al., 1994) and when stream aggradation increased in the Transverse Ranges (Weldon, 1983) and central coastal California (Rypins et al., 1989).

The preliminary results of pollen analyses of varves deposited in Santa Barbara Basin between 1989 and 1974, however, show little correlation between annual pollen concentration and precipitation in Santa Barbara or runoff from the Ventura and Santa Clara rivers (Schimmelmann and Tegner, 1992; C. Lange and L. Heusser, unpubl. data). In addition, variability in pollen concentration and accumulation rates does not appear to correlate with patterns of other sedimentary parameters from Hole 893A (%C organic, magnetic susceptibility, and sediment flux; Gardner and Dartnell, this volume; Rack et al., this volume) that are also genetically related to precipitation/runoff. This apparent lack of correspondence may, at least in part, reflect the polygenetic origin of all the sedimentary components, as well as the complex relation between pollen productivity, transport, and deposition (Solomon, 1972; Solomon and Hayes, 1972; Solomon and Silkworth, 1986).

Undoubtedly, aeolian transport and marine currents also play a role in pollen sedimentation in Santa Barbara Basin (Heusser, L.E., 1978). Chenopod pollen from salt marshes bordering Santa Barbara Channel may be carried to the shelf both by wind and tidal flux. Winds associated with winter and early spring storms may carry substantial amounts of pollen offshore from those plants that bloom early in the year in southern California (e.g., *Alnus*, *Juniperus*, and *Quercus*), and less-frequent summer storms may transport shrub and herb pollen produced at that time of year (Karau, 1968). Unfortunately, data relating aeolian dispersal of pollen from modern southern California plant communities are lacking. The closest most relevant studies (from the Sierra Nevada and from the Mojave and Sonoran deserts) show that contemporary pollen rain can be used to distinguish vegetation types such as oak grassland/woodland and chaparral, montane and subalpine forests, and desert communities (Solomon and Hayes, 1972; Anderson and Davis, 1988; Leopold, 1967). Studies of atmospheric pollen accumulation in montane regions elsewhere show that aeolian transport accounts for ~1/5 of pollen influx (Fall, 1992).

Once in marine waters, rapid deposition of pollen, like other terrigenous particles, is suggested by the similarity in the composition and concentration of pollen in sediment traps moored at different depths in the same location, by the preservation of seasonal variations

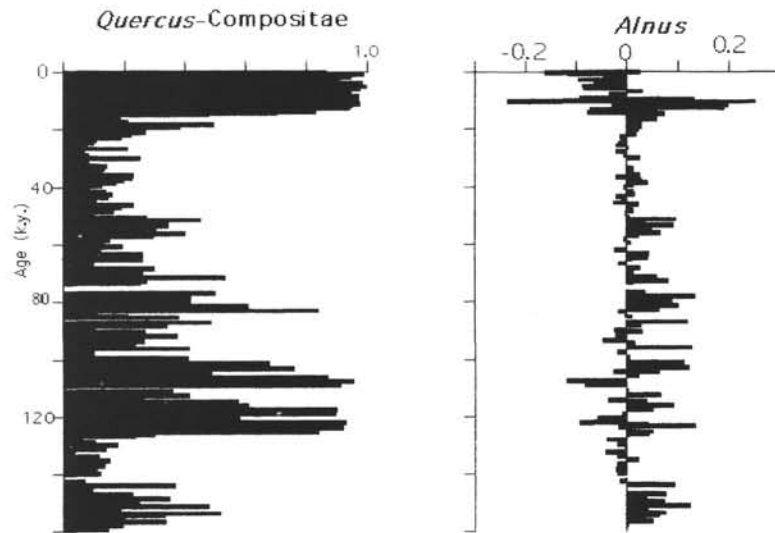


Figure 11. Time series of pollen assemblages (factors) from Hole 893A.

in annual pollen assemblages, and by the similarity between the geographic distribution of marine pollen assemblages and terrestrial vegetation formations onshore (Heusser, 1988; Heusser and Balsam, 1977; L.E. Heusser, unpubl. data). For example, pollen assemblages deposited in Santa Barbara Basin since the nineteenth century include pollen from alien plant species that were introduced in coastal southern California during that time (e.g., *Erodium*, *Eucalyptus* and *Aca-cia*) (Mensing, 1993; C. Lange and L. Heusser, unpubl. data).

Using the principle of least astonishment, interpretation of the fossil pollen data from Hole 893A is based on the assumption that fossil pollen in the sediment deposited in Santa Barbara Basin mirrors the vegetation of coastal southern California in the same manner as recent marine pollen records reflect onshore vegetation (Gardner et al., 1988; Mensing, 1993). Although there are no pollen data from the southern coast of California with which the entire 160-k.y. pollen record from Santa Barbara Basin can be compared, comparison of Holocene pollen data from Santa Barbara Basin (the upper ~20 m of Hole 893A and Core Y71-10-117P; Heusser, L.E., 1978) with terrestrial pollen records of comparable duration (six relatively short records ≤ 12 k.y.; Peterson, 1980; Davis, 1992; Cole and Liu, 1994; Mensing, 1993; Morgan et al., 1994; West, 1994) indicates that Holocene marine pollen data from Santa Barbara Basin show the same major vegetational changes seen in the onshore pollen data.

