

Ventilation changes in the northeast Pacific during the last deglaciation

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Abstract. Under present climate conditions, convection at high latitudes of the North Pacific is restricted to shallower depths than in the North Atlantic. To what extent this asymmetry between the two ocean basins was maintained over the past 20 kyr is poorly known because there are few unambiguous proxy records of ventilation from the North Pacific. We present new data for two sediment cores from the California margin at 800 and 1600 m depth to argue that the depth of ventilation shifted repeatedly in the northeast Pacific over the course of deglaciation. The evidence includes benthic foraminiferal Cd/Ca, $^{18}\text{O}/^{16}\text{O}$, and $^{13}\text{C}/^{12}\text{C}$ data as well as radiocarbon age differences between benthic and planktonic foraminifera. A number of features in the shallower of the two cores, including an interval of laminated sediments, are consistent with changes in ventilation over the past 20 kyr suggested by alternations between laminated and bioturbated sediments in the Santa Barbara Basin and the Gulf of California [Keigwin and Jones, 1990; Kennett and Ingram, 1995; Behl and Kennett, 1996]. Data from the deeper of the two California margin cores suggest that during times of reduced ventilation at 800 m, ventilation was enhanced at 1600 m depth, and vice versa. This pronounced depth dependence of ventilation needs to be taken into account when exploring potential teleconnections between the North Pacific and the North Atlantic.

Introduction

The North Pacific is ventilated today at relatively shallow depths by cooling and mixing in the Sea of Okhotsk and the Gulf of Alaska [Reid, 1965; Warren, 1983; Van Scoy *et al.*, 1991; Talley, 1991]. The signature of this process is readily followed as a broad salinity minimum across the North Pacific that reflects the low salinity of high-latitude source waters. The depth of this feature increases from 500 to 900 m from east to west (Figures 1a and 1b). Low salinities in the northeast Pacific extend to the surface because of the entrainment of fresh high-latitude water into the broad, southward flowing California Current. There is also a pronounced oxygen minimum (nutrient maximum) in the northeast Pacific centered around 800 m depth (Figure 1c) due, at least in part, to advection from the south of low-oxygen, high-nutrient water of equatorial origin. The distribution of salinity off California suggests that northern source waters weaken or partially ventilate the oxygen minimum zone (OMZ) today. Fluctuations in water temperature (5.5°-6.5°C), salinity (34.1-34.3), and oxygen content (15-30 μM) at 500 m depth recorded

by the California Cooperative Fisheries Investigation (CalCoFI) program at Station 80.60 (Figure 2) since the 1950s indicate that the contributions from northern and southern sources to this convergence zone vary both seasonally and interannually [Lynn and Simpson, 1987]. There is also evidence that ventilation of the North Pacific at intermediate depths is sensitive to large-scale climate variability such as the El Niño/Southern Oscillation [Van Scoy and Druffel, 1993]. The delicate balance between contributions of northern and southern source waters at the depth of the OMZ today provides a context for interpreting changes in circulation on 10^3 -year timescales recorded by two cores from the California margin.

Changes in ventilation during deglaciation at these sites were recorded by four proxy-indicators. The first indicator is provided by finely laminated sections reflecting bottom water oxygen levels below 10 μM that prevent bioturbation by macrofauna. Such conditions are akin to bottom waters of the Santa Barbara Basin and the oxygen minimum of the Gulf of California today [Keigwin and Jones, 1990; Kennett and Ingram, 1995]. A second indicator of ventilation used in this study is radiocarbon. Under present climate conditions, the highest water-column radiocarbon ages in the ocean are measured in the northeast Pacific between 2 and 3 km depth, indicating that this water mass has been isolated longest from the atmosphere (Figure 3a). At Geochemical Ocean Sections Study (GEOSECS) Station 201 off California, the

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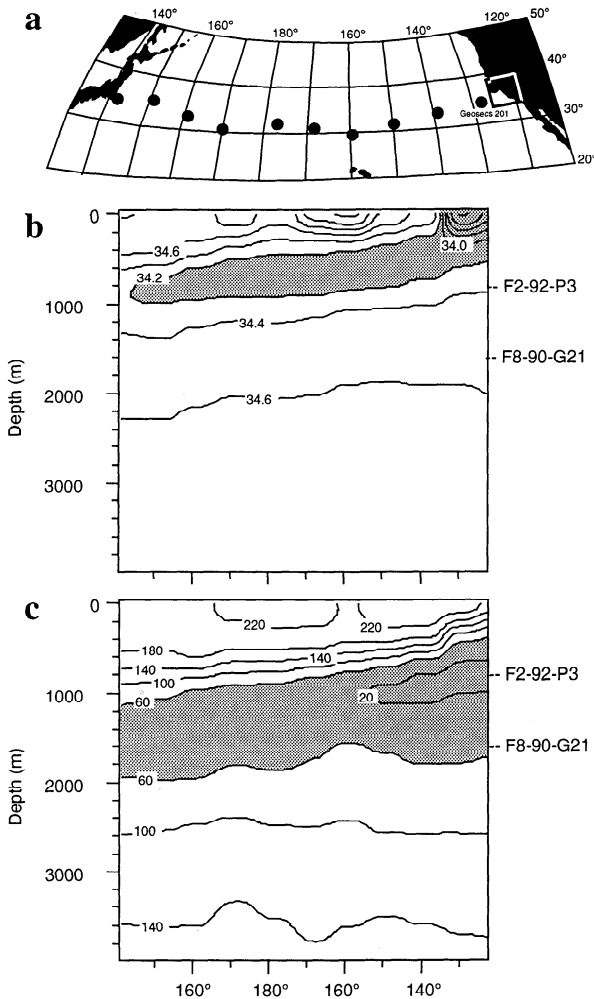


Figure 1. (a) Location of GEOSECS water-column profiles including Station 201 ($34^{\circ}10'N$, $127^{\circ}53'W$, August 1973) used to construct salinity and oxygen sections for the North Pacific [Ostlund *et al.*, 1987; Craig *et al.*, 1981]. The area covering the location of the California margin cores is enlarged in Figure 2. (b) Salinity section of the North Pacific based on the GEOSECS data augmented with profiles C-I and C-II of Bruland [1980]. Isohalines are at intervals of 0.2 units. (c) Same as Figure 2b for dissolved oxygen. Concentrations are in $\mu\text{mol.kg}^{-1}$.

radiocarbon age difference between the water at the surface and at 800 and 1600 m is 1100 and 1600 years, respectively [Ostlund *et al.*, 1987]. In principle, past apparent age differences between surface and deep water can be reconstructed by radiocarbon dating of planktonic and benthic foraminifera from the same sediment horizon [Broecker *et al.*, 1990].

