Kennett, J.P., Baldauf, J.G., and Lyle, M. (Eds.), 1995
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# 2. RADIOCARBON CHRONOLOGY AND PLANKTONIC-BENTHIC FORAMINIFERAL $^{14}$C AGE DIFFERENCES IN SANTA BARBARA BASIN SEDIMENTS, HOLE 893A[1]

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## ABSTRACT

Radiocarbon dating by accelerator mass spectrometry of planktonic and benthic foraminifers separated from sediments from Ocean Drilling Program Hole 893A, Santa Barbara Basin (576.5 m water depth), were used to provide the chronology for the upper 70 m of the core. Radiocarbon ages were corrected to calendar ages using two calibration techniques, which gave similar results. One was based on tree-ring calibration and the other based on U-Th dating of corals.

The maximum reliable planktonic foraminiferal radiocarbon age in the core, at a corrected depth of 43.18 mbsf, was 25,470 ± 240 radiocarbon yr, with a corrected age of 28,896 yr before present. The youngest age obtained for the core was from 1.55 mbsf, with an age of 1850 radiocarbon yr, and corrected age of 950 yr, assuming a reservoir age, *R(t)*, of 825 yr. A total of 43 samples was analyzed between these two levels, exhibiting a near linear sedimentation rate of 14.53 cm/100 yr.

The Younger Dryas cooling event, represented in Santa Barbara Basin by a climatic change based on oxygen isotopic changes of benthic and planktonic foraminifers, occurs in a non-laminated interval within laminated sediments (17.60 to 20.40 mbsf). The event was dated using six planktonic foraminifer samples. Radiocarbon ages for the event are 11,980 to 10,630 yr. The corrected age (calendar age) for the initiation of the Younger Dryas is 12,970 yr BP, which is similar to those determined in North Atlantic sediments, glacial deposits in New Zealand, and Greenland ice cores. The corrected age for the termination of the Younger Dryas in Santa Barbara Basin is poorly constrained, due to its occurrence during the 1300-yr radiocarbon plateau, and falls between 10,900 and 12,300 yr BP. We have used an interpolated age of 11,200 yr BP.

Pairs of planktonic and benthic foraminifers separated from the same depth were also measured to determine radiocarbon age differences, presumably reflecting the age of upper intermediate waters entering the basin. The age differences vary between 40 and 740 radiocarbon yr, with smallest age differences occurring within the non-laminated Younger Dryas (based on three samples with an average $^{14}$C age difference of 90 yr) and the last glacial maximum at ~20 ka (100 yr). Paired samples in laminated sediments older and younger than the YD have an average $^{14}$C age difference of 470 yr. The decrease in surface to bottom age difference during the Younger Dryas and the last glacial maximum reflects a change in source of intermediate waters, with a greater proportion originating from a more proximal source.

## INTRODUCTION

Santa Barbara Basin Hole 893A was cored at 34°17.25'N, 120°02.2'W, 20 km south of the Santa Barbara coastline (Fig. 1) in a water depth of 588 m, recovering 196.5 m of alternating laminated and homogenous (non-laminated) sediments. Oxygen isotopic stratigraphy (Kennett, this volume) supported by assemblage changes in planktonic foraminifera (Kennett and Venz, this volume) and pollen (Heusser, this volume) indicates the presence of a continuous paleoclimatic/paleoceanographic record for the last 156,000 yr, extending from isotope Stage 6. Changes in planktonic foraminifer assemblages suggest that average sea-surface temperatures varied by ~9°C from glacial to interglacial extremes (Kennett and Venz, this volume). Pollen assemblages in the core reflect fluctuations between cold-dry pine dominated vegetation during glacials to warmer oak-dominated vegetation during interglacials (Heusser, this volume).

Within the interval datable by radiocarbon (0 to 45,000 yr, from 0 to about 100 mbsf), the lithofacies changed from intermittently laminated sequence of silty clay to non-laminated silty clay (interpreted to be late Pleistocene age), to a laminated diatom nannofossil clayey silt in the uppermost 24.2 m (Fig. 2). The radiocarbon analyses were used to provide the chronology for the upper 50 m of the core, supported by two datums from the oxygen stratigraphic (Kennett, this volume) and pollen (Heusser, this volume) investigations. An age model for Hole 893A for depths greater than 50 m is based on datums from oxygen isotopic stratigraphy (Kennett, this volume) and pollen (Heusser, this volume). In this study, we present and discuss the chronology established for Hole 893A based on accelerator mass spectrometry $^{14}$C measurements of planktonic foraminifers. We also discuss data showing the temporal variations in the planktonic-benthic radiocarbon ages differences, and interpret these variations in the context of changes in stable isotopic composition, lithofacies and biofacies, over the past 20,000 yr.

## METHODS

### Samples

Sediment samples from Hole 893A were selected from the upper 100 m of the section from Cores 146-893A-1H through -8H, for radiocarbon dating of hand-picked foraminifers. In spite of the mid-latitude location of 34°N, modern and Holocene planktonic foraminifer assemblages in Santa Barbara Basin are cool temperate in character because of the influence of the cool California Current and the upwelling of the cool intermediate waters to the west of the Southern California Borderland Province. The present-day average seasonal