What is surprising is that variations in the relative abundance of the most abundant pollen types in the cores from Hole 893A in Santa Barbara Basin are generally similar to variations in the relative abundance of the same pollen types in cores taken in the North Coast Range of California (Adam, 1988; Sims et al., 1981), an ecologically and climatologically very different area (Fig. 12). The oak curves from the 197-m Hole 893A record from arid, coastal southern California and the 115-m record from Clear Lake, a more mesic site on the leeward side of the north California Coast Range, appear similar in amplitude and length (Adam et al., 1981). The most apparent difference between the southern and northern California oak pollen records plotted in the depth domain is the 3-point peak centered ~133 mbsf in Hole 893A. Precise comparison of these two curves in the time domain is problematic due to differences in ^{14}C calibration in the younger parts of the records, and to the subjective age models used—of necessity—in the older parts of the Clear Lake record (compare the age assignment of 64,000 ka [Adam and West, 1983] at ~72 m in core CI-4 with the radiocarbon date of $29,300 \pm 390$ for the same interval [Adam et al., 1981]). It would appear that the basal oak maximum in

core CI-4 (pollen zone I-2; Adam et al., 1981) corresponds with the basal oak maximum in Hole 893A (PAZ 9) which was deposited during OIS-5e (Fig. 7).

Downcore variations in the relative abundance of oak pollen in Hole 893A (Figs. 5 and 7) imply major changes in the abundance and distribution of open oak woodlands, woodland or scrub oak chaparral, and/or coastal scrub in south coastal California over the past 160 k.y. Variations in the importance of the *Quercus* factor (Fig. 11) also imply optimal development of oak-dominated communities during interglacials (OIS-1 and -5e) and minimal representation during glacial maxima (OIS-2 and -6). Subtle differences in the percentages of the principal taxa in the interglacial *Quercus* assemblages (PAZs 1 and 9; Fig. 5), for example the higher percent of Chenopodiaceae and TCT in PAZ 9, suggest that the mosaic of oak-dominated plant communities now growing in the Santa Barbara region is a postglacial development. The oak pollen assemblage deposited between ~128 and ~116 k.y. resembles modern pollen rain from oak woodland in the foothills of the central Sierra Nevada (Anderson and Davis, 1988) and is also suggestive of Pliocene *Quercus-Juniperus* woodland (Ax-

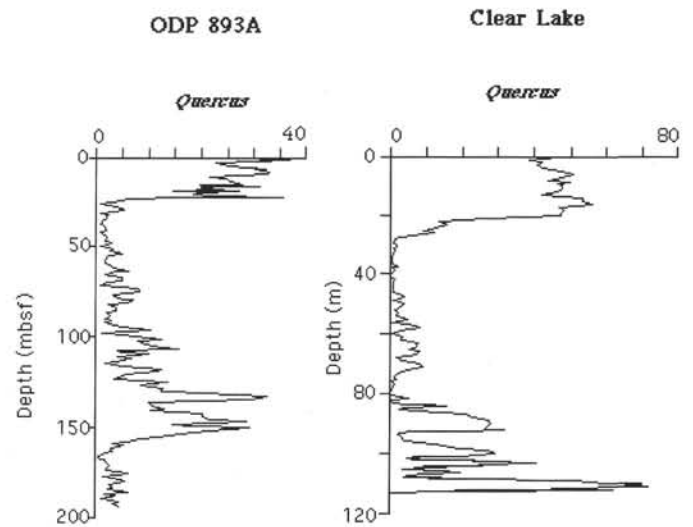


Figure 12. Depth plots of the relative abundance (%) of *Quercus* in Hole 893A and in Clear Lake (Adam et al., 1981).