The third indicator of ventilation is provided by foraminiferal Cd/Ca. The oceanic distribution of cadmium is controlled by the production of plankton in surface waters and closely parallels the distribution of the nutrient phosphate [Bruland, 1980]. Because Cd is incorporated into the shell of benthic foraminifera in proportion to dissolved Cd in ambient bottom water, foraminiferal Cd/Ca ratios are a proxy for the past nutrient content of the deep ocean [Boyle, 1988, 1992]. Today, the highest concentrations of dissolved Cd in the open ocean coincide with the core of the OMZ in the northeast Pacific at 800

m depth (Figure 3b). Most of the remineralization of labile plankton matter takes place at this depth, which today is shallower than the radiocarbon minimum (Fig. 3).

Plankton production and decay also have a major influence on the distribution of the isotopic composition of inorganic carbon dissolved in seawater because the $^{13}\text{C}/^{12}\text{C}$ ratio of plankton organic matter is lower than that of inorganic carbon in surface water [Kroopnick, 1985]. The lowest ratio of these isotopes also marks the OMZ (nutrient maximum) of the northeast Pacific (Figure 3c). The fourth ventilation proxy is provided by the carbon isotopic composition of benthic foraminiferal shells, which under certain conditions reflects the isotopic composition of bottom water.

Methods

Piston core F2-92-P3 ($35^{\circ}37.4'N$, $121^{\circ}36.3'W$) and gravity core F8-90-G21 ($37^{\circ}13.4'N$, $123^{\circ}14.6'W$) were raised from 799 m and 1605 m depths off Central California (Figure 2). Both cores are composed of slightly mottled, grayish foraminifer- and diatom-bearing clay to silty clay with no physical structures or other evidence of displaced sediment. Detailed sedimentological studies of benthic foraminifera and diatoms in both cores show no evidence of downslope transport (J. V. Gardner, unpublished data, 1996). Core F2-92-P3 was collected within the present-day OMZ and contains a section of fine laminations preserved between 204 and 214 cm.

Radiocarbon ages of mixed and monospecific planktonic and mixed benthic foraminifera were determined by accelerator mass spectrometry (AMS ^{14}C) at Lawrence Livermore National Laboratory following the methods of Vogel *et al.* [1987] and Davis *et al.* [1990]. The weight fraction of CaCO_3 in both cores was determined by CO_2 coulometry [Gardner and Dartnell, 1995].

Cd/Ca ratios were measured on batches of 10-15 cleaned shells of *Uvigerina peregrina*. The cleaning procedure of Boyle and Keigwin [1985/86] was modified on the basis of a separate

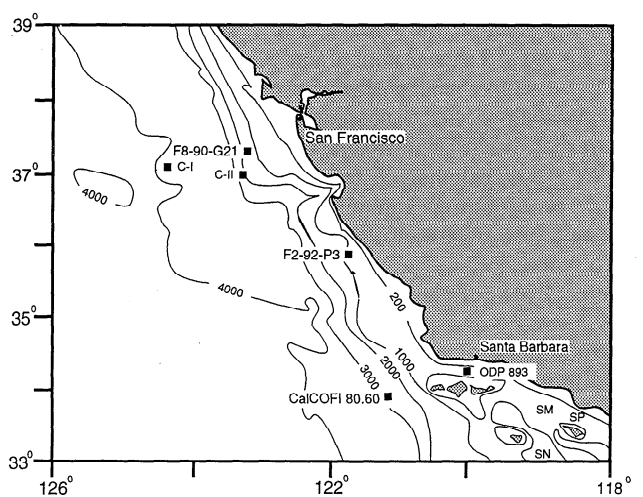


Figure 2. Enlarged view of the central California margin showing the location of cores F2-92-P3 and F8-90-G21, as well as salinity, oxygen, and cadmium water column profiles C-I and C-II of Bruland [1980]. CalCOFI Station 80.60 and ODP Site 893 are also indicated. Bathymetry is in meters.