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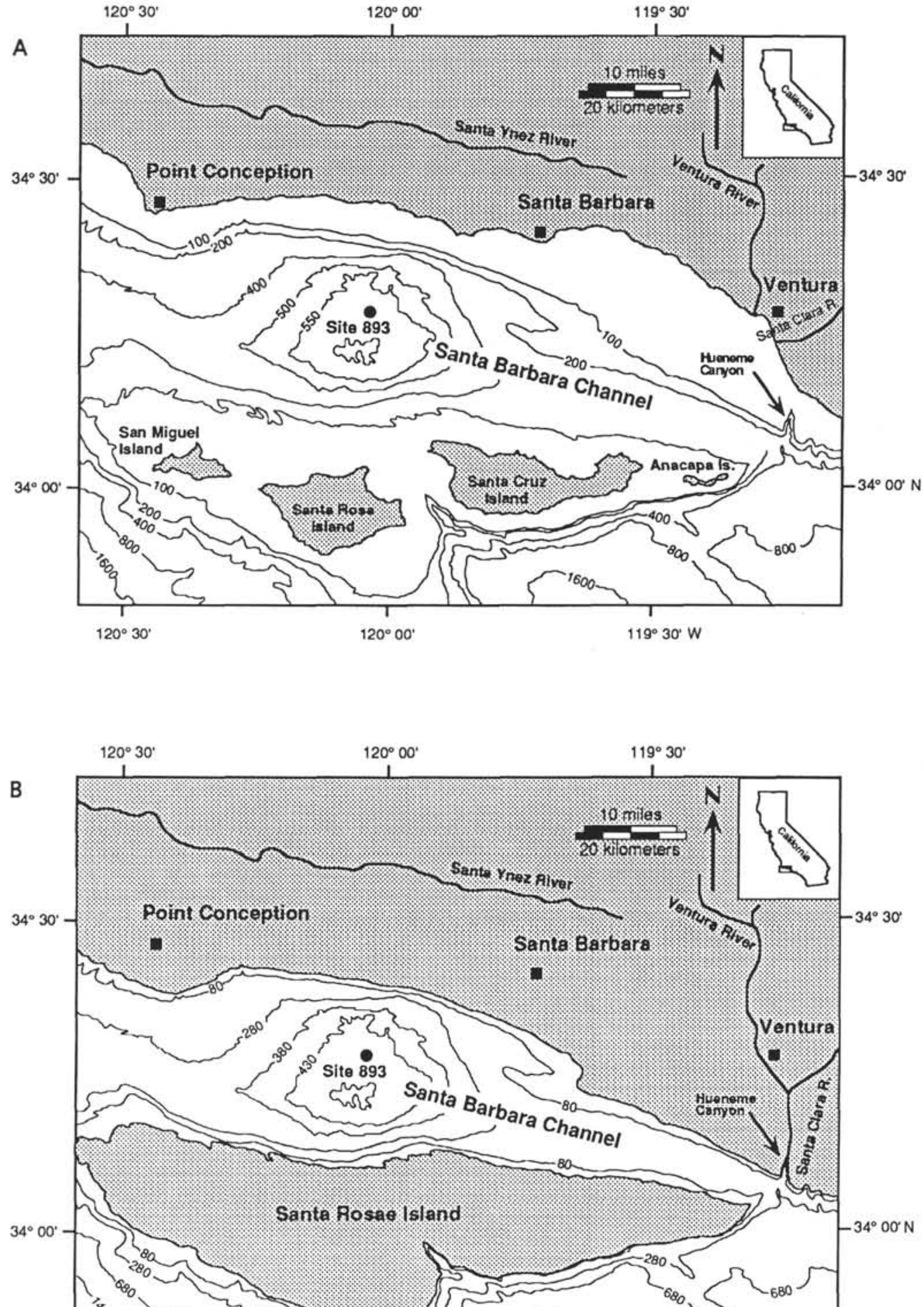


Figure 1. Location of Site 893 in Santa Barbara Basin, showing (**A**) the present-day physiography, and (**B**) the last glacial maximum, when sea level was 120 m lower 18,000 yr ago than at present.

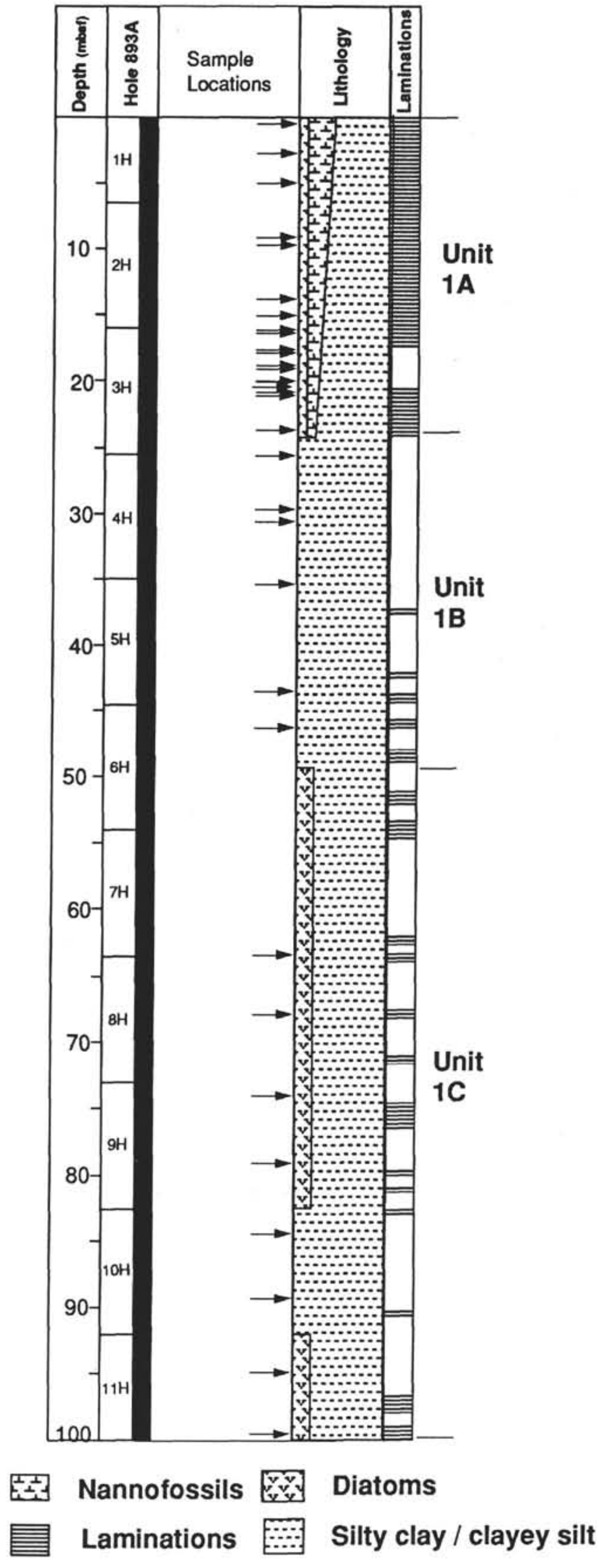


Figure 2. Stratigraphic column of upper 100 m of sediment, showing sedimentary structure (laminated vs. non-laminated), lithology, sedimentary units, and sample levels for radiocarbon analyses.

sea-surface temperature (SST) range is ~12°C to 17°C. During El Niño/Southern Oscillation (ENSO) events, which occur every several years, SSTs rise to 20°C and subtropical assemblages are transported to the Santa Barbara Basin. Planktonic foraminifer assemblages in Santa Barbara Basin are dominated by dextrally coiled *Neogloboquadrina pachyderma.* Other relatively warm forms are *Neogloboquadrina dutertrei, Globigerinoides ruber, Globorotalia inflata, Globorotalia truncatulinoides, Orbulina universa,* and several others. In distinct contrast, the glacial episodes are marked by assemblages of lower diversity, dominated by sinistrally coiled *Neogloboquadrina pachyderma.* Planktonic foraminiferal assemblages of the last glaciation in Southern California are typical of the modern Subarctic Pacific. In addition to sinistral *Neogloboquadrina pachyderma,* the assemblage contains *Globigerina bulloides, Globigerina quinqueloba,* and *Globigerinita uvula. Globigerina bulloides* and *Globigerina quinqueloba* are important species in both interglacial and glacial assemblages.

