On the preservation of laminated sediments along the western margin of North America

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[1] Piston, gravity, and multicores as well as hydrographic data were collected along the Pacific margin of Baja California to reconstruct past variations in the intensity of the oxygen-minimum zone (OMZ). Gravity cores collected from within the OMZ north of 24°N did not contain laminated surface sediments even though bottom water oxygen (BWO) concentrations were close to 5 μmol/kg. However, many of the cores collected south of 24°N did contain millimeter- to centimeter-scale, brown to black laminations in Holocene and older sediments but not in sediments deposited during the Last Glacial Maximum. In addition to the dark laminations, Holocene sediments in Soledad Basin, silled at 290 m, also contain white coccolith laminae that probably represent individual blooms. Two open margin cores from 430 and 700 m depth that were selected for detailed radiocarbon dating show distinct transitions from bioturbated glacial sediment to laminated Holocene sediment occurring at 12.9 and 11.5 ka, respectively. The transition is delayed and more gradual (11.3–10.0 ka) in another dated core from Soledad Basin. The observations indicate that bottom-water oxygen concentrations dropped below a threshold for the preservation of laminations at different times or that a synchronous hydrographic change left an asynchronous sedimentary imprint due to local factors. With the caveat that laminated sections should therefore not be correlated without independent age control, the pattern of older sequences of laminations along the North American western margin reported by this and previous studies suggests that multiple patterns of regional productivity and ventilation prevailed over the past 60 kyr. *INDEX TERMS:* 1050 Geochemistry: Marine geochemistry (4835, 4850); 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 4267 Oceanography: General: Paleoceanography; 4834 Oceanography: Biological and Chemical: Hypoxic environments; *KEYWORDS:* oxygen-minimum zone, laminations, bioturbation, deglaciation, California margin

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1. Introduction

[2] Without deep ocean convection, the photosynthetic conversion of carbon dioxide into reduced organic carbon and molecular oxygen by phytoplankton would inevitably lead to a pronounced contrast between an oxic euphotic zone and an anoxic deep ocean. Anoxia has indeed prevailed at depth across entire ocean basins at various points in Earth's history, presumably because deep convection was severely inhibited [e.g., *Ryan and Cita*, 1977]. Under current climate conditions, however, there are few locations where the water column is truly anoxic because convection driven by surface cooling at high latitudes supplies sufficient oxygen to the deep ocean. The water column is anoxic, or close to it, on a significant scale today only in the Black Sea [*Arthur and Dean*, 1998, and references therein] and a number of well-studied basins where circulation is restricted by topography, including Santa Barbara Basin (not quite anoxic [*Sholkovitz and Gieskes*, 1971; *Reimers et al.*, 1990]) and Cariaco Basin (truly anoxic [*Peterson et al.*, 1991]). A number of high-resolution archives of past changes in climate and/or ocean circulation have been recovered from these basins because their sediment accumulation rate is typically high and low bottom-water oxygen (BWO) concentrations inhibit bioturbation by benthic organisms [e.g., *Behl and Kennett*, 1996; *Peterson et al.*, 2000]. Although this paper documents several new sites along the western margin of North America where preserved laminations indicate that bioturbation is currently inhibited, our focus here is not specifically on the high-resolution records retrievable from these

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cores as much as the precise timing of the transitions between laminated and bioturbated sections, their relation to BWO concentrations and other factors, and the implication of these transitions for our understanding of past climate change. The present study does not attempt to separate the effects of past productivity and ventilation changes on BWO concentrations.

[3] The importance of sediment mixing by burrowing benthic organisms as a filter of climate-driven proxy signals has long been recognized [*Berger and Heath*, 1968; *Peng et al.*, 1979; *Bard et al.*, 1987; *Bard*, 1998; *Anderson*, 2001]. In offshore regions where sediment accumulation is relatively slow (~1 cm/kyr), quantitative evidence of bioturbation is provided by undisturbed core tops where the radiocarbon age of planktonic or benthic foraminifera exceeds local reservoir ages by several thousand years [*Berger and Killingley*, 1982; *Matsumoto et al.*, 2001]. Along productive oceanic margins, sedimentation reaches rates of 10–100 cm/kyr because of a higher input of organic matter produced in overlying waters as well as a greater supply of detrital matter resulting from continental erosion. At mid-latitudes, the inputs of these two components often alternate seasonally, which sets the stage for the formation and potential preservation of millimeter-scale sediment laminations. In Santa Barbara Basin at 590 m depth, for instance, where BWO concentrations are sometimes undetectable and typically below 5 μmol/kg, alternating millimeter-thick layers composed predominantly of diatoms or detrital matter [*Soutar and Crill*, 1977; *Thunell et al.*, 1995] are preserved today and have been for most of the past 10 kyr [*Kennett and Ingram*, 1995].

[4] The organisms responsible for bioturbation on the shallower flanks of Santa Barbara Basin (~500–550 m) have been well studied. They include tubificid oligochaetes, tubicolous ampeliscid amphipods, dorvilleid polychaetes and the bivalve *Lucinoma aequizonata* [*Levin et al.*, 2001, 2002; *Cary et al.*, 1989; L.A. Levin, unpublished data]. In general, bioturbation results from foraging activities of deposit feeding animals, although other activities such as tube building also affect sediment structure. In some cases, such as *L. aequizonata*, the organism invades deep sediment layers to gain access to a particular chemical species (e.g., hydrogen sulfide to fuel endosymbionts [*Cary et al.*, 1989]). BWO concentrations clearly play an important role as a determinant of bioturbation since on the flank of Santa Barbara Basin at 550 m depth, where oxygen concentrations are almost always detectable and range between ~2–8 μmol/kg, millimeter-scale laminations are already partially erased even though bulk sediment accumulation is very similar [*Zheng et al.*, 2000a]. Whether the difference in the benthic fauna between these two sites is determined by average BWO concentrations or by occasional excursions to true anoxia at the bottom of the basin is unclear. At a shallower depth of 500 m, where BWO concentrations range ~7–15 μmol/kg in the same basin, the action of benthic organisms essentially homogenizes the color and texture of the sediment. Bioturbation, or lack thereof, is not always easy to determine from sediment structure, however. *Grimm et al.* [1996] point out that occasionally homogeneous sediment layers deposited in the bottom of Santa Barbara Basin may not be bioturbated. *Pike et al.* [2001] and *Bernhard et al.* [2003], on the other hand, have documented patterns of micro-bioturbation in laminated sediments from the deeper parts of the basin (590 m) that are not visible to the naked eye.

[5] Probably nowhere as extensively as along the western margin of North America have laminated sediments been studied to infer past ocean variability. For several decades, various teams have sought, with variable success, to retrieve high-resolution records of environmental change from the laminated sediment of Santa Barbara Basin [e.g., *Soutar*, 1971; *Pisias*, 1978; *Lange et al.*, 1987; *Schimmelmann et al.*, 1990; *Kennedy and Brassell*, 1992; *Baumgartner et al.*, 1992; *Weinheimer and Cayan*, 1997; *Emmer and Thunell*, 2000; *Field and Baumgartner*, 2000]. The most detailed and longest proxy records were recovered from this location at ODP Site 893 [*Kennett and Ingram*, 1995; *Behl and Kennett*, 1996]. Sections of homogeneous sediment recovered from Santa Barbara Basin indicate that BWO concentrations were high enough in the past to support bioturbation during the Last Glacial Maximum (LGM). Effectively building on the notion that bioturbating organisms have different oxygen requirements, *Behl* [1995] categorized variations in the aspect of Santa Barbara Basin sediment across a semi-quantitative spectrum of conditions that range from oxic (homogeneous and therefore presumably bioturbated) to nearly anoxic (finely laminated). These painstaking reconstructions have produced a remarkable sequence of laminated and bioturbated intervals that, over most of the past 160 kyr, closely resembles the pattern of variations in oxygen isotopes in Greenland ice [*Grootes and Stuiver*, 1997], with warm interglacial periods and interstadials generally corresponding to more reducing conditions in Santa Barbara Basin (Figure 1).