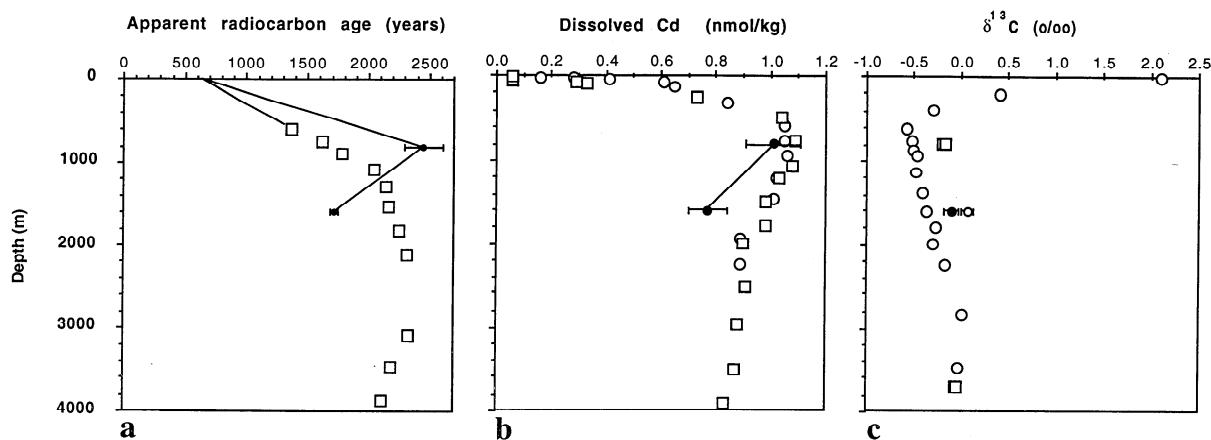


Figure 3. Comparison of northeast Pacific water-column profiles with conditions 11-9 ka. (a) Apparent radiocarbon-age profile at GEOSECS Station 201 [Ostlund *et al.*, 1987; Craig *et al.*, 1981] calculated from $^{14}\text{C}_{\text{age}}$ (years) = $-8033 \ln(1 + \Delta^{14}\text{C}/1000)$. Low tritium content of shallowest sample shown (0.23 ± 0.09 tritium units (TU)) at 555 m depth indicates that contribution of bomb-radiocarbon at this level was negligible. Two lines extend profile to a surface age of 630 years, the average value obtained for prebomb intertidal mollusc shells of known age collected off central California [Stuiver and Brazunias, 1993]. Solid line indicates gradient in apparent age at 800 and 1600 m depth for 11-9 ka calculated from benthic and planktonic foraminifera averaged over several depth intervals (Table 2). (b) Composite of two dissolved Cd profiles representative of the northeast Pacific [Bruland, 1980]. The Cd maximum at about 800 m depth coincides with the oxygen minimum zone (Figure 1). Distribution coefficients used for converting foraminiferal Cd/Ca to dissolved Cd in the water were calculated assuming data from the 4 to 0-ka intervals reflect today's water-column composition (Figures 4b and 4d). Solid line shows the water-column Cd gradient for 11-9 ka. Error bars are the standard deviation of 14 and 15 individual Cd/Ca determinations at 800 and 1600 m, respectively. Note that the standard error of the mean (not shown) is reduced by the square root of the number of determinations. (c) Profile of water-column inorganic carbon $^{13}\text{C}/^{12}\text{C}$ ratios at Geosecs Station 201 with corrections prescribed by Kroopnick [1985]. Also shown are water-column data closer to the California margin (open squares) from McCorkle and Klinhammer [1991]. Superimposed are $^{13}\text{C}/^{12}\text{C}$ data for *P. wuellerstorfi* in the 4 to 0-ka (open circles) and the 11 to 9-ka (solid circle) intervals at 1600 m depth. Error bars show the standard deviation of determinations in these intervals (Figures 4c and 4g).

optimization study for an estuarine benthic species, *Elphidiella hannai*. The modifications described by Lynch-Stieglitz *et al.* [1996] were adopted after half the samples from core F8-90-G21 were run. All samples from F2-92-P3 were analyzed using the modified procedure. No difference in the results between the two procedures can be detected, probably because the authigenic Cd content of the sediment at 1600 m is low [van Geen *et al.*, 1995; Rosenthal *et al.*, 1995]. Cd was quantified in the dissolved shell solutions by graphite-furnace atomic absorption (AA) on a Perkin-Elmer Zeeman 3030 instrument. Ca was measured by flame AA on a Perkin-Elmer 5000 instrument. Reproducibility between runs for a consistency standard of Cd and Ca contents similar to those from foraminiferal solution was 0.113 ± 0.006 $\mu\text{mol}/\text{mol}$ ($n=14$).

The carbon and oxygen-isotopic composition of the benthic foraminifera *U. peregrina* and *Planulina wuellerstorfi* was determined on 50 to 150- μg samples at Lamont-Doherty on a Finnigan MAT 251 mass spectrometer calibrated with an NBS-20 standard normalized to Pee Dee belemnite. The precision of these determinations was $\pm 0.05\text{‰}$ for both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. Samples from both cores and from different depth intervals were interspersed over several mass spectrometer runs. We therefore believe that the variability in benthic $^{18}\text{O}/^{16}\text{O}$ in the upper part of core F2-92-P3 is real.

Results

Radiocarbon ages were determined for mixed species of planktonic and benthic foraminifera (Table 1, Figures 4a and 4c). Radiocarbon ages were also determined on single species at three depth intervals in core F2-92-P3 (Table 1). The single-species determinations are consistent with the mixed-species data, with the exception of ages for *Bolivina spissa* and *B. argentea* at 102 cm (Table 1). The origin of the differences between these two benthic species is not known. Radiocarbon ages from four intervals in each core were used as control points to construct the age models. Planktonic radiocarbon ages were used unless dissolution had either reduced the abundance too much or biased ages toward older values (Table 1). In such cases, mixed benthic ages at 800 and 1600 m were converted to equivalent planktonic ages by subtracting 1060 and 1570 years, respectively, based on the GEOSECS 201 radiocarbon profile (Figure 3a) and the apparent age of surface water of 630 years [Stuiver and Brazunias, 1993]. Variations in the radiocarbon age of bottom water on the order of a few hundred years would not significantly affect these age models. Surface mixed-layer radiocarbon ages at the four control points in each core were converted to calendar years using a reservoir correction of 630 years and the radiocarbon timescale calibration based on tree rings [Stuiver and

Table 1. Accelerator Mass Spectrometry Radiocarbon Data

Mixed Species, Core F2-92-P3 (800 m)			Mixed Species, Core F8-90-G21 (1600 m)		
Depth, cm	Planktonic	Benthic	Depth, cm	Planktonic	Benthic
(trig.)1	1,770± 60	2,220± 70	10		2,570± 70*
2		3,860± 80*	25		2,840±320
90 ⁺	9,500± 90*	11,280±190	33		3,920± 80
100 ⁺	9,540± 90	11,540±220	40		4,520±150*
120 ⁺	10,020±100	11,710±230	62 ⁺	9,200± 60*	10,320± 90
140	10,620±100	11,600±100	65 ⁺	9,570± 70	10,650± 65
160	11,810±110	12,590±110	75 ⁺	9,800±140	10,850± 90
170	12,150±140	13,020±160	83	10,050±190	10,740± 80
214	13,140±110*	13,720±110	155	14,280± 90*	15,800± 90
298	16,650±220*	17,590±180			

Single Species, Core F2-92-P3 (800 m)					
Depth, cm	Planktonic		Benthic		
102	<i>G. bulloides</i>	9,450± 80	<i>U. peregrina</i>	11,040± 80	
102	<i>N. pachyderma</i>	9,430± 70	<i>B. spissa</i>	10,160±240	
102			<i>B. argentea</i>	12,610±250	
163	<i>G. bulloides</i>	11,790±230	<i>U. peregrina</i>	12,590± 90	
163			<i>B. spissa</i>	12,690±110	
163			<i>B. argentea</i>	12,500± 90	
200	<i>G. bulloides</i>	12,930±200	<i>B. argentea</i>	13,680±120	
200	<i>N. pachyderma</i>	13,020±200			

Asterisks denote age model control points, and plus signs indicate samples within carbonate maximum.