Glacial maximum benthic assemblages, indicating more highly oxygenated environments, include *Uvigerina, Epistominella, Nonionellina, Nonionella* and *Cassidulina.* In contrast, Holocene benthic assemblages are dominated by those favoring low-oxygen environments, including *Bolivina* and *Globobulimina.* The foraminifers used for radiocarbon dating were limited to those that were most abundant in the sediments. These include several species of *Bolivina, Uvigerina,* and various forms of rotalids. In all samples, there were insufficient numbers of single planktonic species for radiocarbon analyses; therefore, a mixed planktonic assemblage was required for radiocarbon dating.

The highest density of sampling was from lithologic Unit IA (Fig. 2), the upper laminated sequence of diatom nannofossil clayey silt and diatom nannofossil silty clay, at a depth of 0 to 24 mbsf. Below this Unit, six samples were analyzed from Unit IB (the upper non-laminated sequence of silty clay and clayey silt with diatom silty clay and common sand beds). Eight samples were measured from Unit IC (an intermittently laminated sequence of silty clay and diatom silty clay; Fig. 2).

Sediment samples were wet-sieved and planktonic and benthic foraminifers were picked from the >150 μm fraction. In samples with less abundant foraminifers, mixed benthics were picked for radiocarbon analyses. The foraminifers were generally well-preserved, although many were filled with pyrite aggregates (Kennett, this volume). Sample size ranged from 1.4 to 16.0 mg. The larger samples (≥8.0 mg) were split for duplicate analyses.

To calibrate and correct the radiocarbon ages for reservoir effects, radiocarbon ages of mussel shells (*Mytilus californianus*) collected in the Santa Barbara Basin prior to bomb testing (pre-1950) were determined (with D. J. Kennett, Dept. of Anthropology, University of California, Santa Barbara). We assume *Mytilus* radiocarbon content reflects that in surface waters.

## Laboratory Methods

Carbonate samples were weighed, placed in a 10-mL vacutainer, and evacuated. After evacuation to below 20 milliTorr pressure, 0.5 mL of phosphoric acid was added to the vacutainer with a syringe, and the sample was reacted for 30 to 60 min at 90°C to generate $CO_2$.

Reactors were preconditioned for graphitization by heating (at 400°C) 3 to 4 mg Co catalyst powder and $H_2$ gas (at a pressure of about 750 Torr) in Pyrex or supracil quartz reactor tubes for 60 min. Following preconditioning, the $CO_2$ sample was purified (i.e., non-condensibles such as nitrogen removed) cryogenically in a dry ice-isopropanol slurry water trap. The $CO_2$ sample was transferred frozen into the reactor chamber and reacted with twice the $CO_2$ volume of $H_2$ gas at 575°C for 5 hr, to reduce the $CO_2$ to graphite (see Vogel et al., 1987). $^{14}C/^{12}C$ ratios were measured by accelerator mass spectrometry at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory (Davis et al., 1990). We

**Table 1. Radiocarbon dates (yr) for benthic and planktonic foraminifer samples (with age uncertainties ± years), void-corrected depths (mbsf), and corrected ages (years before present) for planktonic foraminifers.**