[6] An unambiguous explanation has yet to emerge among the various mechanisms that have been proposed for the striking correlation between the pattern of laminations in Santa Barbara Basin and the Greenland isotope record. Studies of laminations and other indicators linked to BWO levels along the western margin of North America indicate that the Santa Barbara Basin record is probably related to broad-scale changes in the intensity of the OMZ along the margin of western North America [*Keigwin and Jones*, 1990; *van Geen et al.*, 1996; *Cannariato and Kennett*, 1999; *Zheng et al.*, 2000b; *Keigwin*, 2002]. However, the original attribution of changes in OMZ intensity along the western margin of North America linked to changes in ventilation either from the north [*Behl and Kennett*, 1996; *Cannariato and Kennett*, 1999] or from the south [*Lund and Mix*, 1998] was recently challenged by *Stott et al.* [2000a] based on evidence of the sensitivity of BWO concentrations in several silled basins of the region to changes in productivity. Extension of such observations to the open ocean is complicated because such silled basins are only periodically refilled with water from the OMZ on the open margin [*Sholkovitz and Gieskes*, 1971; *Reimers et al.*, 1990]. The sensitivity of low-oxygen environments to climate change has broader implications since a close

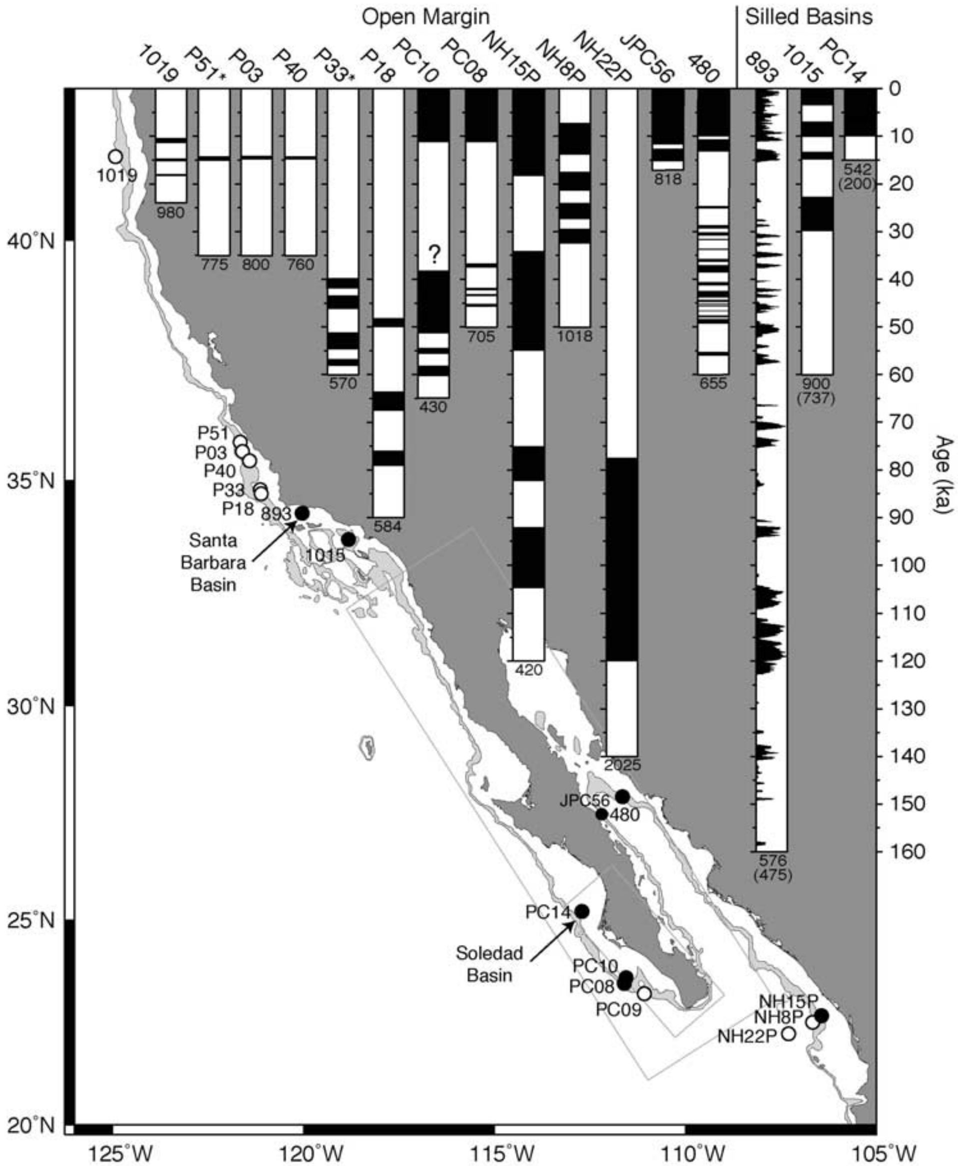

Figure 1. Distribution and timing of preservation of laminated sediment (black) in piston cores collected along the western margin of North America. Homogeneous sections, assumed to be bioturbated, are indicated in white. In the case of Santa Barbara Basin (ODP893), the smoothed record of a semi-quantitative description of sediment structure is shown, with peaks to the right corresponding to laminated sections [*Behl and Kennett*, 1996; and update from R. Behl, personal communication]. The sequences are from sediment records collected within the OMZ on the open margin as well as semi-enclosed basins. Two new records from the open Pacific margin of southern Baja California (GC31/PC08 and GC32/PC10) and one from a semi-enclosed basin (GC41/PC14) are included. The depth of each record (m) is listed below each bar (with sill depth in parentheses where relevant). Bathymetry contours are shown at 500 and 1000-m depth. The two rectangles delineate areas enlarged in Figures 2 and 4. Data for ODP Sites 1015 and 1019 from *Lyle et al.* [1997]; P51, P03, P40, and P18 from *Gardner et al.* [1997]; NH15P, NH8P, and NH22P from *Ganeshram and Pedersen* [1998]; ODP Site 893 from *Behl* [1995]; DSDP Site 480 from *Keigwin and Jones* [1990] and unpublished data from K. Cannariato and E. B. Roark; JPC56 from *Keigwin* [2002].

relation has also been documented, for instance, between the characteristics of the sediment accumulating within the OMZ of the Arabian Sea and the Greenland isotope record [*Schulz et al.*, 1998].

[7] The difficulty of relating records of laminations from a silled basin to open-ocean conditions is one motivation for studies that focus on OMZ sites of the northeast Pacific where, although circulation is not restricted as in Santa

Barbara Basin, laminations have occasionally been preserved [*Gardner and Hemphill-Haley*, 1986; *Anderson et al.*, 1989; *Keigwin and Jones*, 1990; *Ganeshram et al.*, 1995; *Dean et al.*, 1997; *Zheng et al.*, 2000b]. Existing records from these regions show homogeneous and laminated sequences that in some locations bear some resemblance to the Santa Barbara Basin record and in other locations are quite different (Figure 1). Some differences in patterns for the open margin sites have a straightforward oceanographic explanation. For example, the OMZ today is deeper and considerably less intense off Central California (35°N) than it is off Mazatlan (23°N). This reflects proximity to areas of ventilation to the north and is why laminations are preserved today on the open margin only within the OMZ of the southern sites. Some available records show that bioturbation is active today off Mazatlan, but that is because those particular cores were collected well below the core of today's OMZ (Figure 1). One consistent feature across all records along the west coast of North America, including Santa Barbara Basin and the Gulf of California, is that oxygen levels within the depth range of today's OMZ were sufficient for bioturbation during the LGM. Older sequences of laminations on the open margin suggest that, in contrast, the OMZ may have been more intense than it is today during the Bolling-Allerod (~15–13 ka) warm period [*Zheng et al.*, 2000b] and possibly during earlier warm interstadials between 60 and 30 ka [*Gardner et al.*, 1997]. Although the pattern suggests a general relation between climate and OMZ intensity in the northeast Pacific, with warmer conditions corresponding to an intense OMZ and vice versa, there are also enough differences between sites and time intervals to suggest that a bimodal interpretation of these patterns may be an oversimplification [*Hendy and Kennett*, 1999, 2000; *Stott et al.*, 2000b].

[8] This study reexamines the lamination patterns along the western margin of North America by presenting several new records and a detailed analysis of the conditions under which layered sediment patterns are formed and preserved. We first compare core tops from a suite of sites along the Pacific margin of Baja California with concurrently measured hydrographic data obtained in October–November 1999. The comparison covers a series of open margin sites as well as three semi-enclosed basins, one of which is Santa Barbara Basin, and suggests that the supply of organic matter plays a role in both the generation and the preservation of non-bioturbated sequences. We proceed by dating four new records from southern Baja California with 53 radiocarbon measurements of benthic and/or planktonic foraminifera. The new data show that the most recent transition from bioturbated late glacial sediment to non-bioturbated Holocene sediment was not synchronous at southern Baja California sites, despite their proximity. The implication is that sequences of laminations should therefore not be used to correlate records from different locations without independent age control. We conclude by showing that, despite these complications, a better understanding of the various patterns of laminations preserved along the western margin of North America over different time intervals is likely to provide new insights on the way climate and ocean circulation interact in the North Pacific and beyond.

2. Methods

[9] Between October 29 and November 22, 1999, a total of 55 gravity cores (up to 4 m in length), 16 piston cores (up to 16 m), and 18 sets of multicores were recovered along the open margin of Baja California, two semi-enclosed basins in the same region, as well as Santa Barbara Basin. The sediment cores were all cut in 1.5 m sections, logged on a multi-sensor track, split, described, and digitally photographed on board ship. In addition, a CTD-rosette water sampler was deployed to collect hydrographic data at 19 of these locations (Figure 2). Core locations, hydrographic data, and detailed core descriptions were compiled in LDEO Technical Report 2001–01 [*van Geen et al.*, 2001].