Brazunias, 1993]. The coral-based ^{230}Th - ^{234}U calibration of *Bard et al.* [1993] was used for ages >10,000 radiocarbon years. The resulting timescale in calendar years is shown to the right of Figures 4b, 4d, 4f, and 4h. The oldest horizons in the cores from 800 and 1600 m depth correspond to about 19 and 16 ka, respectively, and do not quite extend to full glacial conditions (Figure 4). The age models show that a carbonate maximum was deposited simultaneously at both depths from 11 to 9 ka (Figures 4a and 4e). The upper and lower limits of the interval of finely laminated sediments in the shallower of the two California margin cores are dated at 14.3 and 14.7 ka, respectively.

The benthic oxygen-isotope record of both cores is consistent with the age model determined from radiocarbon. The temperature of bottom water on the California margin is about 4.4° and 2.3°C at 800 and 1600 m, respectively [Bruland, 1980]. This temperature difference could account for the 0.5‰ difference in isotopic composition of *U. peregrina* between the two core tops [McCorkle et al., 1990] (Figures 4f and 4h). The offset in $^{18}\text{O}/^{16}\text{O}$ between *U. peregrina* and *P. wuellerstorfi* in core F8-90-G21 is consistent with previous observations of differences between species [McCorkle et al., 1990]. The ~1.5‰ range between core tops and bottoms for *U. peregrina* in both cores and *P. wuellerstorfi* in the deeper core is slightly larger than the 1.3‰ global change in ocean composition inferred from the Barbados sea level record [Fairbanks, 1989], suggesting a bottom water warming of perhaps 1°C from late glaciation to the present. In contrast to the deep core in which changes in $^{18}\text{O}/^{16}\text{O}$ are

monotonic throughout the record, variability in the core from 800 m depth increased significantly after 13 ka. A similar increase in variability in oxygen-isotopic composition of benthic foraminifera was observed in a nearby core from 610 m depth (J. V. Gardner, unpublished data, 1996). The isotope data suggest increased variability of temperature and/or salinity at the depth of today's OMZ since 13 ka.

The interpretation of AMS ^{14}C ages in terms of differences between benthic and planktonic foraminifera is restricted to the carbonate maximum which corresponds to a section of fairly constant abundances of planktonic and benthic foraminifera in core F2-92-P3 and local maxima in abundances in core F8-90-G21 (J. V. Gardner, unpublished data, 1996). This should limit the artifact that can be caused by bioturbation and dissolution [Broecker et al., 1990]. Benthic-planktonic age differences calculated at three levels in the carbonate maximum of each of the two cores are shown in Table 2. Comparison with today's radiocarbon profile shows that bottom water at 800 m depth was 800 years older at 11-9 ka than today. In contrast, bottom water at 1600 m depth was 600 years younger during the same period. The corresponding reversal in the radiocarbon age gradient with depth is shown in Figure 3a.

Core-top Cd/Ca ratios for benthic foraminifera average 0.12 and 0.18 $\mu\text{mol}/\text{mol}$ at 800 and 1600 m depth, respectively, (Table 3, Figures 4b and 4d) whereas water-column Cd concentrations slightly decrease over the same depth range from 1.05 to 1.00 nmol/kg (Figure 3b). Corresponding distribution coefficients (K_d

Table 2. Benthic-Planktonic Age Differences 11-9 ka

Depth, cm	Age difference
<i>Core F2-92-P3 (800 m)</i>	
90	1,780±280
100	2,000±310
120	1,690±330
Mean 11-9 ka	1,823±159
Today	1,060
<i>Core F8-90-G21 (1600 m)</i>	
62	1,120±150
65	1,080±135
75	1,050±230
Mean 11-9 ka	1,083± 35
Today	1,570

The estimated uncertainty in the mean age difference is the standard deviation of the three individual determinations in each core. Today's age difference was determined from the radiocarbon profile at GEOSECS Station 201 (Figure 3a) and the apparent age of surface water in the region of 630 years [Stuiver and Braumias, 1993].

= $(\text{Cd}/\text{Ca})_{\text{foram}}/(\text{Cd}/\text{Ca})_{\text{water}}$ of 1.1 and 1.8 at the two depths agree with the consistent increase in K_d with depth observed for core-top benthic foraminifera in different ocean basins at depths ≤ 2000 m [Boyle, 1992]. The foraminiferal Cd/Ca record at 1600 m depth shows that the water column was significantly depleted relative to today throughout much of the last deglaciation, indicating increased ventilation. Water-column Cd steadily increased from about 0.76 to 1.00 nmol/kg after formation of the carbonate maximum at 11-9 ka. The increase in Cd at 800 m depth over the same period was smaller, from 0.96 to 1.05 nmol/kg. During the 1.5 kyr following preservation of laminations in the shallower of the two cores, low foraminiferal Cd/Ca ratios may indicate depleted bottom waters under conditions similar to those of today's Santa Barbara Basin [van Geen et al., 1995]. Comparison of the water-column Cd profile at the carbonate maximum shows that today's reverse Cd gradient below the OMZ was further accentuated 11-9 kyr ago (Figure 3b).