| Sample (cm) | Corrected depth (mbsf) | $^{14}C$ age benthic | ± (yrs) | Average benthic $^{14}C$ age | $^{14}C$ age planktonic | ± (yrs) | Average planktonic $^{14}C$ age | Average planktonic $^{14}C$ age −825 | Corrected age Bard (1) $R(t) = 825$ | Corrected age Bard (2) $R(t) = 825$ | Corrected age S. & B. | B–P (yrs) | ± (yrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 146-893A- | | | | | | | | | | | | | |
| 1H-1, 79–82 | 0.79 | 1590 | 60 | 1570 | — | — | — | — | — | — | — | — | — |
| | | 1550 | 60 | — | — | — | — | — | — | — | — | — | — |
| 1H-1, 55–57 | 1.55 | 2430 | 50 | 2430 | 1850 | 60 | 1850 | 1025 | — | — | 950 | 580 | 80 |
| 1H-3, 63–66 | 3.63 | 3000 | 60 | 3000 | 2520 | 70 | 2520 | 1695 | — | — | 1670 | 480 | 90 |
| 1H-4, 117–120 | 5.67 | 4130 | 80 | 4130 | 3460 | 60 | 3555 | 2730 | — | — | 2780 | 670 | 100 |
| | | | | | 3650 | 70 | | | | | | | |
| 2H-1, 55–57 | 7.04 | 5210 | 50 | 5210 | 4800 | 50 | 4800 | 3975 | — | — | 4510 | 390 | 70 |
| 2H-2, 71–74 | 8.71 | 6570 | 150 | 6570 | 6200 | 70 | 6200 | 5375 | — | — | 6190 | 370 | 170 |
| 2H-3, 48–51 | 9.89 | 7560 | 120 | 7560 | — | — | — | — | — | — | — | — | — |
| 2H-4, 105–107 | 11.77 | 8570 | 70 | 8570 | 8300 | 90 | 8235 | 7410 | — | — | 8230 | 335 | 115 |
| | | | | | 8170 | 70 | | | — | — | | | |
| 2H-6, 48–51 | 13.91 | 9230 | 150 | 9230 | 9150 | 150 | 9050 | 8225 | — | — | 9340 | 130 | 215 |
| | | | | | 9050 | 90 | | | — | — | | | |
| 2H-6, 55–57 | 13.98 | — | — | — | 9180 | 80 | 9180 | 8355 | — | — | 9400 | — | — |
| 2H-7, 8–11 | 15.00 | 9540 | 90 | 9595 | — | — | — | — | — | — | | | |
| | | 9650 | 90 | | | | | | — | — | | | |
| 3H-1, 6–8 | 16.06 | 10860 | 110 | 10860 | 10160 | 70 | 10160 | 9335 | — | — | 10659 | 700 | 130 |
| 3H-1, 55–57 | 16.52 | 19670 | 110 | 10670 | 10300 | 80 | 10300 | 9475 | — | — | | 370 | 135 |
| 3H-, 87–90 | 16.84 | 10630 | 70 | 10630 | 10280 | 70 | 10280 | 9455 | 10812 | 10884 | 10790 | 350 | 100 |
| 3H-1, 99–102 | 16.96 | 10890 | 90 | 10890 | 10170 | 70 | 10170 | 9345 | 10672 | 10748 | 10470 | 720 | 115 |
| 3H-2, 11–14 | 17.58 | — | — | — | 10720 | 90 | 10720 | 9895 | 11374 | 11430 | 11310 | | |
| | | | | | 10780 | 170 | | | | | | | |
| | | | | | 10660 | 90 | | | | | | | |
| 3H-2, 13–16 | 17.60 | — | — | — | 10630 | 90 | 10630 | 9805 | 11260 | 11318 | 11060 | | |
| 3H-2, 113–115 | 18.60 | 11290 | 100 | 11290 | 11180 | 180 | 11180 | 10355 | 11959 | 12000 | — | 110 | 205 |
| 3H-2, 128–131 | 18.75 | — | — | — | 11070 | 220 | 11070 | 10245 | 11820 | 11864 | — | — | — |
| 3H-3, 98–101 | 19.91 | 11740 | 320 | 11740 | — | — | — | — | — | — | — | — | — |
| 3H-3, 112–115 | 20.05 | 11950 | 110 | 11950 | 11830 | 290 | 11830 | 11005 | 12781 | 12806 | — | 120 | 310 |
| 3H-3, 147–150 | 20.40 | 12020 | 100 | 12020 | 11980 | 180 | 11980 | 11155 | 12971 | 12992 | — | 40 | 205 |
| 3H-5, 9–12 | 21.94 | 12820 | 80 | 12820 | 12350 | 60 | 12350 | 11525 | 13436 | 13451 | — | 470 | 100 |
| 3H-6, 96–99 | 24.12 | 13580 | 100 | 13580 | 13130 | 120 | 13130 | 12305 | 14411 | 14418 | — | 450 | 160 |
| 4H-1, 8–11 | 25.58 | 15190 | 150 | 15190 | 14630 | 120 | 14630 | 13805 | 16267 | 16278 | — | 560 | 190 |
| 4H-2, 5–7 | 26.80 | 15530 | 250 | 15530 | 15210 | 150 | 15210 | 14385 | 16978 | 16997 | — | 320 | 290 |
| 4H-3, 57–60 | 28.73 | 16270 | 180 | 16270 | 15720 | 140 | 15720 | 14895 | 17599 | 17630 | — | 550 | 228 |
| 4H-4, 3–5 | 29.61 | — | — | — | 16260 | 190 | 16260 | 15435 | 18254 | 18299 | — | | |
| 4H-4, 90–93 | 30.34 | 17200 | 100 | 17200 | 16820 | 180 | 16820 | 15995 | 18929 | 18994 | — | 380 | 205 |
| 4H-5, 57–60 | 31.39 | 17510 | 100 | 17510 | 17410 | 150 | 17410 | 16585 | 19637 | 19725 | — | 100 | 180 |
| 4H-5, 73–76 | 31.52 | 17640 | 120 | 17690 | 18380 | 680 | 18380 | 17555 | 20792 | 20928 | — | −740 | 690 |
| | | 17740 | 130 | | | | | | | | | | |
| 5H-1, 11–14(r) | 35.11 | 20430 | 220 | 20430 | — | — | — | — | — | — | | | |
| 5H-1, 11–14(u) | 35.11 | 20410 | 220 | 20410 | — | — | — | — | — | — | | | |
| 5H-7, 11–14 | 43.18 | 26080 | 320 | 26080 | 25470 | 240 | 25470 | 24645 | 28896 | 29720 | — | 610 | 400 |
| 6H-2, 48–51 | 45.96 | 29990 | 530 | 29990 | — | — | — | — | — | — | — | — | — |
| 8H-2, 27–30 | 63.92 | 41160 | 3130 | 41160 | — | — | — | — | — | — | — | — | — |
| | | 21500 | 480 | — | — | — | — | — | — | — | — | — | — |
| 8H-5, 32–35 | 67.54 | 30430 | 630 | — | — | — | — | — | — | — | — | — | — |
| | | 41480 | 1760 | 41480 | — | — | — | — | — | — | — | — | — |
| 9H-2, 52–55 | 74.74 | >39600* | — | — | — | — | — | — | — | — | — | — | — |
| | | >38100* | — | — | — | — | — | — | — | — | — | — | — |
| 9H-5, 101–103 | 79.12 | >38100* | — | — | — | — | — | — | — | — | — | — | — |
| 10H-2, 100–102 | 84.86 | >38200* | — | — | — | — | — | — | — | — | — | — | — |
| 10H-6, 0–2 | 89.88 | >40500* | — | — | — | — | — | — | — | — | — | — | — |
| 11H-3, 18–21 | 95.07 | >45700* | — | — | — | — | — | — | — | — | — | — | — |
| | | >41000* | — | — | — | — | — | — | — | — | — | — | — |
| 11H-6, 129–132 | 99.70 | >38200* | — | — | — | — | — | — | — | — | — | — | — |

Notes: Three correction methods were used, as indicated in text. The benthic-planktonic $^{14}C$ age differences are indicated by B–P. * = radiocarbon content in sample same as background level; thus, represents a minimum age.

assumed a $^{13}C/^{12}C$ ratio of 0‰ in the calculation of the $^{14}C/^{13}C$ ratio in correcting for mass-dependent fractionation. The conventional radiocarbon ages were determined by calculating the ratio of normalized sample activity to the activity of an NBS standard (ox-1) that represents atmospheric $^{14}C$ activity of the late 19th century. The ratio was then converted to a conventional $^{14}C$ age using the radioactive decay law, following the conventions in Stuiver and Polach (1977).

## RESULTS AND DISCUSSION

### Radiocarbon Ages

Samples from 35 depth intervals were analyzed. The samples consisted of planktonic and/or benthic foraminifers (depending on availability and sample size), as listed in Table 1. The more abundant samples were measured in duplicate, and the average of the two analyses were used. In determining sediment ages, only the planktonic radiocarbon ages were used, because these are less affected by radiocarbon-depleted intermediate waters. The radiocarbon ages ranged from 1570 yr at 0.79 mbsf to 41,480 yr at 67.54 mbsf for benthic foraminifers, and 2520 yr at 3.63 mbsf to 25,470 yr at 43.18 mbsf for planktonic foraminifers. The samples from ≥74.74 mbsf had radiocarbon contents close to background, and thus only minimum ages could be determined. The ages from these samples (74.74 to 99.70 mbsf) had minimum radiocarbon ages of 38,100 to 45,700 yr before present (Table 1). Two samples (from 63.92 and 67.54 mbsf), both measured in duplicate, had inconsistent ages. For these samples, we assume the older age is correct, and the sample with the much younger age probably was contaminated with modern carbon. One sample (146-893A-5H-1, 11–14 cm), from 35.11 mbsf, contained enough foraminifers to allow selection of two benthic genera (*Uvigerina* and *Epistominella*). The radiocarbon ages were essentially identical; the sample of *Epistominella* had a $^{14}C$ age of 20,430 ±220 radiocarbon yrs, and *Uvigerina* had a $^{14}C$ age of 20,410 ±220 radiocarbon yrs (Table 1).