[10] Hydrographic data were obtained with a SeaBird 911+ instrument calibrated on board with discrete salinity samples from Niskin bottles mounted on the rosette. To ensure the quality of dissolved oxygen measurements, the SeaBird SBE 13 oxygen sensor mounted on the rosette was re-calibrated with shipboard analysis of discrete rosette samples by Winkler titration. The calibration shows a very consistent linear relation between the sensor and Winkler data for oxygen concentrations ranging between 0 and 300 μmol/kg ($r^2 = 0.9994$, n = 187). Sensor-derived oxygen concentrations were increased by 5.7% and an additional constant 1.5 μmol/kg on the basis of the intercalibration with Winkler titrations (Figure 3). Low-oxygen bottom waters were also analyzed colorimetrically by the micro-Winkler method [*Broenkow and Cline*, 1969]. Although the micro-Winkler data agree reasonably well with the other oxygen measurements, the comparison suggests that the Winkler titration and corrected sensor data may overestimate oxygen concentrations by 1–2 μmol/kg in the 0–4 μmol/kg range (Figure 3). Water samples collected with the rosette system were also analyzed on board for nutrients (phosphate, silicate, nitrate plus nitrite, nitrite and ammonium) with a modified 4- or 5-channel Technicon AutoAnalyzer II using standard colorimetric methods described by *Gordon et al.* [1992].

[11] Non-bioturbated sections in cores off southern Baja California were generally identified on board as sub-centimeter dark brown to black, coarse, millimeter- to centimeter-scale laminations rather than by the millimeter-scale fine laminations characteristic of Santa Barbara Basin (Table 1). Piston cores, gravity cores, and multicores from two sites at 430 m and 700 m water depth on the open margin of southern Baja California, one piston core from 1270 m water depth, and a piston and a gravity core from 540 m depth in nearby Soledad Basin (Figure 4) were selected for radiocarbon dating (Table 2). With the exception of the piston core from 1270 m depth, all cores contained sections of coarsely laminated sediments. Picked benthic foraminifera from the open margin sites, mostly low-oxygen *Bolivina* spp., were ^{14}C dated at the National Ocean Sciences Accelerator Mass Spectrometry facility in Woods Hole, Massachusetts. In Soledad Basin, well-preserved mixed planktonic foraminifera (mostly *G. bulloides* and *G. ruber*)

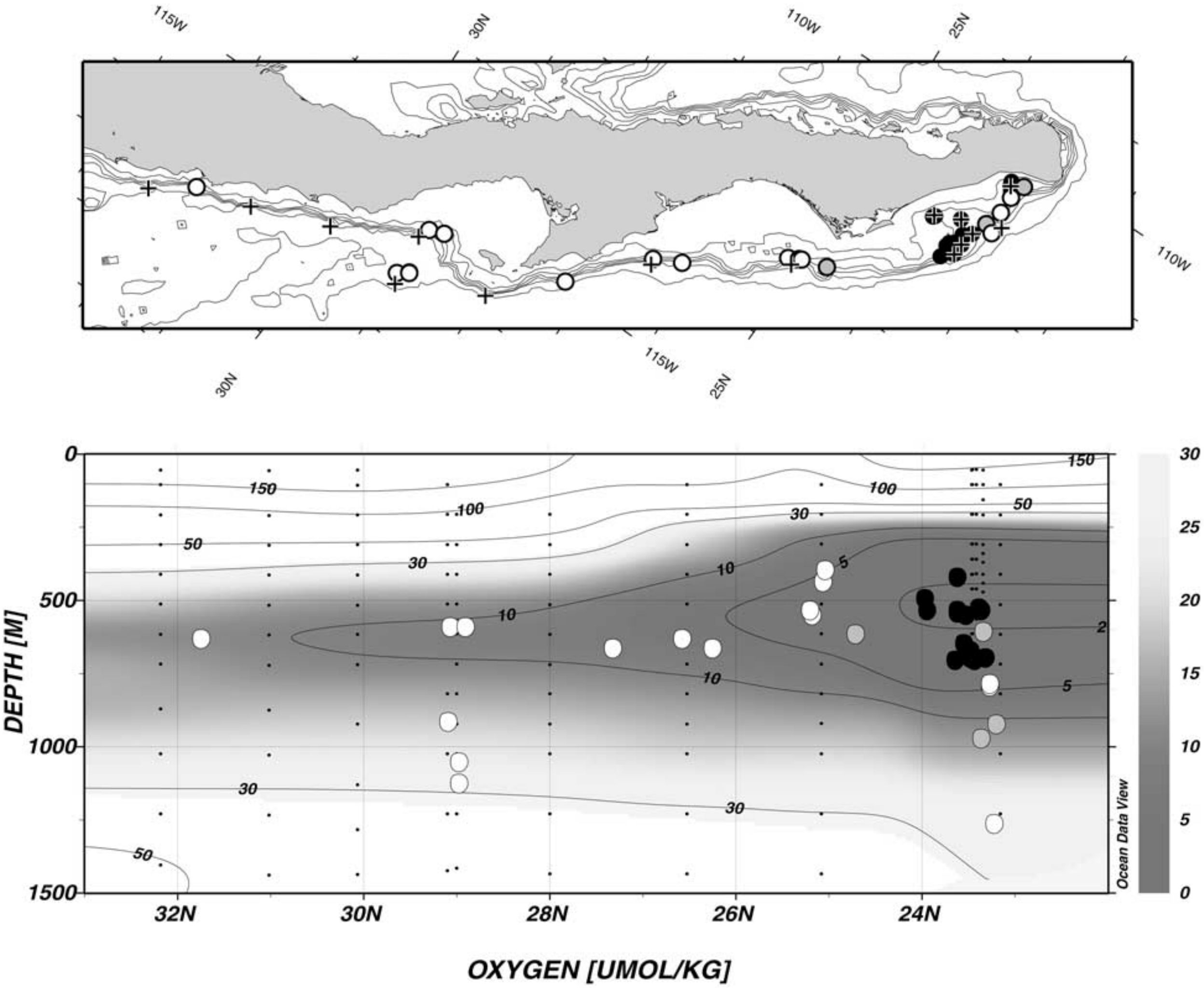

Figure 2. (top) Enlarged and rotated view of the Baja California peninsula with the location of sediment cores (circles) and CTD-rosette casts (crosses) collected in October-November 1999. Open circles indicate gravity cores containing homogeneous Holocene sediment and black circles indicate cores containing coarsely laminated Holocene sediment. Gravity cores with visible burrows or a faint banding pattern are indicated by gray circles. (bottom) A dissolved oxygen section along the Pacific margin of Baja California based on the CTD-rosette casts collected in 1999. Sample locations are indicated by small black dots. Contours drawn at 2, 5, 10 μmol/kg emphasize the core of the OMZ. Sediment characteristics of the upper portion of the cores, presumed to be of late Holocene age for the undated cores, collected at various depths along the margin are indicated by black (coarsely laminated), gray (faintly laminated or partially bioturbated), and white circles (homogeneous). Contour plot from Ocean Data View (available from R. Schlitzer, at http://www.awi-bremerhaven.de/GEO/ODV, 2002).

were used, in addition to a few samples of mixed benthic foraminifera for comparison.

[12] The GEOSECS station closest to our study area (Station 201 at 34.1°N; 127.5°W [*Ostlund et al.*, 1987]) indicates a nearly linear relation between the radiocarbon age of inorganic carbon in the water column and depth in the 400 to 1300 m range. From these measurements, radiocarbon reservoir ages of 1100, 1500, and 2100 years are calculated for the open margin sites at 430, 700, and 1270 m, respectively. To convert the benthic radiocarbon data to calendar ages using the Calib 4.3 program of *Stuiver and Reimer* [1993], a model age of 400 years was subtracted from these reservoir ages and an estimated uncertainty of ±100 years was assigned to the resulting ΔR values. The youngest and the oldest age of the resulting 2-sigma (sometimes multiple) age intervals were then used to calculate a mid-point and a range in calendar ages (Table 2). A somewhat different procedure was followed to convert radiocarbon data based on planktonic foraminifera to calendar ages in Soledad Basin. *Stuiver and Brazunias* [1993] list a ΔR of 225 ± 25 years for surface water of the region (i.e., a reservoir age of 625 years) based on radiocarbon measurements for pre-bomb mollusk shells. *Ingram and Southon* [1996] more recently estimated a ΔR of 233 ± 60 years for the area. In