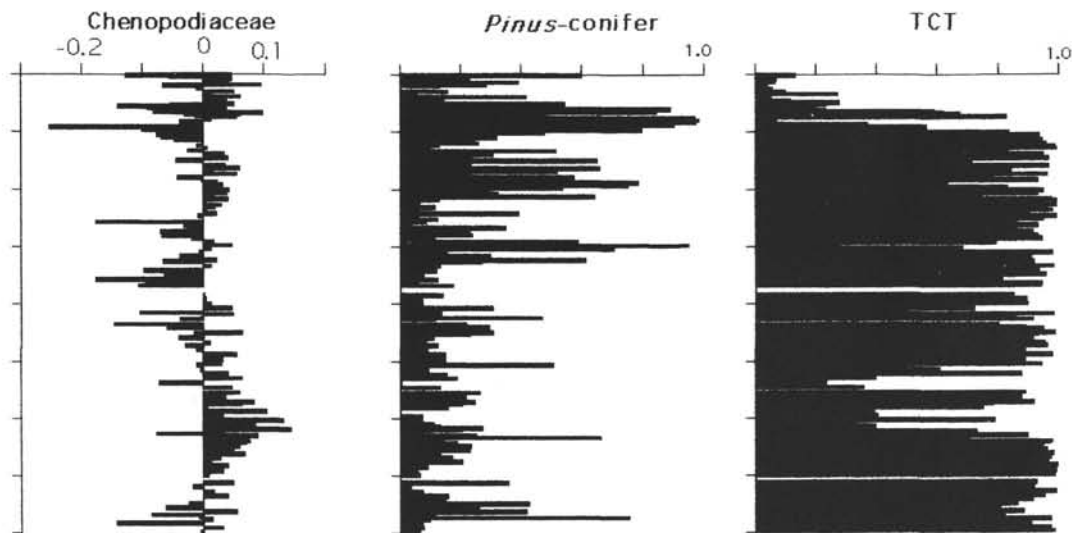


Figure 11 (continued).

elrod, 1977). Other paleobotanical evidence from California also is interpreted as evidence of the relative youth of present oak woodland taxa (*Q. agrifolia* and *Q. engelmannii*) (Axelrod, 1977). Glacial/interglacial fluctuations in the value of positive loadings of the chenopod factor (Fig. 11) vary in the same general manner as global sea level (e.g., peaking during interglacial and interstadial intervals). One interpretation of the variations in this factor is that the development of coastal salt marshes near Santa Barbara Basin is positively related to regional sea level changes (Martin and Gray, 1962; Macdonald, 1977). It is also possible that some of the chenopod pollen in this factor reflects long-distance transport from areas with high soil salinity, (e.g., salt pans in eastern California or Baja California; Benson and Thompson, 1987; Leopold, 1967), and that variations in the chenopod factor also reflect the expansion and contraction of saline habitats due to changes in aridity.

Glacial vegetation near Santa Barbara Basin and in coeval sediments deposited off California between $\sim 32^{\circ}\text{N}$ and $\sim 36^{\circ}\text{N}$ (Heusser, 1994) is reconstructed as conifer woodland in which *Quercus* was sparse, and in which representatives of lowland Pacific coastal forest (e.g., *T. heterophylla*, *S. sempervirens*, and *P. sitchensis*) were essentially absent. Interpreting the most prominent coniferous assemblage as *Juniperus*-dominated implies widespread distribution of communities like those now found in montane-juniper woodlands in the Transverse Ranges. This interpretation would concur with similar altitudinal depression of vegetation postulated elsewhere in the southwest (Axelrod, 1977), and with the expansion of juniper in the interior (Leopold, 1967; Van Devender et al., 1987). Montane coniferous communities (mid-montane conifer forest or lower montane woodlands) would also have been present if some of the inaperturate conifer pollen is ascribed to *Libocedrus decurrens*, which was present in the Santa Cruz Mountains during "moister phases of the Quaternary" (Axelrod, 1977).

Although *Juniperus* definitely was growing on the southern California coastal plain during the Pleistocene (the Rancho La Brea macroflora; Axelrod, 1977), it is also probable that *Cupressus* formed a part of coastal vegetation during the last glacial. The present-day disjunct spatial distribution of cypress—isolated small stands scattered along the California coast—has been interpreted as evidence of widespread distribution prior to the Holocene (Vogl et al., 1977).

The periodic prominence of *Pinus*-dominated vegetation suggests altitudinal and possible latitudinal expansion of upper montane coniferous forest communities similar to those now growing above ~ 1600

m in the Transverse Ranges during glacial intervals of the past 160 k.y. Another possibility is that closed-cone pine and cypress stands, now restricted to scattered small groves associated with chaparral and foothill woodland communities in southern California, formed part of the southern California pine-dominated glacial assemblages. Both interpretations of the *Pinus* component from Hole 893A, and from marine cores taken elsewhere off the southern California coast (L.E. Heusser, unpubl. data), concur with previous reconstructions of Pleistocene vegetation from other paleobotanical evidence (Axelrod, 1977; West, 1994).

The relative abundance of herbs and shrubs represented by nonarboreal pollen (Fig. 13), shows glacial/interglacial modulations that are even more similar to those of the oxygen isotope curve than those of *Quercus* (Fig. 7). Open vegetation communities, such as chaparral, sage, oak scrub, and woodland, are best developed during interglacials (OIS-1 and -5e), as are salt marshes with *Chenopodiaceae* (Mudie, 1975; Figs. 5 and 11). In arid southern California, as in arid