## Radiocarbon Age Calibration

Radiocarbon ages deviate from calendar ages due to variations in the initial atmospheric $^{14}C$ activity with time. In addition, there is an offset between the $^{14}C$ activity in the marine reservoir compared with the atmospheric reservoir, expressed as the reservoir $^{14}C$ age, $R(t)$ (Stuiver and Braziunas, 1993). Variations in atmospheric $^{14}C$ are caused by changes in $^{14}C$ production rate due to solar wind modulation, changes in the geomagnetic dipole intensity, or redistribution of $^{14}C$ between carbon reservoirs induced by climate change (Stuiver, 1990). The calibration of the atmospheric $^{14}C$ ages over the past 10,500 yr has been achieved by high-precision radiocarbon dating of wood dated independently by dendrochronology (tree ring counting). A similar calibration curve has been derived for marine samples, by calculating the response of the world oceans to these atmospheric $^{14}C$ variations (Stuiver and Braziunas, 1993).

Ocean surface water in the Northern Hemisphere has a reservoir age of 400 years (Stuiver et al., 1986). However, regional differences in $^{14}C$ activity (expressed as $\Delta R$) reflect oceanic mixing and circulation processes (Stuiver and Braziunas, 1993).

Secular variations in $\Delta R$ are determined by radiocarbon measurements of intertidal molluscan shells of known age collected prior to bomb $^{14}C$ input in 1950 (Stuiver et al., 1986; Robinson, 1981). Large values of $\Delta R$ may be caused by coastal upwelling of $^{14}C$-deficient water. For example, along northern coastal California, an average $\Delta R$ of 225 has been attributed to wind-driven upwelling of Pacific Intermediate Water (Stuiver et al., 1986). However, various studies indicate that the $\Delta R$ values along the California coast are extremely variable, with values as great as 500 years (Bouey and Basgall, 1991).

For the Santa Barbara Basin, radiocarbon ages of mussel shells (*Mytilus californianus*) collected from Santa Barbara Channel prior to 1950 range between 720 and 960 yr, with an average of 825 yr (B.L. Ingram and D.J. Kennett, unpubl. data). The average corresponding $\Delta R$ of 425 yr is used for age calibrations in this study.

Because this value of $\Delta R$ can only be determined reliably in historically collected shells of known age, one must assume that it remains constant over time. However, various studies and climate modeling indicate that upwelling rates have varied significantly over at least the past 18,000 years (van Geen et al., 1992; COHMAP Members, 1988). As discussed previously (Robinson, 1981; Stuiver et al., 1986; Stuiver and Braziunas, 1993), changes in upwelling rates and ocean circulation would affect the amount of $^{14}C$-depleted water brought to the surface in coastal regions. Determining temporal changes in the value of $\Delta R$ requires knowledge of the content in the marine and atmospheric reservoir, such as radiocarbon measurements of coexisting organic carbon (that would represent the atmospheric reservoir), and marine carbonate (representing the marine reservoir). We are presently measuring the radiocarbon ages of closely associated charcoal and marine shell from stratified archeological deposits (shell mounds) from San Miguel Island in the Santa Barbara Basin to assess changes in reservoir age throughout the Holocene (with D.J. Kennett and J. Erlandson).

Three different age calibration methods were used to convert the radiocarbon ages to calendar ages, indicated as corrected age in Table 1. In the first, we used the marine calibration curve based on tree ring dendrochronology and modeling of atmospheric $^{14}C$ changes in the ocean discussed above (Stuiver and Braziunas, 1993; denoted as S.&B. in Table 1). This calibration curve applies only to samples with radiocarbon ages between 0 and 10,500 yr before present. The other calibration methods were developed by Bard et al. (1990a, 1990b, 1993, and pers. comm., 1992), based on $^{14}C$ and $^{230}Th$ age determinations in corals (the $^{230}Th$ ages represent the actual calendar ages of the sample), which yielded two equations:

$$[\text{Corrected age (yr BP)} = -5.85 \times 10^{-6}[^{14}\text{C age} - R(t)] + 1.39[^{14}\text{C age} - R(t)] - 1807] \quad (1)$$

$$[\text{Corrected age (yr BP)} = 1.24\,(^{14}\text{C age} - R(t)) - 840]. \quad (2)$$

The first equation is denoted as Bard (1) in Table 1, and the second as Bard (2). The two equations yielded essentially identical corrected ages (Table 1). We have arbitrarily chosen the ages from the Bard (1) equation for plotting our results.

A near-linear sedimentation rate of 14.53 cm/100 yr is determined using these corrected ages (with the Bard(1) equation) and their depths (Fig. 3). The corrected ages are in excellent agreement with a chronology based on paleoclimatic history from changes in planktonic foraminiferal assemblages and pollen (Kennett, Baldauf, et al., 1994).

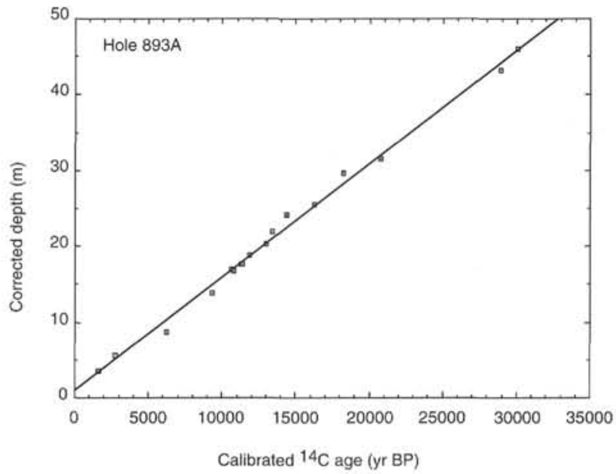


Figure 3. Corrected radiocarbon ages of planktonic foraminifers, plotted against depth (mbsf) corrected for all gaps resulting from sediment displacement due to gas expansion.