The evidence for changes in ventilation of the North Pacific from the $^{13}\text{C}/^{12}\text{C}$ ratio of benthic foraminifera is ambiguous. The $^{13}\text{C}/^{12}\text{C}$ records of *P. wuellerstorfi*, believed to more closely reflect the composition of the water column, and *U. peregrina* indicate little change in the isotopic composition of Pacific waters at 1600 m depth from 16 ka to the present (Table 3, Figure 4h). Relatively constant foraminiferal $^{13}\text{C}/^{12}\text{C}$ ratios have been previously reported for the last glacial maximum in a number of North Pacific cores in the 1400-2600 m depth range and attributed to increased ventilation because the isotopic composition of the global oceanic carbon pool was $\sim 0.3\%$ lower during glacial time [Duplessy et al., 1988; Herguera et al., 1992]. This interpretation may need to be reevaluated in light of the temperature dependence of the initial isotopic composition of

high-latitude source waters [Broecker, 1993; Charles et al., 1993; Lynch-Stieglitz and Fairbanks, 1994]. Particularly low $^{13}\text{C}/^{12}\text{C}$ ratios for *U. peregrina* in the shallower of the two cores around the laminated section most likely reflect changes in the microenvironment surrounding the foraminifer rather than in the water column [McCorkle et al., 1990]. Similar reductions in foraminiferal $^{13}\text{C}/^{12}\text{C}$ have been attributed elsewhere in the North Pacific to an increased supply of ^{13}C -depleted organic matter at the sediment-water interface [Keigwin et al., 1992].

Discussion

Two features of the California margin cores, the laminated interval in the shallower core and the carbonate maximum in both cores, have been observed at other locations. For the past 11 kyr, laminations produced by the seasonally varying flux of detrital and biogenic matter have been preserved in poorly ventilated basins such as the Santa Barbara Basin and the Gulf of California [Keigwin and Jones, 1990; Kennett and Ingram, 1995; Behl and Kennett, 1996]. Oxygen levels increased sufficiently for bioturbation to mix these laminations from the last glacial maximum to 15 ka in both basins, and again for a short period between 13 and 11 ka during the Younger Dryas cool interval. Laminations have also at times been preserved on the California margin at the depth of the OMZ [Gardner and Hemphill-Haley, 1986; Anderson et al., 1989; Hemphill-Haley and Gardner, 1994]. The exact timing of transitions between intervals of laminated and bioturbated sediments in the Santa Barbara Basin determined by Kennett and Ingram [1995] is indicated by light shading in Figure 4. Comparison with the position of the laminated section in the shallower of the two California margin cores (dark shading) shows that it occurred within a period when laminations were also preserved in the Santa Barbara Basin and the Gulf of California. At both locations, variations in ventilation appear to be the primary factor determining whether laminated sediment is preserved [Sancetta, 1995; Kennett and Ingram, 1995]. Although elevated levels of primary production in the northeast Pacific no doubt contribute to the depletion of oxygen in the water column, the brief preservation of laminations on the California margin is most likely also due to reduced ventilation rather than a change in productivity [Lyle et al., 1992; Sancetta et al., 1992]. An increased flux of organic matter reaching the sediment-water interface due to lower oxidation within the water column could explain the low $^{13}\text{C}/^{12}\text{C}$ ratios of *U. peregrina* in core F2-92-P3 between 15 and 13 ka. The absence of laminations in the upper 200 cm of core F2-92-P3 indicates that oxygen depletion at 800 m never was again as pronounced as it was from 14.7 to 14.3 ka. This is consistent with the semiquantitative record of lamination in the Santa Barbara Basin reconstructed by Behl and Kennett [1996] which shows intermittent periods of bioturbation over the past 11 kyr.

A deglacial carbonate maximum has been observed in many cores from the North Pacific, although the timing of deposition relative to the California margin records is not always clear [Berger, 1977; Lyle et al., 1992; Karlin et al., 1992; Keigwin et al., 1992]. The origin of these carbonate maxima is still open to different interpretations [Broecker et al., 1993] and will not be resolved here. The carbonate maximum provides a check on the age model for our two cores and is used to interpret the benthic-planktonic radiocarbon age differences. The carbonate maximum corresponds to a time when the radiocarbon content of the