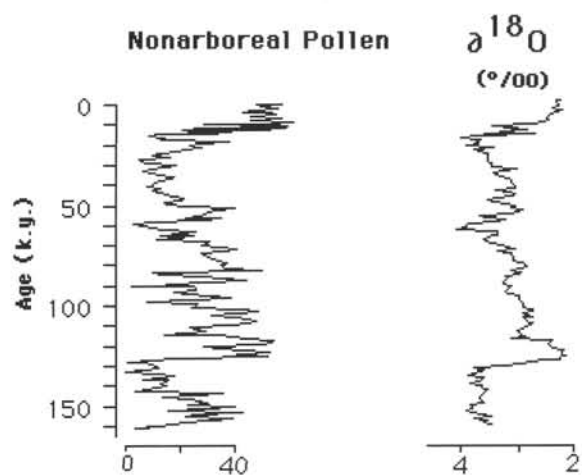


Figure 13. Plot of the relative abundance (%) of nonarboreal pollen types and $\delta^{18}\text{O}$ from Hole 893A. The sum of nonarboreal types includes Compositae, Gramineae, Cyperaceae, and other minor herbaceous taxa (Kennett, this volume).

northern Chile (Heusser, 1983), the relative abundance of nonarbooreal pollen during the last glacial cycle is the reverse of nonarbooreal abundance in pollen diagrams from temperate regions with more abundant and evenly distributed rainfall (e.g., Washington, France, and New Zealand; Woillard, 1978; Heusser and Heusser, 1990; Heusser and van de Geer, 1994).

The meager amount of Gramineae in the pollen record prior to the last ~14 ka (Fig. 5) does not appear to support extensive grassland or grassy oak savannas near Santa Barbara Basin. Minimal amounts of nonarbooreal pollen (~10%) and the limited amount of total variance explained by the shrub- and herb-dominated factor in glacial intervals (e.g., OIS-4 and -6) suggest that glacial vegetation may have been more like closed forest than open woodland.

Fire has undoubtedly played a role in the vegetation dynamics of southern California during the last glacial cycle. Fire is, and has been, a significant factor in the shifting landscape mosaic of lowland biomes, and in the composition of montane yellow pine and juniper forests, in which suppression of fire in recent decades has encouraged the expansion of conifers, commonly at the expense of oak (e.g., *Libocedrus* in mid-montane conifer forest, and *Pinus* in oak woodland) (Barbour and Major, 1977; Callaway and Davis, 1993; Mensing, 1993). In fire-adapted communities, such as coastal sage scrub, chaparral, oak woodlands, and closed-cone pine and cypress, seed release, germination, and seedling establishment of many species are enhanced by fire. Charcoal fragments were noted in all samples (L.E. Heusser, unpubl. data); therefore, it seems probable that at least some of the changes in the vegetation reflected in the pollen record from Hole 893A were fire-related. The analyses of charcoal in recent Santa Barbara sediments (Byrne et al., 1977; Mensing, 1993) have shown some interesting correlations between charcoal and large fires in the adjacent Coast Ranges of southern California. Between 730 and 1505 AD and 1931–1970 AD, Byrne (Byrne et al., 1977) found a strong correlation between large charcoal fragments and conflagration fires within 50 km of the Santa Barbara Basin sediments. Although fire frequency in the last 10 k.y. may, at least in part, reflect human activity in southern California, records from other arid environments that are ≥ 40 k.y. suggest a correspondence between charcoal frequency and effective rainfall (Singh et al., 1981; Heusser, 1983). The role of fire in the vegetational landscape near Santa Barbara Basin presumably is also linked to climatic changes of the last 160 k.y.

The regional and temporal scale of changes in the vegetation of south coastal California inferred from the pollen data from Hole 893A, corroborated by other marine and terrestrial floral data, implies climatic forcing. Temperature is often the major factor determining plant distribution, and in California, the mean annual temperature amplitude (the warmest month minus the coldest month) is regarded as an important factor in the distribution of southern oak (*Q. agrifolia*) woodland (Barbour, 1988). Although mean annual temperatures of oak woodlands in California are not significantly different (~16°C), the mean monthly temperature range (17°C – 11°C = 6°C) of southern California lowland oak communities is far less than the ~19°C annual temperature amplitude of oak (*Q. douglasii*) woodland in northern California (Elford, 1974; Barbour, 1988). In the Santa Barbara region, above the fog belt and away from the moderating influence of the ocean waters, equability (mean annual temperature amplitude) decreases, and the annual range of temperature doubles to ~13°C in the coniferous forests of the Transverse Range (Elford, 1974).

The virtual absence of oak pollen (both in relative and "absolute" abundance) in glacial sediments implies that mean annual temperatures were $< -16^\circ\text{C}$ (the mean annual temperature of oak woodlands in California), and that the mean monthly temperature range in coastal southern California increased substantially, probably due to lower winter temperatures. A substantial increase in annual temperature

amplitude or equability and a concomitant decrease in mean annual temperature would also be implied if the coniferous pollen assemblages that dominated glacial intervals were derived from montane vegetation. During the last glacial, mean annual temperatures inferred from the expansion of montane conifers may have been as low as ~5°C (Barbour, 1988), temperatures that would be consistent with the development of glaciers in the San Bernardino Mountains of southern California (Sharp et al., 1959) and with sea-surface temperature estimates in Santa Barbara Basin (CLIMAP Project Members, 1981). Farther north in the Coast Range, full-glacial temperatures of ~7° to 8°C less than present were calculated using a linear relation between elevation and oak (oak + pine) pollen ratios from Clear Lake, California (Adam and West, 1983). Elsewhere in the southwestern United States, vegetational reconstructions imply similar treeline and temperature depression (Van Devender et al., 1987), and estimates of ~5°–7°C lowering of mean annual air temperatures during the late Wisconsin derive from physical records of Great Basin lakes (Benson and Thompson, 1987). It is interesting to note that while these annual estimates of temperature differences between the last glacial maximum and present agree with the simulation results of Hostetler et al. (1994), the seasonal estimates of temperature depression implied by pollen data from Santa Barbara Basin do not. This probably reflects the problem of scale as well as the peculiar maritime climate of Santa Barbara.