## Younger Dryas Event

In Santa Barbara Basin, the Younger Dryas cooling event, as clearly reflected by increased oxygen isotope values (Kennett, this volume) and in cooler planktonic foraminiferal assemblages (Kennett and Venz, this volume), is associated with a non-laminated (bioturbated) interval within the uppermost laminated sequence (Subunit 1A), between 17.60 and 20.40 mbsf (Fig. 2). A high-resolution chronology for the Younger Dryas event was established with radiocarbon dating of six planktonic foraminifer samples within and bracketing the non-laminated interval. Radiocarbon ages within non-laminated interval range between 11,980 ± 180 yr and 10,630 ± 90 yr (Table 1). To compare these radiocarbon ages with other Younger Dryas radiocarbon ages of either marine or terrestrial deposits, the local reservoir age (825 yr) must be subtracted (to yield a "reservoir corrected" radiocarbon age). The "reservoir corrected $^{14}C$ age" for the beginning and end of the Younger Dryas in Santa Barbara Basin is 11,155 to 9,805 yr. This "reservoir corrected" $^{14}C$ age for the beginning of the Younger Dryas (11,155 yr) is the same as that obtained by Denton and Hendy (1994) for wood samples in glacial deposits from New Zealand, which shows the beginning of the Younger Dryas to be 11,050 yr BP. It is also the same as the reservoir-corrected $^{14}C$

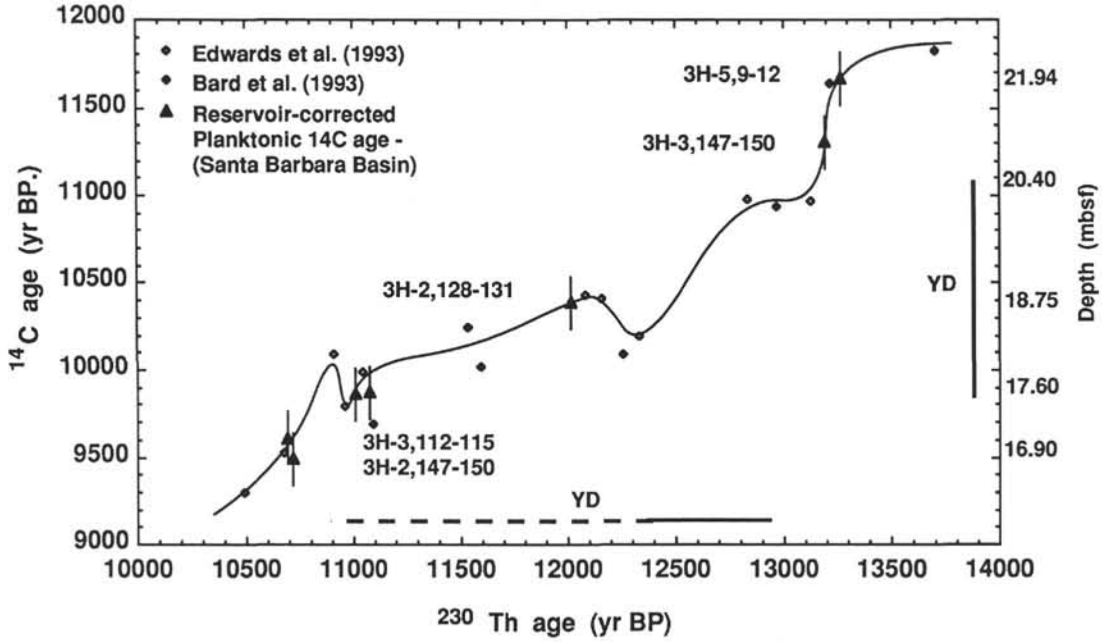


Figure 4. Plot of $^{14}C$ ages (from 9,000 to 12,000 yr) and $^{230}Th$ ages from corals, showing 1300-yr plateau. Samples from within and close to the Younger Dryas (YD) interval of Santa Barbara Basin are also plotted. The radiocarbon ages are reservoir-corrected (825 years subtracted).

dates from the North Atlantic Ocean (11,200 to 11,010 $^{14}C$ yr BP) from cores SU81-18 (Duplessy, 1989) and Troll 3.1 (Lehman and Keigwin, 1992).

Calibrated age (or calendar-year age) for the initiation of the Younger Dryas event in Santa Barbara Basin is 12,970 yr BP. The calibrated age for the termination of the Younger Dryas in Santa Barbara Basin is poorly constrained, due to its occurrence during the 1300-yr radiocarbon plateau (Fig. 4), and falls between 10,900 and 12,300 yr BP. This plateau has been defined by Bard et al. (1993), Edwards et al. (1993), and Gray et al. (1993), as illustrated with a plot of the "reservoir corrected" radiocarbon ages of the planktonic foraminifers from the Younger Dryas event with $^{230}Th$ and radiocarbon ages of corals measured by Bard et al. (1993) and Edwards et al. (1993; Fig. 4). We have used an interpolated age of 11,200 yr BP for the end of the Younger Dryas.

The ages for the Younger Dryas in Santa Barbara Basin agree well with those based on counting annual layers in ice cores, which indicate the Younger Dryas occurred between 12,940 ± 260 yr BP to 11,640 ± 250 yr BP (Alley et al., 1993; Johnsen et al., 1992). The duration of the Younger Dryas in Santa Barbara is between 670 and 2070 years (we show 1,730 years), not inconsistent with the 1300-yr duration counted in ice core layers.

## Planktonic-benthic Radiocarbon Age Differences

Differences in radiocarbon age between surface and bottom waters in Santa Barbara Basin is recorded in paired planktonic-benthic foraminifers from the same depth interval in the core. The benthic foraminifers, which calcified their tests at depths from 576.5 to 455.5 m during the late Quaternary, acquired carbon from dissolved bicarbonate in Pacific Intermediate Water, which in the easternmost part of the North Pacific is depleted in $^{14}C$. This $^{14}C$ depletion results from a large component of Pacific Deep Water that in part was originally derived from the North Atlantic as North Atlantic Deep Water (NADW) (Broecker and Peng, 1982). Radiocarbon measurements in the Pacific (in the Geochemical Ocean Section Study, or GEOSECS), describing the major Pacific water masses, show that in the eastern Pacific, the water with the lowest $\Delta^{14}C$ (or "oldest" water) occurs at 2000 to 3000 m depth (plate 2 in Ostlund and Stuiver, 1980). Water entering Santa Barbara Basin, at a depth of 500 to 600 m, has $\Delta^{14}C$ values of −150‰ to −160‰, with a corresponding radiocarbon age of 1200 to 1300 yrs (Ostlund and Stuiver, 1980). In contrast, the surface mixed layer in Santa Barbara Basin has an average $^{14}C$ age of 825 years (see discussion above). This water is composed largely of California Current Water containing dissolved $CO_2$ from atmospheric exchange, as well as upwelled Pacific Intermediate Water. Surface waters of Santa Barbara Basin also have a component of surface subtropical waters transported northward in the Davidson Countercurrent. The modern benthic-planktonic $^{14}C$ age difference should be about 375 to 475 yrs.

Changes in the planktonic-benthic age difference with time may reflect changes in the rate of oceanic thermohaline circulation affecting the North Pacific and/or changes in the strength of Pacific Intermediate Water, which determines the $^{14}C$ age of upper intermediate waters entering Santa Barbara Basin. For example, a decrease in the proportion of distal waters derived indirectly from the North Atlantic, with a corresponding increase in the proportion of more proximal Antarctic Intermediate Water or water derived from high latitudes in the northwest Pacific, should cause a decrease in the benthic-planktonic $^{14}C$ age difference.