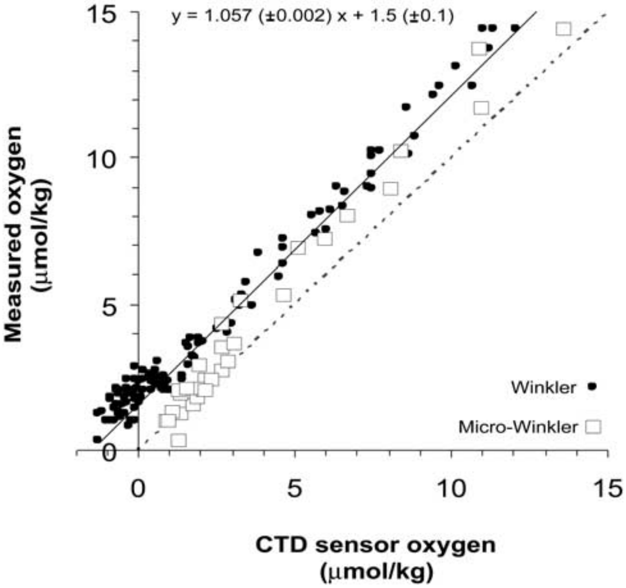

Figure 3. Comparison of oxygen concentrations measured by Winkler titration (filled circles) and by micro-Winkler colorimetry (open squares) as a function of the output from the oxygen sensor mounted on the CTD/Rosette. The dashed line indicates a one-to-one correspondence. The thin solid line is function obtained from the linear regression of the Winkler titration data as a function of oxygen sensor output that extends over a range in oxygen concentrations that is broader than the one displayed. The same function was used to re-calibrate the oxygen sensor data shown in Figure 5.

upwelling regions, however, the depth of origin of nearshore water in which mollusks grow could be different from the depth at which planktonic foraminifera calcify [*Robinson*, 1981; *Takesue and van Geen*, 2002]. To convert the radiocarbon ages to calendar ages, we therefore increased the uncertainty of the reservoir age of 600 years to ±100 years.

3. Results

3.1. Sediment Structure and Hydrography on the Open Margin

[13] The assumption before the cruise was that somewhere along the Baja California peninsula laminations would be preserved on the open margin under present hydrographic conditions. This was based on recent laminations observed on the open margin to the south, off Mazatlan [*Ganeshram et al.*, 1995], the lack of laminations in Holocene sediment accumulating to the north off Central California [*Gardner and Hemphill-Haley*, 1986; *Hemphill-Haley and Gardner*, 1994; *Dean et al.*, 1997; *Mix et al.*, 1999; *Zheng et al.*, 2000b], and the gradual southward intensification of the OMZ. This prediction was confirmed by a suite of gravity cores collected within the core of the OMZ at about 500-m depth on the southward leg of the cruise. However, no well-defined features indicative of inhibited bioturbation (banding or laminations) were observed until a latitude of 24°N was reached (Figure 2). This came as somewhat of a surprise because BWO concentrations were approaching the apparent threshold for bioturbation of ~5 μmol/kg suggested by the depth distribution of laminations in Santa Barbara Basin at 26°N [*Zheng et al.*, 2000a]. Most gravity cores collected from the core of the OMZ south of 24°N under BWO concentrations below 2 μmol/kg contained millimeter- to centimeter-scale coarse laminations ranging from black to brown in color (Figure 2). The 2–5 μmol/kg range in BWO concentrations appears to be transitional, with some core tops containing well-defined coarse laminations, others indications of partial bioturbation or fainter laminations, and others yet entirely homogeneous (Table 1 and Figure 5). This preliminary analysis assumes that the lack of bioturbation necessarily leads to the preservation of coarse laminations and that, at the sites where multicores were not collected, the tops of the gravity cores reflect present hydrographic conditions. The pattern of laminations was similar in multicores and gravity cores at all sites where both were collected.

[14] The transition from homogeneous sediment to coarsely laminated material was within the reach of gravity coring at all sites off southern Baja California on the open margin. The thickness of the laminated sections in the upper portion of the cores varied considerably from one location to the other, however. The thickest laminated sections (324 and 309 cm) were recovered on the open margin at 700 m depth (GC31 and GC36 in Figure 4). Closer to shore at 500 m, the thickness of the laminated section was reduced to 209 cm (GC35). However, the laminated section was slightly thicker (234 cm) at an even shallower site located further offshore (GC32 at 430 m). Of all the open margin sites that were sampled, only the easternmost sites closest to the tip of the peninsula contained finer millimeter-scale features similar in appearance to the laminations in Santa Barbara Basin. The upper laminated portion of the sediment at this location was considerably thinner, however (126 cm in GC39). Comparison of banding patterns between matched pairs of multicores and gravity cores from several sites generally indicate a loss of no more than ~25 cm of surface sediment from the tops of the gravity cores. Such losses are unlikely to be significant when comparing the tops of gravity cores with current hydrographic conditions in areas where dating shows that sediment accumulation is high, but they might be for other sites with undated cores.

[15] The coarse laminations are also visible in the upper part of most piston cores collected from the open margin off southern Baja California. These laminated sections typically are ~1.5 m thinner than in the gravity cores from the same locations due to loss of surface sediment by piston coring. Several piston cores from the open margin also reached deeper sections that were coarsely laminated. The thickest of these laminated sections was recovered in PC10 (the site of GC32) at 430 m depth (Figure 4). The section that separates the deeper and the shallow laminated material is 6.2 m thick in this core and occasionally has been only partially homogenized, as indicated by mottled patterns and burrows. The equivalent layer of often partially homogenized sediment separating the upper and deeper laminated sections is 8.2-m thick in PC08, at the site of GC31 at 700 m depth (Figure 4). Closer to shore at the sites of GC35 (500 m) and GC39 (540 m), no coarsely laminated sections were recovered in the

Table 1. Selection of Gravity Cores Collected off Southern Baja California

Core Number	Latitude, °N	Longitude, °W	Depth, m	Oxygen,[a] μmol/kg	Sediment Type	Description
GC-11	25.16	112.89	555	3.6	homogeneous	open margin near CTD 8
GC-52	25.04	112.82	441	5.2	homogeneous	open margin near CTD 8
GC-53	25.01	112.81	400	5.3	homogeneous	open margin near CTD 8
GC-22	23.26	110.79	798	4.7	homogeneous	open margin near CTD 10
GC-23	23.26	110.53	790	4.5	homogeneous	open margin near CTD 10
GC-38	23.22	111.08	1270	32	homogeneous	open margin near CTD 10
GC-12	24.69	112.70	620	3.8	burrows	open margin near CTD 8
GC-37	23.33	111.02	974	11.4	burrows	open margin near CTD 10
GC-28	23.33	110.37	610	2.1	faint bands	open margin near CTD 10
GC-30	23.31	110.46	700	3.0	faint bands	open margin near CTD 10
GC-29	23.19	110.32	930	9.7	faint bands	open margin near CTD 10
GC-45	25.21	112.68	494	2.9	laminations	Soledad Basin near CTD 17
GC-41	25.20	112.72	542	4.8	laminations	Soledad Basin at CTD 17
GC-42	25.20	112.74	532	4.8	laminations	Soledad Basin near CTD 17
GC-54	25.18	112.74	537	4.8	laminations	Soledad Basin near CTD 17
GC-43	25.18	112.75	501	3.0	laminations	Soledad Basin near CTD 17
GC-44	25.17	112.68	532	4.8	laminations	Soledad Basin near CTD 17
GC-50	25.16	112.76	442	4.8	laminations	Soledad Basin near CTD 17
GC-46	25.16	112.76	439	4.8	laminations	Soledad Basin near CTD 17
GC-35	23.94	111.33	504	0.8	laminations	open margin at CTD 11
GC-19	23.92	111.31	540	0.8	laminations	open margin near CTD 11
GC-40	23.63	111.80	720	1.1	laminations	deep basin at CTD 9
GC-36	23.63	111.15	711	1.8	laminations	open margin at CTD 12
GC-32	23.61	111.56	430	1.3	laminations	open margin near CTD 16
GC-33	23.60	111.51	540	0.8	laminations	open margin near CTD 16
GC-14	23.59	111.72	547	1.9	laminations	open margin near CTD 13
GC-34	23.54	111.46	650	1.0	laminations	open margin near CTD 16
GC-25	23.51	111.32	555	1.2	laminations	open margin near CTD 15
GC-31	23.47	111.60	705	2.3	laminations	open margin at CTD 13
GC-16	23.46	111.43	680	1.0	laminations	open margin at CTD 16
GC-17	23.42	111.23	712	3.0	laminations	open margin at CTD 15
GC-27	23.36	110.35	536	1.6	laminations	open margin near CTD14
GC-39	23.34	110.41	544	1.6	laminations	open margin at CTD 14

[a]Oxygen concentrations are from recalibrated SBE 13 sensor at nearest available CTD station.

deeper sections of piston cores PC03 and PC06, respectively (Figure 4). Even if bioturbation did not entirely homogenize the sediment at these sites, there are fewer sections with remnants of distorted banding patterns or burrows in near-shore cores PC03 and PC06 than in cores PC08 and PC10 located further offshore. Piston cores were also recovered from two deeper sites (Figure 4). Whereas GC37 (970 m) contains some darker burrow mottles suggesting partial bioturbation at some point in the past, the deeper sections of PC07 from the same site are entirely homogeneous. At 1270 m depth, both GC38 and PC09 contain entirely homogeneous nanoplankton- and foraminifer-bearing clay.