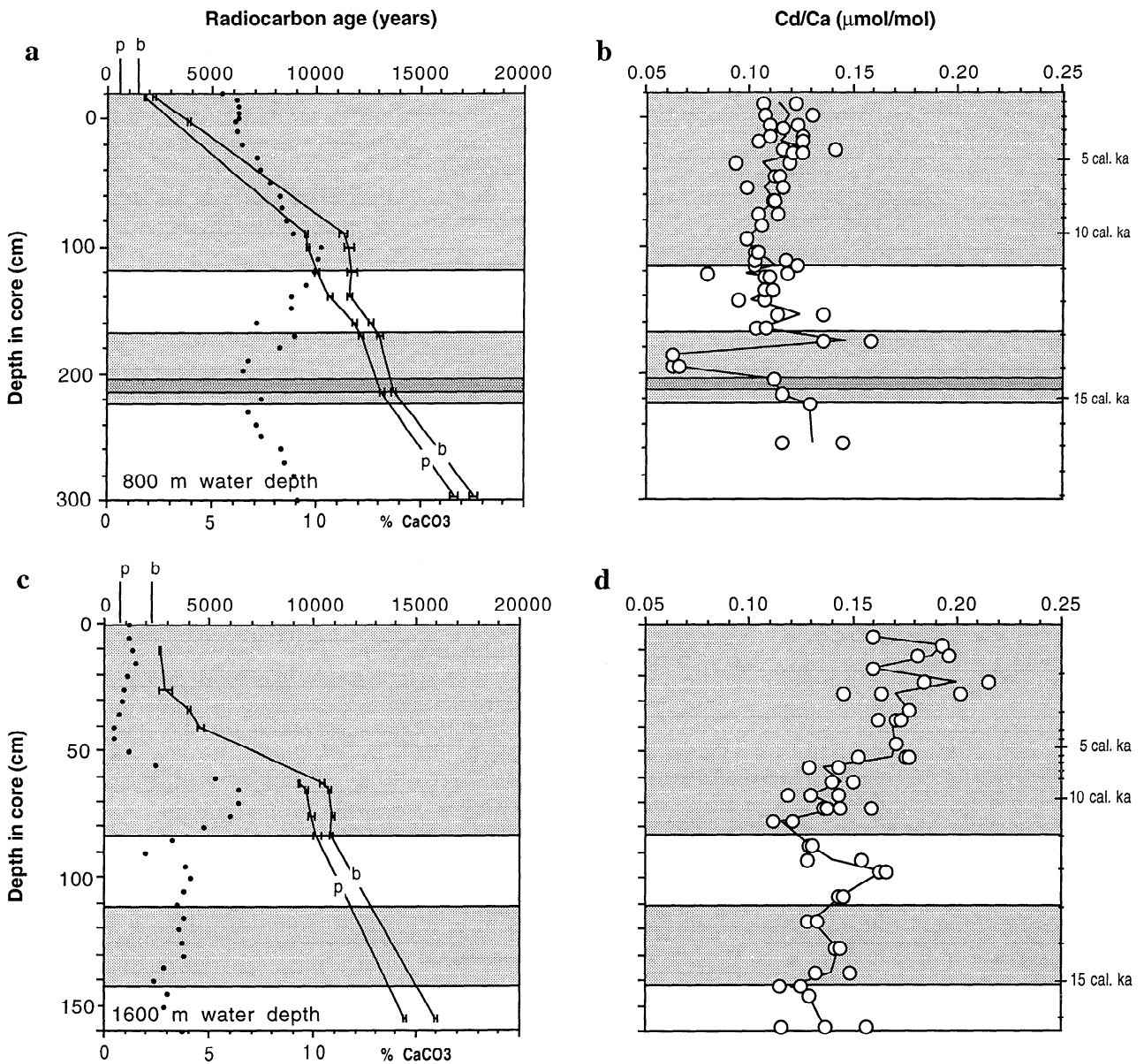


Figure 4. AMS ^{14}C ages of mixed planktonic (p) and benthic (b) foraminifera (Figures 4a and 4c). Analytical errors for each determination are indicated by error bars. The apparent radiocarbon ages of surface water and intermediate waters at 800 and 1600 m depth indicated by vertical lines above the scale correspond to the profile in Figure 3a. The trigger-weight gravity core of F2-92-P3 was used to recover the upper 20 cm of sediment apparently lost by the piston core. Radiocarbon and Cd/Ca from the trigger-weight core are shown above the 0-cm horizon. Intervals corresponding to preservation of laminations in the Santa Barbara basin are shown by grey shading [Kennett and Ingram, 1995]. The location of a finely laminated interval in core F2-92-P3 is marked by darker shading. Discrete dots and the bottom scale show variations in the carbonate content of the two cores. Foraminiferal Cd/Ca ratios for *U. peregrina* (Figures 4b and 4d). Each open circle represents a separate determination for a batch of 8-15 shells cleaned of organic matter and Fe and Mn oxide phases. Solid lines indicate the mean of determinations at each sampling interval. Six out of a total of 112 Cd/Ca determinations are not shown because of suspected contamination (Table 3). Figures 4e and 4g show $^{13}\text{C}/^{12}\text{C}$ ratios of benthic foraminifera *U. peregrina* (open circles) and *P. wuellerstorfi* (solid circles) expressed in per mil deviations relative to Pee Dee belemnite (PDB). Figures 4f and 4h show $^{18}\text{O}/^{16}\text{O}$ ratios of benthic foraminifera *U. peregrina* (open circles) and *P. wuellerstorfi* (solid circles) expressed in per mil deviations relative to PDB. A calendar-years-before-present timescale for each core is included to the right of the figure.