The benthic-planktonic age difference measured in samples with corrected ages of 29,000 years and younger varies between 40 and 720 years (Table 1; Fig. 5). In general, the average benthic-planktonic age difference in the laminated sediments is 480 years. Several lines of evidence indicate that sedimentary changes in Hole 893A reflect major changes in ocean circulation between glacial and interglacial episodes, including the Younger Dryas event (Kennett and Ingram, this volume; Behl, this volume). Glacial to near glacial sediments (as well as the Younger Dryas cool event) are non-laminated, while sediments deposited during interglacials and interstadials are dominantly laminated. Well-laminated Santa Barbara Basin sediments are a result of suboxic (<0.1 mL/L oxygen) bottom waters in the basin below ~475 m, combined with highly productive surface waters which generate abundant organic material that consumes the

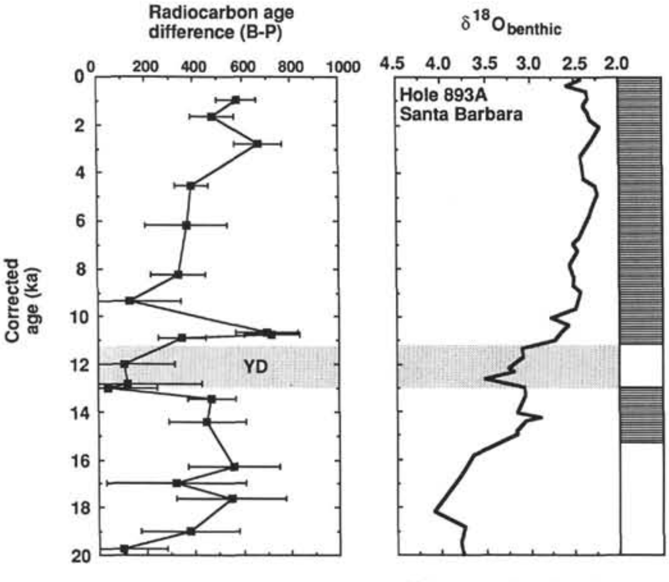


Figure 5. Benthic-planktonic age differences ($^{14}C$ years) plotted against corrected age, also showing laminated and non-laminated intervals for the last 20 k.y. in Hole 893A. Oxygen isotope variations in benthic foraminifers also shown to illustrate association of radiocarbon age difference (B–P) changes with Younger Dryas (YD) cool interval and last glacial maximum (from Kennett, this volume). The Younger Dryas interval is shaded.

small supply of oxygen that enters the basin (Kennett, Baldauf, et al., 1994). The presence of persistent laminations associated with low oxygen conditions is confirmed by the presence of benthic foraminiferal assemblages typical of very low-oxygen environments (Kennett, Baldauf, et al., 1994). More detailed sampling of the laminated and non-laminated intervals for planktonic-benthic radiocarbon measurements is currently underway.

We selected three paired planktonic-benthic foraminifer samples from the Younger Dryas for radiocarbon dating to determine if changes existed in surface to bottom water age differences between the event and the surrounding laminated sediments, that might be associated with the inferred changes in bottom water oxygen content. The radiocarbon age differences from these pairs are 40, 110, and 120 yr (averaging 90 yr; Fig. 5), with age uncertainties between 200 and 300 yr (Table 1; Fig. 5). The radiocarbon age differences between planktonic and benthic foraminifers in the Younger Dryas are much smaller than those in laminated sediments above and below in the core, by ~400 yr (the average benthic-planktonic age difference in laminated sediment above and below the Younger Dryas event is 480 yr; Fig. 5). This decrease in benthic-planktonic age difference correlates with the positive oxygen isotopic excursion present in both benthic and planktonic foraminiferal $\delta^{18}O$ records (Fig. 5).

Although initially thought to have been restricted to high latitudes of the North Atlantic Ocean and adjacent continental areas, Younger Dryas cooling and associated oceanographic changes were global, data indicate (e.g., Flower and Kennett, 1990; Molfino and McIntyre, 1990; Keigwin and Jones, 1990; Linsley and Thunell, 1990; Kennett, Baldauf, et al., 1994; Denton and Hendy, 1994). A similar non-laminated interval within laminated sediments was found from Deep Sea Drilling Project (DSDP) Site 480 (Guaymas Basin, Gulf of California), with $^{14}C$ ages within a non-laminated interval of 10,800 to 10,300 yr BP (Keigwin and Jones, 1990), which are within the range of radiocarbon ages reported here (11,980 and 10,630 yr BP).

The cause for the change in sedimentary facies within the Younger Dryas is inferred to be largely related to an increase in oxygen content of intermediate waters entering the basin (Kennett, Baldauf et al., 1994; Kennett and Ingram, this volume), such as illustrated in Figure 6. Increased oxygenation (or ventilation) of intermediate waters may have resulted indirectly from decreased flux of NADW to the world's oceans. Changes in benthic foraminifer assemblages (Schnitker, 1979), Cd/Ca ratios in benthic foraminifers (Boyle and Keigwin, 1987), and carbon isotopic composition of benthic foraminifers (Duplessy et al., 1988) in North Atlantic sediments suggest that glacial to near-glacial episodes are marked by a substantial decrease in production of North Atlantic Deep Water and related weakening of the Atlantic's conveyor circulation. The reduction in flow of waters originally derived from the North Atlantic to the North Pacific would have resulted in greater influence in offshore California of intermediate waters from more proximal sources (Kennett and Ingram, this volume). The origin of such a source of intermediate waters in unclear. During cooler episodes, the well-oxygenated upper intermediate waters influencing Santa Barbara Basin may have been from the Antarctic or the northwest Pacific region (Keigwin, 1987; Keigwin et al., 1992; Ohkouchi et al., 1994). The observed decrease in the planktonic to benthic $^{14}C$ age difference in Santa Barbara Basin reported here is consistent with a major switch in sources of intermediate waters that changed the ventilation of Santa Barbara Basin between interglacial and glacial episodes.

Edwards et al. (1993) report a large offset in $^{14}C/^{12}C$ and $^{230}Th$ ages in corals from the Huon Peninsula (Papua New Guinea) during the Younger Dryas, presumably due to a 15% drop in atmospheric $^{14}C/^{12}C$. The coral record also indicates a reduction in the rate of sea level rise (from reduced melting), which Edwards et al. (1993) argued should have *increased* the rate of ocean ventilation as a result of changes in the North Atlantic during the latter part of the Younger Dryas. We cannot rule out the possibility that a lowering of atmospheric $^{14}C/^{12}C$ may have caused the decrease in planktonic-benthic $^{14}C$ age difference by decreasing the $^{14}C/^{12}C$ in surface water. However, increased Younger Dryas deep ocean ventilation is not supported by the sequence of changes in benthic faunas, lithofacies and radiocarbon ages in Santa Barbara Basin. Furthermore, our data show that the reduced radiocarbon age occurred in the benthic rather than the planktonic foraminifers. This indicates that the changes in planktonic-benthic $^{14}C$ age difference resulted from changes in intermediate rather than surface waters in Santa Barbara Basin.