It is not inconceivable that summer temperatures on the Santa Barbara coast were sometimes equal to or even higher than present during the last 160 k.y. Although this concept is consistent with descriptions of higher temperatures during the last interglacial, it is not consistent with conceptual models of regional glacial climates (Atwater et al., 1986; Hostetler et al., 1994; Van Devender et al., 1987) or with model simulations of a 6.0°C July temperature depression during the last glacial maximum (Hostetler et al., 1994). Depression of summer temperatures on the Santa Barbara coast is now related to the presence of fog. Temperatures of mid-montane forests above the fog are 5°C higher than at sea level. If changes in summer sea surface temperatures and other hydrographic features of Santa Barbara Basin resulted in the absence of fog, summer lowland temperatures, even during glacial periods, would most likely approach present-day mid-montane temperatures (Pisias, 1978; Gardner and Dartnell, this volume; Hemphill-Haley and Fourtanier, this volume; Kennett, this volume).

The prominence of pollen which could be attributed to montane conifers (representatives of the Taxodiaceae, Cupressaceae, Taxaceae, and *Pinus*) in the record from Hole 893A is also interpreted as evidence of increased precipitation in and around Santa Barbara Basin during much of the last 160 k.y. If precipitation on the coastal lowland during glacial intervals was comparable to that of present coastal montane conifer forests, annual rainfall may have been as high as 600 to 1000 mm (Barbour and Major, 1977; Elford, 1974; Mehringer and Wigand, 1986; Van Devender et al., 1987; Barbour, 1988).

Even with 600 to 1000 mm of rainfall per year, however, Santa Barbara would have been arid during the last glacial interval. Rainfall apparently was never sufficient to support coastal forests with substantial amounts of *T. heterophylla* and/or *Sequoia sempervirens*. This suggests that effective precipitation was less than that of coastal central and northern California today. Estimates of precipitation reconstructed from pollen/vegetation assemblages during the last full glacial in Santa Barbara Basin agree with the 10-cm increase in precipitation during the last glacial maximum shown in the simulation results of a regional general circulation model (Hostetler et al., 1994), and with glacial precipitation estimates reconstructed from vegetation in other arid regions of the southwestern United States (Van Devender et al., 1987).

SUMMARY

The initial results of pollen analyses of 159 samples from the 161 k.y. core from ODP Hole 893A show glacial/interglacial variations in the diagnostic taxa of vegetation assemblages of southern California. In the laminated sequence from the last interglacial (OIS-5e) pollen assemblages that are characterized by taxa representative of present coastal oak woodland, chaparral, and coastal sage scrub imply climatic conditions similar to the warm, arid conditions that have prevailed since the last glacial maximum. Pollen assemblages in the bioturbated glacial-age sediments are dominated by coniferous taxa (representatives of the Taxodiaceae, Cupressaceae, Taxaceae, and Pinaceae), implying comparatively cool, less arid conditions on shore. Variable representation of coniferous forest and oak woodland characterize stadial and interstadial bioturbated and intermittently laminated sediments.

During the last full-glacial cycle, changes in the composition of pollen/vegetation groups of arid coastal southern California appear to be primarily controlled by climatic change. These variations, which reflect regional atmospheric and oceanographic variations, are similar in amplitude and duration to global climatic changes reconstructed from correlative pollen and oxygen isotope data from sites outside Santa Barbara Basin.

ACKNOWLEDGMENTS

I would like to gratefully acknowledge ODP and Professor James Kennett for obtaining the Santa Barbara Basin cores. In addition, I would like to thank the reviewers (R. Byrne, O.K. Davis, and J. Gardner) for their thoughtful comments.