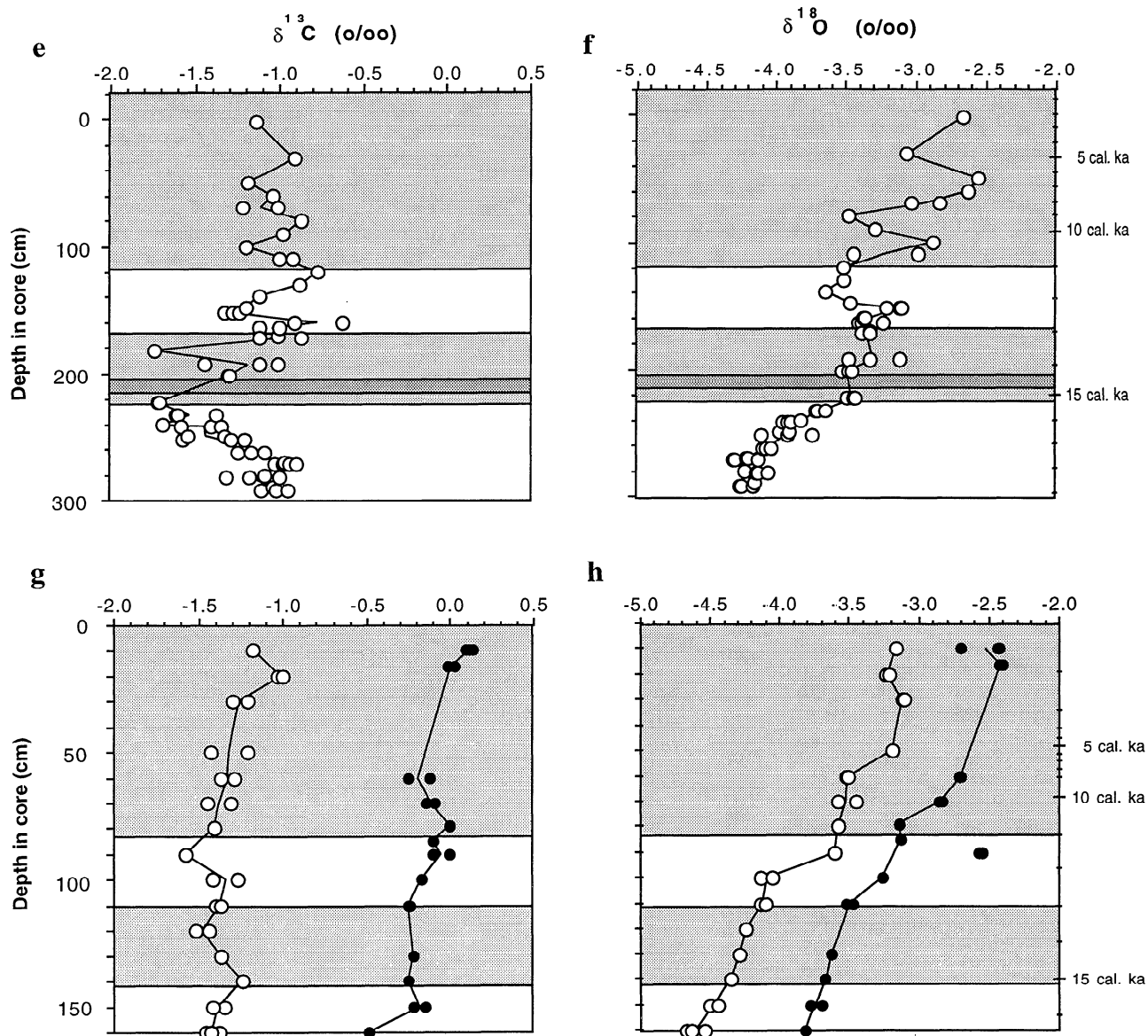


Figure 4. (continued)

atmosphere was decreasing rapidly [Bard *et al.*, 1990; Edwards *et al.*, 1993]. The propagation of such a transient signal through the ocean complicates the interpretation of benthic-planktonic age differences. However, because the carbonate maximum was deposited simultaneously at 800 and 1600 m depth, the relative benthic-planktonic radiocarbon age difference between the two depths should not be affected. Similar observations in California margin cores at 610 and 1720 m depth (J. V. Gardner *et al.*, unpublished data, 1996) reinforce our belief that a reversal in the radiocarbon age gradient with depth took place in the northeast Pacific at 11-9 ka. The reduction in benthic-plankton radiocarbon age difference measured at 978 m depth in the northwest Pacific during the same period [Duplessy *et al.*, 1989] is not necessarily inconsistent with our data because even today, the eastern margin of Hokkaido is hydrographically very different from the California margin [Talley, 1991] (Figure 1). The main point here is that the California margin cores show that

ventilation of the OMZ was significantly reduced at the beginning of both intervals of reduced ventilation recorded in the Santa Barbara Basin and the Gulf of California.

The different ventilation proxies for the California margin are next compared chronologically. The water-column Cd profile of the northeast Pacific during early deglaciation, characterized by significant depletion at 1600 m depth relative to today and little change at 800 m, is consistent with the glacial reconstructions of Boyle [1992] and Ohkuchi *et al.* [1994] for the northwest Pacific. Whatever process enhanced ventilation in the North Pacific during glaciation appears not to have significantly affected the OMZ and nutrient maximum across the North Pacific. The 15 to 13-ka interval is characterized by oxygen levels at 800 m that were greatly reduced and by water-column Cd concentrations at 1600 m that remained at the early deglaciation level. This may have been a period when decoupling between relatively shallow and intermediate depth ventilation was at its most extreme. An