3.2. Hydrography and Sedimentation in Two Semi-Enclosed Basins

[16] One of the silled basins where water column samples and sediment cores were collected during our cruise is Soledad Basin, located about 200 km north of the open margin sites (Figure 4). This basin, occasionally also named Magdalena Basin, has been studied intermittently since the 1970's [*Soutar*, 1971] although detailed studies to exploit its paleoceanographic potential have started only recently (T. Baumgartner, J. C. Herguera, personal communications). The SeaBeam data we collected provide, to the best of our knowledge, the most detailed bathymetric map of Soledad Basin. The basin has a very flat bottom with a maximum depth of 540 m (Figure 4). A comparison of hydrographic profiles collected inside and outside the basin indicates that the water column density profiles start to diverge at 290 m depth (Figure 6). The density of the water inside the basin below 290 m also remains fairly constant, indicating that this is the effective sill depth. The bathymetry suggests that water exchange with the open margin occurs either through a gap south of the basin or through another sill in the area that was not surveyed to the north (Figure 4). The initial composition of bottom water for oxygen and nutrients was calculated by linear interpolation as a function of density between the two samples from the open margin that are closest in density. Comparison of these estimates with the actual composition of Soledad Basin bottom water indicates nearly conservative behavior for phosphate, silicate, and nitrate, and a reduction from an initial 8 to ~5 μmol/kg in BWO concentrations (Figure 7). The CTD oxygen profile suggests that, as in Santa Barbara Basin, water at the very bottom of Soledad Basin may be more frequently replenished from the outside by spillage over the sill than slightly shallower water (Figure 5). Coarse laminations were well preserved within Soledad Basin in cores collected under BWO concentrations of 3–5 μmol/kg, whereas open margin cores at the same latitude (GCs 11, 52, 53) and similar BWO levels contain no laminations (Figure 5).

[17] We selected for initial study cores GC41 and PC14 from the considerable suite of multicores, gravity cores, and piston cores collected in Soledad Basin in 1999 [*van Geen et al.*, 2001]. The entire gravity core and much of the piston core contain dark/light coarse laminations similar to the

Table 2. Radiocarbon Data for Selected Southern Baja California Cores

Depth in Section	Core Top	1950 AD[a]	^{14}C Age	Error	Calendar Age	Error
			Reservoir Age of 1500 ± 100 year			
MC-19 10 cm	10	8.5	1720	30	235	118
MC-19 25 cm	25	23.5	2050	35	548	73
MC-19 40 cm	40	38.5	2320	35	779	91
GC31-3 2 cm	2	25.5	2050	30	549	71
GC31-3 22.5 cm	22.5	46	2230	35	710	97
GC31-3 50.5 cm	50.5	74	3030	40	1495	114
GC31-3 70 cm	70	93.5	3690	45	2273	144
GC31-3 100.5 cm	100.5	124	3840	50	2446	146
GC31-3 123 cm	123	146.5	5130	60	4051	168
GC31-2 0.5 cm	150.5	174	5810	40	4984	147
GC31-2 50.5 cm	200.5	224	7190	50	6515	119
GC31-2 100.5 cm	250.5	274	8980	60	8344	120
GC31-1 8.5 cm	300.5	324	10050	410	9576	506
GC31-1 32.5 cm	324.5	348	11600	70	11561	357
GC31-1 58.5 cm	350.5	374	13500	70	14208	389
GC31-1 94.5 cm	386.5	410	13650	150	14350	453
PC08-7 99.75 cm	499.75	679.25	19650	80	21471	363
PC08-6 118 cm	675	854.5	25500	170	28210[b]	155
PC08-4 15 cm	860	1039.5	31200	280	34638[b]	211
			Reservoir Age of 1100 ± 100 year			
MC-17 15 cm	15	14	1680	30	574	74
MC-17 30 cm	30	29	2200	30	1052	107
GC32-2 11.8 cm	11.8	35.8	3390	45	2411	149
GC32-2 31 cm	31	55	3710	35	2770	128
GC32-2 66 cm	66	90	4950	30	4343	138
GC32-2 114 cm	114	138	6940	45	6681	130
GC32-1 3 cm	153	177	8740	40	8573	137
GC32-1 40 cm	190	214	10000	45	9927	187
GC32-1 85.8 cm	235.8	259.8	12000	70	13058	342
PC10-10 90.5 cm	90.5	273.5	12700	80	13440	198
PC10-9 50.5 cm	143.5	326.5	13300	75	14352	446
PC10-9 110.5 cm	203.5	386.5	16200	120	17972	320
PC10-8 20.5 cm	263.5	446.5	15650	85	17333	289
PC10-8 80.5 cm	323.5	506.5	30400	260	34194[b]	200
PC10-8 130.5 cm	373.5	556.5	37900	300	42372[b]	214
PC10-5 20.5 cm	683.5	866.5	45500	790	50312[b]	455
PC10-3 20.5 cm	983.5	1166.5	48100	540	52950[b]	322
			Reservoir Age of 2100 ± 100 year			
GC38-2 20.8 cm	20.75	45.75	11100	65	10098	239
PC09-10 19.8 cm	19.75	239.75	22700	160	24282	152
PC09-08 71.2 cm	304.25	524.25	42400	910	46070	529
			Reservoir Age of 600 ± 100 year			
GC41-2 64.5 cm p	64.5	84.5	1550	35	898	114
GC41-1 2.5 cm p	142.5	162.5	2630	45	2070	129
GC41-1 2.5 cm	142.5	162.5	2730	35	2178	128
PC14-10 103.5 cm p	103.5	245.5	3350	35	2977	127
PC14-10 103.5 cm	103.5	245.5	3610	95	3248	174
PC14-8 90.5 cm p	326.5	468.5	5150	65	5244	163
PC14-7 15.5 cm p	401.5	543.5	5810	70	5995	139
PC14-7 140.5 cm p	526.5	668.5	6580	70	6863	151
PC14-6 140.5 cm p	678.5	820.5	8070	130	8331	181
PC14-5 102.5 cm p	790.5	932.5	8820	75	9303	221
PC14-4 140.5 cm p	966.5	1108.5	10100	50	10788	247
PC14-3 125.5 cm p	1101.5	1243.5	10500	55	11370	268
PC14-3 125.5 cm	1101.5	1243.5	10350	85	11007	303
PC14-2 120.5 cm p	1246.5	1388.5	11650	80	13199	275
PC14-1 120.5 cm p	1396.5	1538.5	12600	65	14206	387

[a]To calculate depth relative to the 1950 AD horizon, 25–1.0 = 24 cm was added to depths in GC32 and 159 + 25 − 1.0 = 183 cm to depths in PC10 listed by *van Geen et al.* [2001]; 25 − 1.5 = 23.5 cm was added to depths in GC31 and 156 + 25 − 1.5 = 179.5 cm to depths in PC08; 25 − 0 = 25 cm was added to depths in GC38 and 195 + 25 = 220 cm to depths in PC09; 25 − 5 = 20 cm was added to depths in GC41 and 122 + 25 − 5 = 142 cm to depths in PC14. Mixed benthic foraminifera were dated, with the exception of intervals in the core Soledad Basin labeled "p" where mixed planktonic foraminifera were used.

[b]Intervals where the polynomial Calendar age = $(-3.0126\ 10^{-6} \times (\text{Res. corr. } ^{14}C \text{ age})^2 + (1.2896 \times \text{Res. corr. } ^{14}C \text{ age}) - 1005$ of *Bard* [1998] rather than the Calib 4.3 program of *Stuiver and Reimer* [1993] was used to convert radiocarbon ages.