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Date of initial receipt: 18 August 1994

Date of acceptance: 13 February 1995

Ms 146SR-279

APPENDIX A

Varimax Factor Matrix of Pollen Data from Hole 893A

Pollen type	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
<i>Pinus</i>	-0.0449	0.0608	0.9935	0.0281	0.0384	0.0653
<i>Tsuga</i>	0	0.0001	0.0003	-0.0005	0.0018	0.0021
<i>Abies</i>	-0.0011	-0.0003	0.0063	-0.0011	0.0013	0.0045
<i>Picea</i>	-0.0005	0.0008	0.0052	0.0016	-0.0201	-0.0083
<i>Quercus</i>	-0.0491	0.6221	-0.0515	0.6296	-0.4307	0.158
<i>Alnus</i>	-0.0073	0.0444	-0.0116	0.1189	0.249	-0.0081
<i>Betulaceae</i>	-0.0003	0.0005	0.0021	0.0023	-0.0007	-0.0062
<i>Juglans</i>	-0.0009	0.0032	0.0023	0.015	-0.0079	-0.0029
<i>Ilex</i>	-0.0004	0.0003	0.0017	-0.0012	0.0008	0.0025
RRA	0.0259	0.2036	-0.0628	0.3354	0.7704	0.0172
<i>Ephedra</i>	-0.0023	0.0061	0.0047	0.0154	0.0102	-0.0114
<i>Gramineae</i>	-0.0013	0.027	0.002	0.004	0.0082	-0.023
<i>Cyperaceae</i>	-0.0008	0.0063	0.0053	0.0145	-0.0058	-0.014
<i>Compositae</i>	0.0608	0.7067	-0.0263	-0.6782	0.0177	0.0029
<i>Artemisia</i>	0.0609	0.1776	0.0532	0.1059	0.0741	-0.9267
<i>Chenopodiaceae</i>	0.0085	0.1829	-0.0271	-0.0282	0.3857	0.3264
TCT	0.9937	-0.0271	0.0425	0.0598	-0.0467	0.064
% sum of squares	59.264	26.587	12.064	1.053	0.415	0.369

APPENDIX B

Varimax Factor Scores of Pollen Data from Hole 893A

Depth (mbsf)	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
0.018	0.998	0.131	0.767	0.599	0.070	-0.162	0.045
0.042	0.998	0.031	0.864	0.416	0.246	-0.127	-0.022
0.076	0.994	0.001	0.841	0.479	0.201	0.025	-0.128
0.891	0.995	0.019	0.985	0.045	0.080	-0.116	-0.057
1.778	0.997	0.067	0.944	0.227	-0.215	-0.045	0.045
2.692	0.996	0.065	0.907	0.390	-0.081	-0.096	0.041
3.606	0.997	0.030	0.938	0.283	0.155	-0.064	0.094
3.917	0.998	0.039	0.984	0.132	0.081	-0.017	-0.066
4.873	0.999	0.055	0.994	-0.007	0.003	-0.087	-0.011
5.788	0.995	0.098	0.974	0.156	0.063	-0.084	0.051
6.692	0.992	0.270	0.945	0.053	-0.148	0.029	0.012
7.539	0.999	0.046	0.904	0.415	-0.057	-0.034	0.060
8.397	0.995	0.052	0.969	0.063	-0.218	-0.030	0.004
9.332	0.992	0.116	0.969	0.145	-0.097	-0.093	0.037
9.680	0.997	0.274	0.943	0.027	-0.117	0.131	0.017
10.022	0.996	0.234	0.961	0.049	-0.031	0.105	0.051
10.048	0.996	0.091	0.788	0.545	0.121	-0.234	0.031
10.305	0.995	0.177	0.940	0.088	0.076	0.252	-0.054
10.635	0.972	0.124	0.937	0.221	-0.164	0.032	-0.045
11.025	0.994	0.121	0.975	0.060	-0.076	-0.017	-0.141
11.357	0.989	0.197	0.948	0.007	-0.062	0.199	-0.091
11.688	0.979	0.185	0.938	0.064	0.210	0.123	-0.038
12.014	0.998	0.011	0.450	0.890	0.011	-0.029	0.038
12.347	0.985	0.233	0.941	-0.018	0.091	0.191	0.024
12.647	0.993	0.591	0.754	0.104	0.232	0.059	-0.082
12.987	0.998	0.077	0.524	0.843	0.031	-0.073	0.047
13.322	0.998	0.620	0.577	0.480	0.203	0.003	0.096
13.656	0.998	0.673	0.655	0.179	0.287	0.046	-0.031
13.938	0.997	0.300	0.829	0.028	0.464	0.004	0.059
14.226	0.996	0.604	0.704	0.244	0.264	-0.076	-0.013
14.522	0.997	0.827	0.476	0.203	0.194	0.073	0.048
14.852	0.999	0.098	0.209	0.970	0.032	0.036	0.054
15.809	0.999	0.043	0.169	0.984	-0.004	0.029	0.013
16.397	1.000	0.069	0.186	0.977	-0.037	0.057	-0.039
17.251	1.000	0.370	0.209	0.904	-0.021	0.028	-0.022
18.203	0.998	0.564	0.495	0.588	-0.156	0.024	-0.254
19.171	0.999	0.449	0.383	0.797	-0.068	0.027	-0.100
20.019	0.995	0.837	0.237	0.477	-0.072	0.022	-0.073
20.951	1.000	0.939	0.269	0.175	-0.092	0.010	-0.078
21.961	1.000	0.917	0.223	0.320	-0.036	0.017	-0.068
22.890	0.999	0.947	0.187	0.248	-0.058	-0.013	-0.048
23.809	1.000	0.960	0.107	0.257	0.007	-0.011	-0.002
24.743	1.000	0.987	0.098	0.127	-0.005	-0.016	-0.012
25.685	1.000	0.992	0.080	0.096	0.021	-0.022	0.006
26.630	1.000	0.831	0.210	0.513	-0.038	0.002	-0.027
27.647	1.000	0.949	0.071	0.304	0.021	-0.021	0.033
28.932	1.000	0.968	0.081	0.232	0.028	-0.007	0.039
29.947	1.000	0.713	0.252	0.650	-0.051	0.025	-0.045
31.695	1.000	0.967	0.083	0.235	0.037	0.000	0.036
32.659	1.000	0.738	0.140	0.657	0.030	-0.002	0.058
33.688	1.000	0.844	0.135	0.519	-0.004	0.013	0.017
34.739	0.999	0.962	0.125	0.229	0.039	0.011	0.055
35.717	1.000	0.784	0.230	0.574	-0.015	0.025	-0.044
36.840	1.000	0.936	0.226	0.268	-0.011	-0.022	-0.002
37.588	1.000	0.584	0.198	0.786	-0.007	0.028	0.022
38.415	0.999	0.632	0.171	0.753	0.018	0.041	0.032
39.365	0.999	0.834	0.124	0.535	0.033	0.011	0.025