Table 3. Composition of Benthic Foraminifera in California Margin Cores

<i>Uvigerina peregrina</i>												<i>Planulina wuellerstorfi</i>		
Core F2-92-P3		Core F8-90-G21		Core F2-92-P3			Core F8-90-G21			Core F8-90-G21				
Depth	Cd/Ca	Depth	Cd/Ca	Depth	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	Depth	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	Depth	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$		
-11.5	0.122	4.5	*0.281	2	2.65	-1.14	10	3.17	-1.18	10	2.43	0.11		
-11.5	0.106	5.5	0.160	30	3.06	-0.91	20	3.23	-1.03	10	2.70	0.13		
-1.5	0.130	8.5	0.193	50	2.54	-1.19	20	3.21	-1.00	10	2.42	0.09		
-1.5	0.107	12.5	0.181	60	2.62	-1.05	30	3.10	-1.30	16	2.43	0.02		
5.5	0.123	12.5	0.196	70	2.82	-1.01	30	3.12	-1.21	16	2.40	-0.01		
5.5	0.109	17.5	0.160	70	3.02	-1.22	50	3.18	-1.21	60	2.69	-0.12		
8.5	0.116	22.5	0.215	80	3.47	-0.87	50	3.19	-1.43	60	2.71	-0.25		
8.5	*0.189	22.5	0.184	90	3.28	-0.98	60	3.51	-1.29	70	2.84	-0.09		
15.5	0.125	22.5	*0.253	100	2.87	-1.20	60	3.51	-1.36	70	2.85	-0.14		
15.5	0.109	27.5	0.202	110	3.43	-0.93	70	3.58	-1.31	79	3.13	-0.01		
18.5	0.104	27.5	0.146	110	2.97	-1.00	70	3.45	-1.44	85	3.13	-0.10		
18.5	0.125	27.5	0.164	120	3.51	-0.78	80	3.58	-1.41	90	2.56	-0.10		
25.5	0.141	33.5	0.177	130	3.51	-0.88	90	3.60	-1.58	90	2.55	-0.00		
25.5	0.116	37.5	0.171	140	3.63	-1.12	100	4.13	-1.26	100	3.25	-0.17		
28.5	0.125	37.5	0.162	148	3.46	-1.20	100	4.05	-1.42	110	3.48	-0.24		
28.5	0.120	37.5	0.173	152	3.10	-1.33	110	4.10	-1.36	110	3.52	-0.25		
35.5	0.093	47.5	0.171	152	3.20	-1.28	110	4.14	-1.40	130	3.63	-0.22		
35.5	0.119	47.5	*0.292	152	3.09	-1.24	120	4.25	-1.44	140	3.67	-0.25		
45.5	0.114	52.5	0.177	160	3.36	-0.91	120	4.25	-1.51	150	3.70	-0.15		
45.5	0.112	52.5	0.176	160	3.35	-0.63	130	4.29	-1.37	150	3.78	-0.22		
55.5	0.098	52.5	0.153	164	3.22	-1.00	140	4.34	-1.24	160	3.82	-0.49		
55.5	0.116	56.5	0.143	164	3.38	-1.00	150	4.50	-1.42					
65.5	0.111	56.5	0.129	164	3.39	-1.12	150	4.45	-1.35					
65.5	0.112	62.5	0.150	170	3.32	-1.01	160	4.67	-1.38					
75.5	0.113	62.5	0.140	172	3.31	-1.12	160	4.63	-1.43					
75.5	0.104	67.5	0.119	172	3.38	-0.87	160	4.53	-1.46					
85.5	0.105	67.5	0.130	182	2.10	-1.75								
95.5	0.098	67.5	0.143	192	3.32	-1.01								
105.5	0.104	72.5	0.159	192	3.10	-1.44								
105.5	0.102	72.5	0.144	192	3.47	-1.12								
112.5	0.117	72.5	0.138	202	3.47	-1.30								
112.5	0.102	72.5	0.136	202	3.51	-1.31								
115.5	0.102	77.5	0.112	202	3.45	-1.29								
115.5	0.123	77.5	0.121	222	3.44	-1.72								
122.5	0.079	87.5	0.129	222	3.42	-1.72								
122.5	0.118	87.5	0.131	222	3.48	-1.73								
125.5	0.107	93.5	0.154	232	3.69	-1.38								
125.5	0.109	93.5	0.128	232	3.64	-1.61								
135.5	0.111	97.5	0.163	232	3.71	-1.61								
135.5	0.107	97.5	0.166	240	3.82	-1.70								
143.5	0.107	107.5	0.144	242	3.94	-1.41								
143.5	0.094	107.5	0.146	242	3.91	-1.35								
155.5	0.113	117.5	0.128	242	3.88	-1.58								
155.5	0.135	117.5	0.133	250	3.89	-1.32								
165.5	0.103	127.5	0.142	250	3.97	-1.54								
165.5	0.108	127.5	0.144	252	3.73	-1.58								
175.5	0.135	137.5	0.132	252	3.91	-1.28								
175.5	0.158	137.5	0.149	252	4.10	-1.21								
185.5	0.063	142.5	0.125	262	4.06	-1.25								
195.5	0.066	142.5	0.115	262	4.03	-1.17								
195.5	0.063	146.5	0.129	262	4.09	-1.09								
205.5	0.112	158.5	0.157	270	4.20	-0.98								
216.5	*0.232	158.5	0.116	270	4.20	-0.97								
216.5	0.116	158.5	0.137	272	4.28	-1.03								
225.5	0.129			272	4.12	-0.94								
246.5	*0.181			272	4.13	-0.98								
255.5	0.145			272	4.30	-0.90								
255.5	0.116			280	4.21	-1.09								
				282	4.05	-1.32								
				282	4.12	-1.00								
				282	4.14	-1.18								
				290	4.15	-1.04								
				292	4.26	-0.95								
				292	4.25	-1.02								
				292	4.16	-1.11								

*Samples suspected of contamination

increase in foraminiferal Cd/Ca ratios during the subsequent Younger Dryas period of enhanced shallow suggests ventilation decreased at 1600 m (Figure 4d). Radiocarbon and Cd/Ca data indicate that the pattern of relative ventilation at shallow and intermediate depths was then reversed again at the time of deposition of the carbonate maximum between 11 and 9 kyr (Figure 3a). The foraminiferal Cd/Ca and radiocarbon data also indicate a gradual return to relatively shallow ventilation over the past 9 kyr. This shoaling of ventilation led to a reduction in the reversed water-column Cd gradient to present conditions (Figure 3b). The change in radiocarbon is not recorded in core-top foraminifera because of dissolution but is inferred by comparing today's radiocarbon profile in the water column (Figure 3a).

A closer look at Figure 1, which shows the present distribution of salinity and oxygen across the North Pacific, suggests that these variations in the depth of ventilation are plausible. As was discussed earlier, the overlap of today's OMZ with the salinity minimum in the northeast Pacific indicates that the OMZ is ventilated to some extent by advection from the north. Our interpretation of the California margin, Santa Barbara Basin, and Gulf of California records is that the depth of the salinity minimum has shifted relative to that of the OMZ over the past 20 kyr. One possible interpretation is that during late glacial time, ventilation was concentrated deeper than today and bypassed the OMZ. The records indicate that this contrast was most accentuated between 15 and 13 ka when laminations were preserved on the California margin at 800 m depth. According to this model, the oxygen minimum was weakened during the Younger Dryas, possibly at the cost of weaker ventilation below. Between 11 and 9 ka, the salinity minimum diagnostic of high-latitude convection may have deepened again, causing a reversal in the apparent radiocarbon age gradient of the water column and an accentuation of the reversed nutrient gradient. Finally, the salinity minimum shoaled to its present level in the northeast Pacific over the past 9 kyr. Temperature and/or salinity fluctuations over this period suggested by variations in the oxygen-isotope record at 800 m are consistent with the instability in relative contributions of northern and southern source waters during the Holocene [Behl and Kennett, 1996].

Conclusion

The data presented here support the notion that alternating sections of laminated and bioturbated sediments in the Gulf of California and the Santa Barbara Basin reflect changes in circulation outside these poorly ventilated basins over the past 20 kyr. The two California margin cores provide a new perspective on changes in the vertical distribution of ventilation over this period. None of the proxy-indicators of ventilation discussed here are unambiguous by themselves. Considered together, however, the records suggest that ventilation was enhanced at 1600 m depth when ventilation was reduced at 800 m, and vice versa. Transitions between these two modes of ventilation appear to correspond to major climatic phases such as the Bolling/Allerod and the Younger Dryas. More detailed and complete records from the California margin, a region sensitive to high-latitude convection, may shed light on the nature of atmospheric and oceanic teleconnections between the North Atlantic and the North Pacific.

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