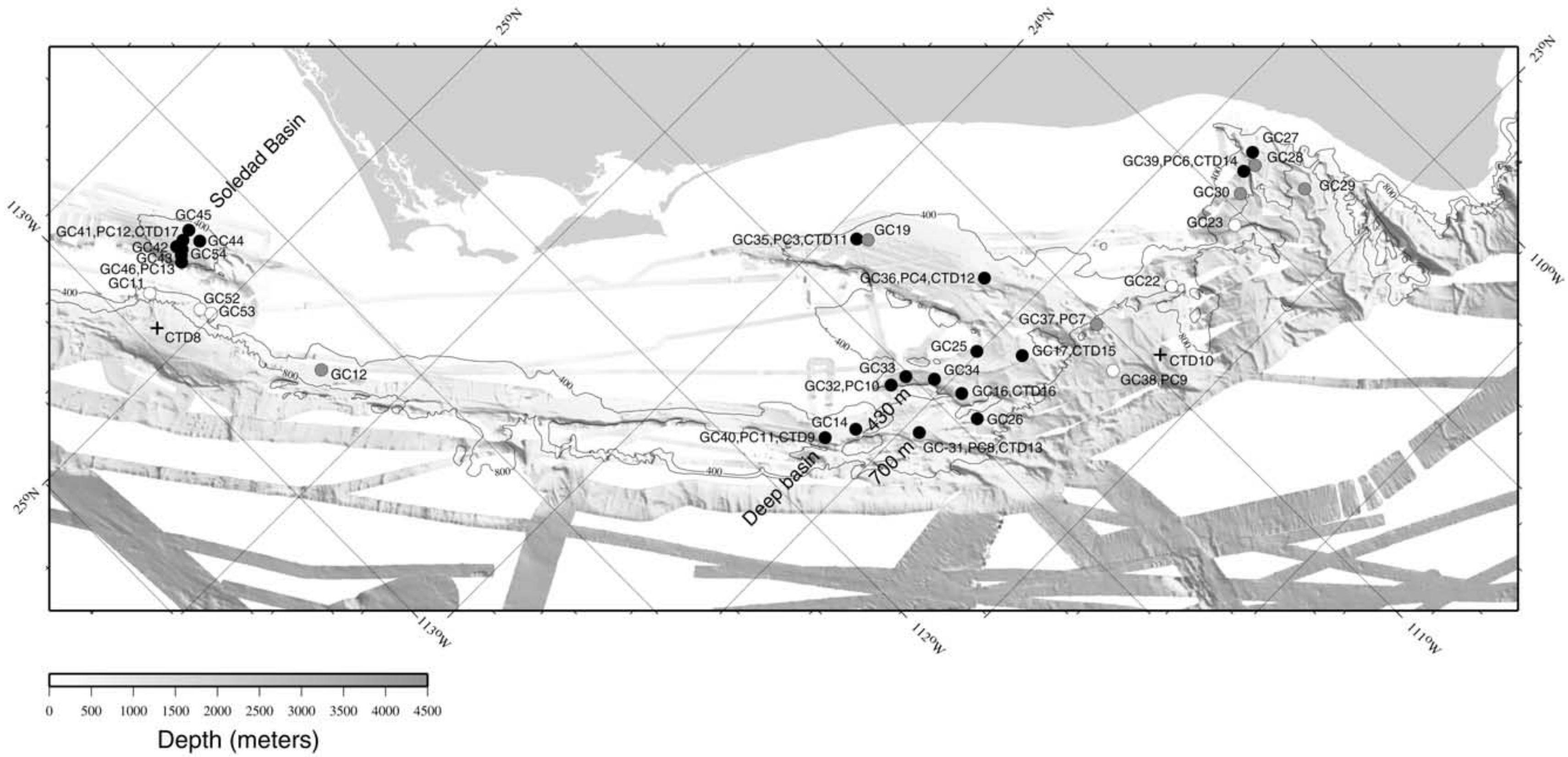

Figure 4. Detailed bathymetry of southern Baja California based on SeaBeam data (in color) and standard bathymetry for the area. Two isobaths at 400 and 800 m that delimit the core of the OMZ are shown. The map shows the location of all cores and CTD-Rosette casts collected in October-November 1999 south of 25.5°N (Table 1). The sites are labeled with the gravity core, piston cores and, where relevant, the CTD station numbers corresponding to each location. See color version of this figure at back of this issue.

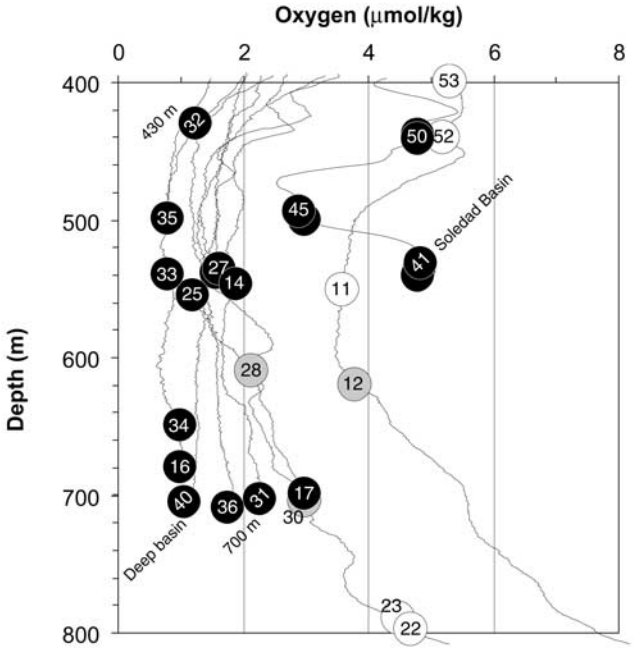

Figure 5. Depth distribution of dissolved oxygen (lines) and sediment gravity cores (circles) collected south of 25.5°N. The circles indicate the nature of the sediment according to the same classification as in Figure 2 and Table 1. The numbers within the symbols indicate the GC number corresponding to a particular site. Some of the CTD oxygen records correspond to the precise location of the sediment cores; others are from nearby stations (Table 1 and Figure 4).

patterns observed on the open margin further south. A difference between Soledad Basin and the open margin sites, however, is that an identical set of distinctive bands can be readily identified in all cores collected in Soledad Basin, some of them up to 5 km apart and spanning a 100-m range in water depth. The banding pattern in PC14 extends almost continuously to 876 cm depth, a much thicker interval than at the open margin sites further south. In addition to the coarse laminations, the cores all contained a considerable number of thin white millimeter-scale laminae composed almost entirely of coccoliths packed in faecal pellets. Interestingly, such coccolith laminae are well preserved to 1093 cm depth in PC14, well beyond the end of the coarsely laminated section.

[18] The 1999 R/V *Melville* expedition sampled another silled basin in the region (GC40 in Figure 4). The maximum depth of the flat bottom of this basin is 710 m. Comparison of the density profile of the water column inside the basin with that of a nearby station on the open margin indicates an effective sill depth of 460 m (Figure 6). Interpolation of water column properties outside the basin to the density of this bottom water indicates, as in the case of Soledad Basin, nearly conservative behavior of the water spilling over the sill (Figure 7). The BWO concentration of this basin is only ~1 μmol/kg, significantly lower than in Soledad Basin (Figure 5). Sediment cores from this basin have not yet been radiocarbon dated, but both GC40 and PC11 from this site contain coarse laminations. The 384-cm-long gravity core at this site did not reach a clearly bioturbated section. The 9.2-m section of homogeneous or highly bioturbated sediment recovered in PC11 from the same site is thicker than the bioturbated section in any of the other piston cores recovered from the open margin.

3.3. Dating of the Sediment Cores

[19] The distribution of calendar ages calculated from the radiocarbon data as a function of depth shows that the available records cover very different time spans (Table 2). To account for sediment loss during piston coring, depths in PC10 (430 m) and PC08 (700 m) were increased by 159 and 156 cm, respectively, relative to the corresponding gravity cores. These offsets were determined by comparing the depth of the well-defined transitions from bioturbated to coarsely laminated sediments in the corresponding piston and gravity cores. The overlap between the two bioturbated

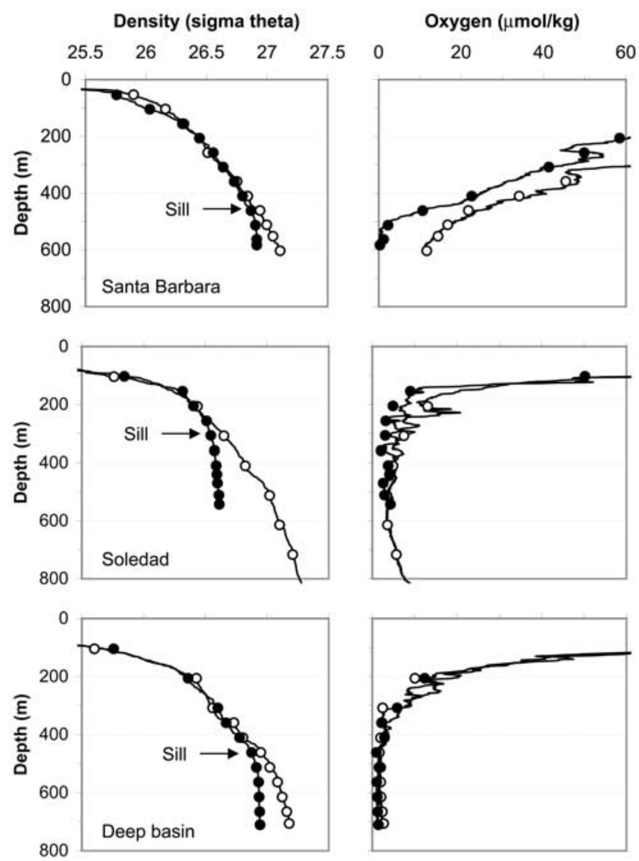

Figure 6. Comparison of density and oxygen profiles based on rosette samples collected inside (black circles) and outside (open circles) three silled basins along the western margin of North America in October–November 1999. Also shown with solid lines are corresponding continuous density and oxygen profiles obtained from the CTD and oxygen sensors. Sill depths were determined by linearly interpolating the density of bottom water in each basin between two intervals outside the basin that are closest in density.