APPENDIX B (continued).

Depth (mbsf)	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
40.409	1.000	0.951	0.088	0.292	0.040	-0.005	0.042
41.473	1.000	0.935	0.139	0.324	0.025	0.011	0.037
42.531	0.999	0.749	0.160	0.641	0.045	0.014	0.016
43.632	1.000	0.978	0.146	0.126	0.055	-0.022	0.040
43.740	1.000	0.992	0.114	0.045	0.033	-0.007	0.021
44.726	1.000	0.992	0.107	0.065	0.000	-0.010	0.004
45.517	1.000	0.994	0.072	0.058	0.034	-0.026	0.028
46.309	0.999	0.965	0.233	0.114	-0.006	0.021	0.019
47.359	1.000	0.981	0.187	0.050	0.017	0.009	0.003
48.359	1.000	0.906	0.163	0.390	-0.001	0.013	0.021
49.244	1.000	0.993	0.105	0.059	-0.003	-0.004	-0.009
50.468	0.999	0.952	0.275	0.124	0.026	0.004	0.000
51.430	0.998	0.863	0.453	0.085	0.001	0.096	-0.178
52.493	1.000	0.936	0.346	0.034	0.001	0.035	-0.033
53.547	0.999	0.863	0.345	0.346	-0.083	0.090	-0.025
54.702	1.000	0.918	0.305	0.230	-0.061	0.048	-0.070
55.925	1.000	0.934	0.267	0.238	-0.012	0.015	-0.007
56.052	1.000	0.907	0.400	0.086	-0.045	0.065	-0.068
57.224	1.000	0.947	0.296	0.114	-0.031	0.022	-0.020
58.371	1.000	0.795	0.152	0.587	0.012	-0.007	0.016
59.552	1.000	0.278	0.131	0.949	0.048	0.007	0.045
60.800	1.000	0.685	0.191	0.703	0.017	0.000	0.013
62.124	1.000	0.980	0.122	0.153	0.000	-0.024	-0.008
63.372	0.999	0.913	0.263	0.298	-0.058	0.043	-0.038
64.620	1.000	0.769	0.175	0.613	0.010	0.041	0.020
65.363	0.999	0.923	0.261	0.266	-0.067	0.009	-0.066
66.763	1.000	0.986	0.101	0.133	0.009	-0.016	0.012
68.270	1.000	0.938	0.299	0.118	-0.080	0.024	-0.099
69.872	1.000	0.959	0.263	0.076	-0.040	0.011	-0.065
71.443	0.999	0.816	0.533	0.123	-0.026	0.057	-0.176
72.821	0.999	0.947	0.275	0.057	-0.089	0.080	-0.091
73.612	0.999	0.942	0.254	0.175	-0.070	0.013	-0.107
76.925	0.999	0.854	0.498	0.141	0.019	0.034	0.001
78.346	0.997	0.895	0.416	0.071	-0.009	0.133	0.004
79.906	0.999	0.901	0.417	0.073	0.002	0.088	0.013
81.476	0.999	0.723	0.610	0.304	0.011	0.101	0.046
82.983	0.999	0.502	0.837	0.135	-0.117	0.064	-0.104
83.475	1.000	0.984	0.114	0.126	0.036	-0.016	0.048
84.896	1.000	0.858	0.212	0.466	0.028	-0.003	-0.006
85.302	0.999	0.917	0.379	0.115	0.020	0.009	-0.039
87.086	0.988	0.804	0.486	0.215	-0.154	0.120	-0.147
88.326	0.999	0.890	0.340	0.293	-0.004	0.027	-0.056
88.539	0.999	0.950	0.284	0.105	-0.010	0.014	-0.061
89.886	1.000	0.988	0.103	0.103	0.037	-0.023	0.029
90.003	1.000	0.947	0.054	0.305	0.054	-0.018	0.063
90.412	0.999	0.935	0.268	0.230	-0.010	0.030	-0.016
91.994	0.999	0.915	0.375	0.109	0.081	-0.022	-0.042
93.586	1.000	0.956	0.264	0.083	0.077	-0.046	0.010
94.601	1.000	0.963	0.236	0.122	0.016	0.014	-0.030
96.225	0.997	0.891	0.415	0.089	-0.080	0.127	-0.012
97.860	1.000	0.981	0.098	0.149	0.038	-0.019	0.055