## CONCLUSIONS

High-resolution radiocarbon measurements of planktonic and benthic foraminifers from Hole 893A provide the chronology for the upper 70 m of the core. Radiocarbon ages were corrected to calendar ages using two calibration techniques, which gave similar results. One was based on tree-ring calibration and the other based on U-Th dating of corals. Ages of planktonic foraminifers ranged between 25,470 ± 240 radiocarbon yr (corrected age of 28,896 yr BP) from a depth of 43.18 mbsf, to 1850 ± 60 radiocarbon yr (corrected age of 950 yr BP) from a depth of 1.55 mbsf, assuming a reservoir age in Santa Barbara Basin of 825 yr. A total of 43 samples was analyzed between these two levels, exhibiting a near linear sedimentation rate of 14.53 cm/100 yr.

The Younger Dryas cooling event, represented in Santa Barbara Basin by a non-laminated interval within laminated sediments (17.60 to 20.40 mbsf), was dated using six planktonic foraminifer samples. Radiocarbon ages for the event are 11,980 to 10,630 yr BP. The corrected age for the initiation of the Younger Dryas is 12,970 yr BP, which is similar to initiation ages determined in the North Atlantic deep sea sediments, glacial deposits in New Zealand, and Greenland ice cores. The corrected age for the termination of the Younger Dryas in Santa Barbara Basin is poorly constrained, due to its occurrence during the 1300-yr radiocarbon plateau, and falls between 10,900 and 12,300 yr BP. We have used an interpolated age of 11,200 yr BP.

Planktonic-benthic $^{14}C$ age difference pairs were measured to determine changes in the source of Pacific intermediate waters entering

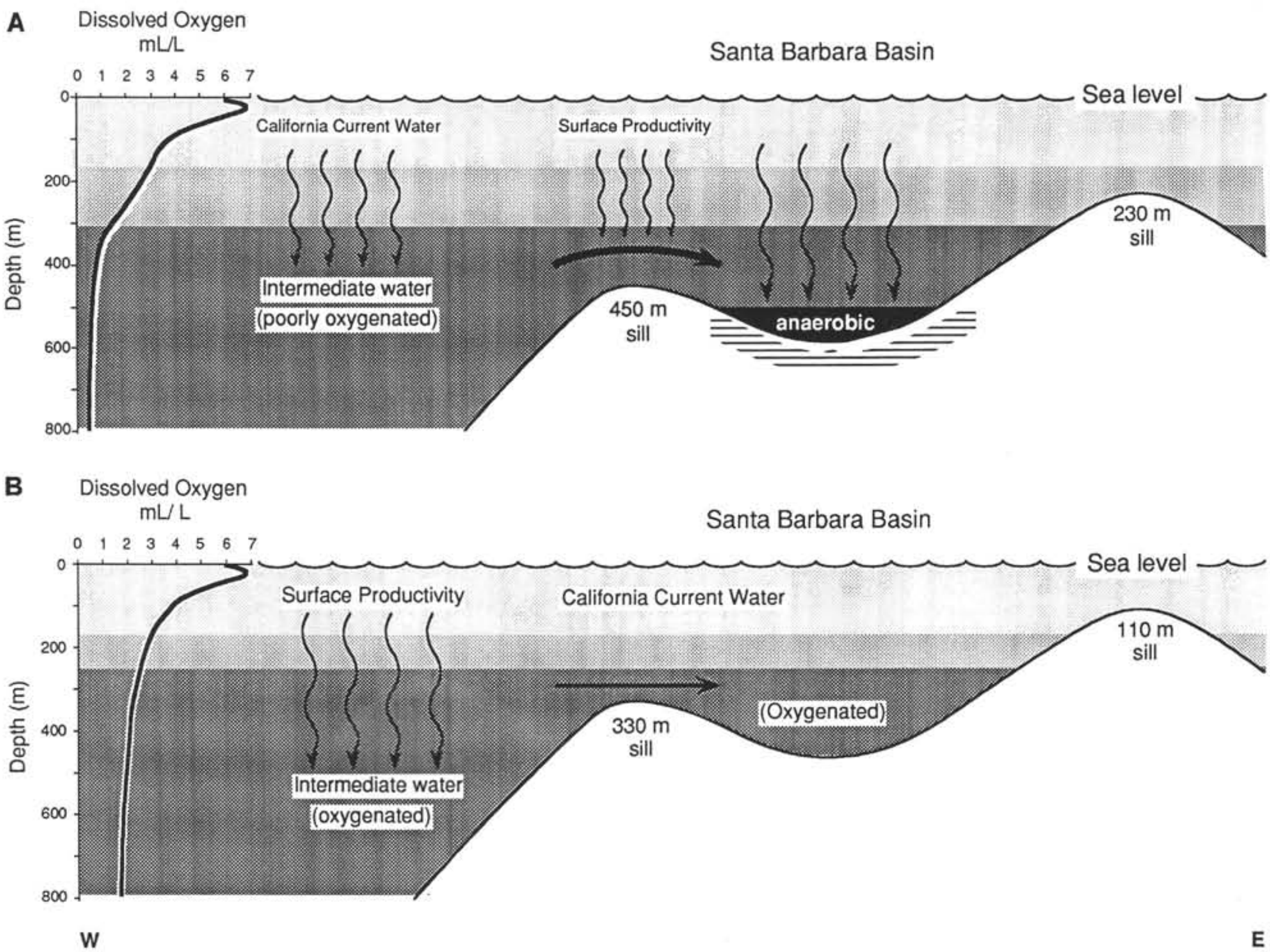


Figure 6. Schematic diagram illustrating mechanisms for changing oxygen content (ventilation) in Santa Barbara Basin during the latest Quaternary and resulting oscillations between (**A**) laminated sedimentary facies during warmer intervals (Bølling/Allerød and Holocene), and (**B**) non-laminated sedimentary facies during cool intervals (last glacial maximum and Younger Dryas).

Santa Barbara Basin. The age differences vary between 40 and 740 radiocarbon yr, with smallest age differences (averaging 90 yr) occurring during the Younger Dryas cooling event. The average $^{14}C$ age difference in laminated sediments older and younger than the Younger Dryas is 470 yr, which is similar to the modern value.

The decrease in planktonic-benthic foraminifer $^{14}C$ age difference during the Younger Dryas and the last glacial maximum appears to reflect a change in source of Pacific intermediate waters, with a greater proportion originating from a more proximal source. This is consistent with Cd/Ca and stable isotope studies of North Atlantic deep sea sediments indicating decreased production of North Atlantic Deep Water during these intervals.

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