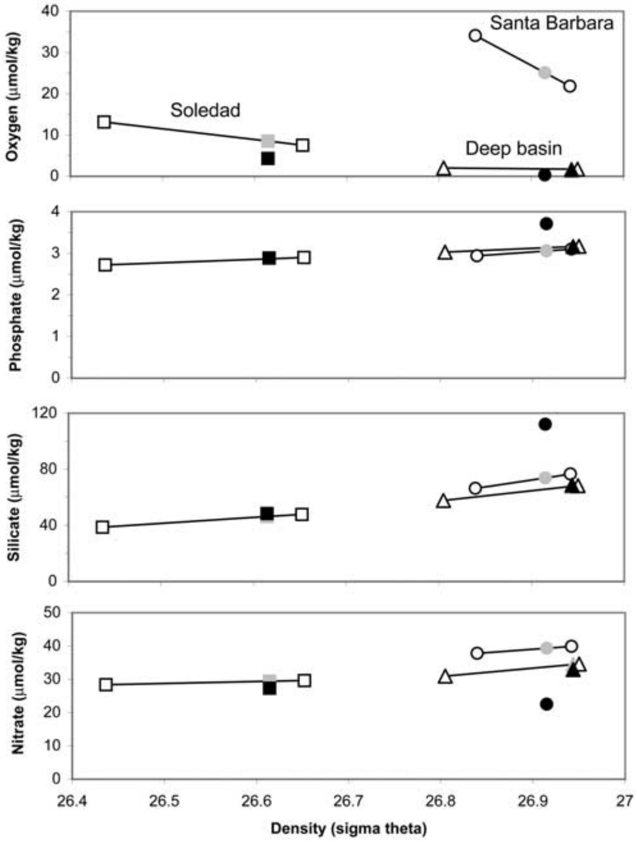

Figure 7. Comparison of bottom water properties in October–November 1999 inside three silled basins (black symbols) with water column properties outside the basin (open symbols) as a function of density. The composition of bottom water assuming conservative mixing in proportion to density is indicated by shaded symbols. Note that the density of bottom water in the new deep basin off southern Baja California is only slightly higher than bottom water in Santa Barbara Basin.

cores at 1270 m depth, determined from overlapping diffuse spectral reflectance patterns, indicates a loss of 195 cm from PC09 relative to GC38 (J. Ortiz, unpublished data). Another 25 cm was added to the depths of all gravity and piston core samples to account for the loss of surficial sediment by gravity coring, as documented with the overlapping banding patterns of MC19 and GC31. Finally, the mean sedimentation rate was used to re-calculate depths relative to the 1950 AD reference interval for radiocarbon dating, based on the 1999 collection date, by subtracting 1, 1.5, and 0 cm from depths in GC32/PC10, GC31/PC08, and GC38/PC09, respectively (Table 2). With the exception of depths listed relative to the 1950 AD horizon in Table 2, the reference for depths referred to in this paper is the top of that particular gravity or piston core, as listed by *van Geen et al.* [2001].

[20] The depth distribution of the inferred calendar ages indicates that sedimentation has been highest (30 cm/kyr) and remarkably steady over the past 35 kyr for the open margin site at 700-m depth (GC31/PC08 in Figure 8). Sedimentation was somewhat lower at the shallower site at 430 m depth (22 cm/kyr) and, more significantly, the distribution of calendar ages indicates much slower sedimentation, or perhaps even a hiatus, during the 40–20 ka period that includes the LGM (GC32/PC10 in Figure 8). The two calendar dates over 50 ka from this site are minimum ages since they are beyond the practical range of radiocarbon dating. Sediment accumulation was slower again at 1270-m depth (13 cm/kyr) and most of the Holocene appears to be missing at this site (GC38/PC09 in Figure 8). Although the interval dated 46 ka at this site appears to be consistent with the other two dates, assuming constant sedimentation, it should be interpreted with caution.

[21] The overlap of distinct patterns of laminations in GC41 and PC14 from Soledad Basin indicates a loss of 122 cm in the piston core relative to the gravity core. A correction of 25 cm was added to depths in GC41 and PC14, assuming the same loss documented on the open margin with the multicorer applies to this location. To calculate depths relative to the 1950 AD horizon, 5 cm was subtracted in both GC41 and PC14 (Table 2). The depth distribution of calendar ages in Soledad Basin determined from planktonic radiocarbon measurements indicates a steady and very high sedimentation rate averaging 108 cm/kyr (Figure 8). Mixed benthic foraminifera were also radiocarbon dated from one interval in GC41 and two in PC14. The results were barely distinguishable from the radiocarbon ages obtained for planktonic foraminifera from the same sediment samples (Table 2). This indicates a pre-bomb radiocarbon age of water at the depth of the sill of Soledad Basin very similar to that of the euphotic zone where planktonic foraminifera calcify.

4. Discussion

4.1. Conditions Leading to the Preservation of Laminations

[22] Distinguishing bioturbated from non-bioturbated sediment off southern Baja California is complicated by the lack of pronounced seasonality in the input of detrital and biogenic sediment material, unlike the Northern and Central California margins [*Gardner and Hemphill-Haley*, 1986; *Anderson et al.*, 1989] and the Gulf of California [*Thunell et al.*, 1993, 1995; *Pike and Kemp*, 1997]. Reduced seasonality at the open margin sites is indicated by the absence of discernable sections of millimeter-scale laminations within the coarser light/dark laminations that clearly have not been bioturbated. Reduced seasonality in sedimentation is also consistent with weaker and relatively constant upwelling-favorable winds that steady phytoplankton productivity off southern Baja California, as well as the limited precipitation in the region compared to northern and central California. The only cores from the open margin that do show millimeter-scale laminations are located close to shore towards the southern extremity of the peninsula (e.g., GC39 in Figure 4) and contain considerably coarser detrital material (mean phi of 5.5 in GC39 vs. 7.5 in GC31; M. Prins, unpublished data). The thinner upper section of non-bioturbated material and the presence of submarine canyons in the area suggest that these thin laminae may reflect hiatuses caused by intermittent periods of erosion rather than variations in the nature of the supply of sediment.

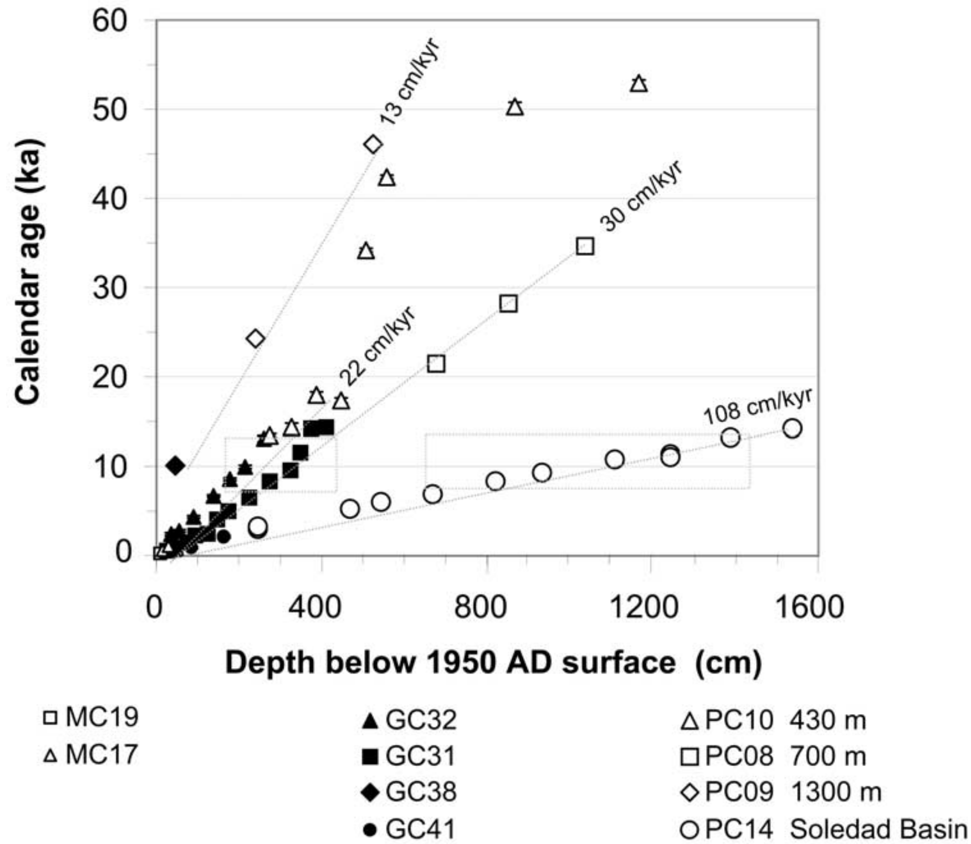

Figure 8. Depth distribution of calendar ages at four sites along the southern Baja California margin derived from radiocarbon measurements on mixed benthic and planktonic foraminifera listed in Table 2. Average sedimentation rates are also indicated. Conversion to common depth scale relative to the 1950 AD horizon for multicores, gravity cores, and piston cores is described in the caption of Table 2. Expanded views in Figure 9 are outlined by two rectangles.