99.463	0.998	0.893	0.409	0.150	0.095	0.003	0.031
101.040	1.000	0.948	0.302	0.069	0.064	0.018	0.029
101.470	0.998	0.487	0.676	0.506	-0.192	0.111	-0.011
103.050	0.988	0.605	0.758	0.093	-0.155	0.121	-0.005
104.610	0.999	0.880	0.466	0.064	-0.044	-0.027	0.039
104.750	0.999	0.851	0.486	0.151	0.106	0.064	0.012
106.040	0.999	0.396	0.870	0.187	0.213	0.022	0.062
107.670	0.999	0.235	0.955	0.006	0.111	-0.117	-0.073
109.300	0.994	0.356	0.910	0.131	0.116	-0.082	0.045
111.020	0.998	0.893	0.357	0.263	0.027	0.001	0.059
112.740	0.999	0.878	0.413	0.218	0.061	0.065	0.036
114.340	0.999	0.922	0.263	0.246	0.106	-0.036	0.083
114.850	0.998	0.785	0.577	0.204	-0.041	0.037	0.063
116.150	0.979	0.751	0.609	0.156	-0.105	0.090	0.006
117.580	0.996	0.390	0.897	-0.014	-0.158	0.049	0.103
119.170	0.999	0.404	0.894	0.071	-0.174	-0.009	0.032
120.650	0.997	0.790	0.578	0.072	0.115	-0.056	0.131
122.120	0.997	0.321	0.929	0.112	0.040	-0.093	0.085
123.050	0.999	0.396	0.857	0.133	-0.295	0.040	0.039
123.360	0.941	0.269	0.882	0.271	0.011	0.133	0.020
124.050	0.989	0.239	0.920	0.204	0.153	-0.015	0.143
124.770	0.999	0.731	0.663	0.025	0.155	0.014	0.029
125.500	0.998	0.509	0.839	0.080	-0.143	0.050	-0.078
126.250	0.997	0.900	0.299	0.252	0.158	0.042	0.089
126.950	0.999	0.703	0.236	0.660	0.096	0.002	0.074
128.210	1.000	0.980	0.063	0.139	0.095	-0.038	0.076
128.610	0.999	0.973	0.103	0.188	0.043	-0.006	0.069
129.920	1.000	0.953	0.178	0.235	0.023	-0.019	0.059
131.220	1.000	0.962	0.138	0.231	0.014	-0.003	0.047
132.650	1.000	0.985	0.036	0.133	0.068	-0.042	0.068
133.950	1.000	0.978	0.115	0.168	-0.011	-0.018	0.027
135.260	1.000	0.967	0.150	0.203	-0.035	0.023	0.012
136.510	1.000	0.996	0.048	0.046	0.030	-0.018	0.039
137.150	1.000	0.987	0.132	0.089	-0.004	0.040	0.011
138.460	1.000	0.992	0.109	0.053	-0.006	-0.022	0.031
139.760	1.000	0.990	0.122	0.063	0.001	-0.018	0.008
142.460	1.000	0.928	0.069	0.357	0.060	-0.014	0.049
143.800	1.000	0.923	0.368	0.033	-0.042	0.093	-0.018

APPENDIX B (continued).

Depth (mbsf)	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
145.710	1.000	0.993	0.096	0.071	0.009	-0.001	0.017
146.930	0.999	0.956	0.228	0.157	0.026	0.077	0.039
148.280	0.997	0.919	0.351	0.147	-0.081	0.038	-0.001
149.560	0.998	0.865	0.250	0.425	-0.010	0.073	-0.024
150.900	0.996	0.807	0.476	0.257	-0.177	0.124	-0.063
152.250	1.000	0.887	0.183	0.418	-0.005	0.041	0.055
153.590	0.998	0.822	0.517	0.114	-0.170	0.076	-0.085
154.350	0.999	0.547	0.331	0.756	-0.122	0.063	-0.007
155.110	1.000	0.975	0.196	0.099	-0.001	0.036	0.014
156.580	1.000	0.911	0.339	0.074	-0.161	0.049	-0.143
157.950	0.999	0.977	0.191	0.078	-0.007	0.001	0.030
159.350	1.000	0.987	0.147	0.065	0.009	-0.001	-0.006
160.700	1.000	0.991	0.059	0.068	0.071	-0.032	0.065