[23] The one exception off southern Baja California where preserved millimeter-scaled features are most likely linked to brief depositional events is in Soledad Basin. The numerous coccolith laminae visible through much of the cores that were recovered in this basin probably reflect individual blooms of the type that have been documented in Soledad Basin with sediment traps (C. Lange, personal communication). We do not know if the coccolith blooms extend further south to the open margin sites today. Even if they did in the past, these laminae would be much more difficult to detect on the open margin where the sedimentation rate is at least three times lower than in Soledad Basin. The presence of coccolith layers in some of the deeper sections of Soledad Basin that otherwise appear homogeneous allows us to make an important distinction that is likely to be applicable to the open margin. Because coccolith laminae would not have been preserved if these sections had been significantly bioturbated, this indicates that the lack of bioturbation does not necessarily lead to the formation of coarse light/dark laminations within the OMZ off southern Baja California. The geochemistry of the formation of the coarse laminations is beyond the scope of this paper, but it is reasonable to postulate that the dark/light patterns reflect diagenetic responses in the redox state of iron and/or sulfur to variations dictated by the degradation of settling organic matter [e.g., *Giosan et al.*, 2002; *Robinson et al.*, 2002, and references therein]. Under this scenario, darker bands could be produced by the reduction of iron and/or sulfur under an increased demand for electron acceptors triggered by an increased supply of organic matter or a reduction in BWO. The presence of non-bioturbated sediments without banding in Soledad Basin therefore suggests that even under very low BWO concentrations, a minimum supply of labile plankton material may be required to generate dark diagenetic bands in the underlying sediment.

[24] There is additional evidence of decoupling between bioturbation and BWO concentrations that is possibly related to the supply of organic matter. As noted previously, cores GC52 and GC53 within the center of the OMZ outside Soledad Basin do not contain any visible dark bands, although BWO levels of ~5 μmol/kg are essentially identical to those inside the basin (Figure 5). This could be because the shallow ridge that separates these sites from Soledad Basin drastically reduces the supply of sediment, and therefore organic matter, to the open margin sites (Figure 4). The implication is that sediment in GC52 and GC53 may not be bioturbated even though the cores appear

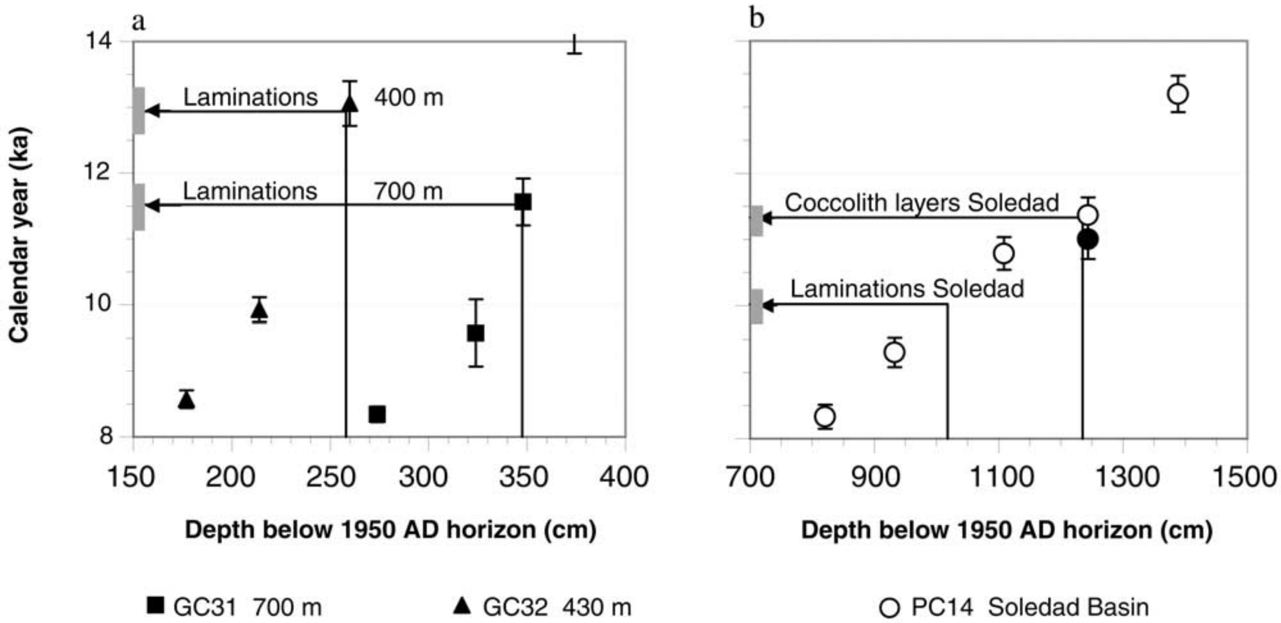

Figure 9. Expanded view of the depth distribution of calendar ages for intervals closest to the transition from bioturbated post-LGM sediment to (a) the coarse early-Holocene laminations preserved on the open margin at 430 and 700-m depth and (b) the first coccolith laminae and the first dark band preserved within Soledad Basin. Error bars derived in the manner described in the caption of Table 1 for individual calendar age estimates are also shown. The depth scale refers to the 1950 AD horizon.

homogeneous. There are other inconsistencies between sediment structure and hydrography indicating that reaching a threshold BWO concentration may be a necessary but not a sufficient condition for the formation and preservation of coarse laminations on the Baja California margin. Cores GC37 and GC29 at 930–970 m depth with a BWO concentration of ~10 μmol/kg still contain faint or partly bioturbated bands, whereas two shallower cores from the same area (GC22 at 800 and GC23 at 790 m) under lower BWO concentrations of ~5 μmol/kg are entirely homogeneous (Table 1 and Figure 2). The key difference between these two pairs of sites may be the local bathymetry that might suggest greater focusing of sediment, and a greater flux of organic matter, at the two deeper sites (Figure 4). Cores GC22 and GC23 may therefore appear homogeneous without being bioturbated because the supply of organic matter has been too low to generate the coarse laminations. Such deviations from a simple relation between a threshold BWO concentrations and the formation and preservation of diagenetic bands must be kept in mind when examining more closely the timing of deposition of the non-bioturbated units following deglaciation.

4.2. Onset of Preservation of Laminations Off Southern Baja California

[25] The onset of preservation of the most recent laminated units on the open margin in GC32 (430 m) and GC31 (700 m) is well constrained by radiocarbon measurements (Figure 9). Interpolation between two dated intervals yields a date for this transition of 12.9 ka at 430 m and 11.5 ka at 700 m depth. The 1.4 kyr difference is significant since the 2-sigma uncertainty in absolute calendar ages is on the order of ±0.5 ka. In reality, the delay in the onset of banding at 700 m relative to 430 m is probably even better constrained because the relative uncertainty in calendar ages is smaller if the difference in reservoir age between the two sites stayed relatively constant over time. The difference also seems larger than could be explained by differential propagation of changes in atmospheric ^{14}C during deglaciation at the two sites [*Adkins and Boyle*, 1997]. In Soledad Basin, the accumulation of the first set of dark bands at 10.0 ka apparently was delayed by another 1.5 kyr (Figure 9). Preservation of the first coccolith laminae in Soledad Basin at 11.3 ka suggests that bioturbation ended before deposition of the laminations, roughly simultaneously with the deposition of the first laminations on the open margin at 700-m depth.

[26] One possible interpretation of the timing of these transitions is an apparent drop in BWO below the threshold for bioturbation in the core of the OMZ at 400 m depth well before a nearby location that is ~300 m deeper. This is oceanographically plausible. The rain rate of labile organic matter in the ocean drops off rapidly with depth and one expects that the re-establishment of an intense OMZ would occur first at shallower depths. The asynchronous preservation of coarse laminations off southern Baja California may therefore indicate that it took on the order of one turnover period of today's deep ocean to broaden the portion of the OMZ with BWO levels below 5 μmol/kg from 430 to 700 m depth. A delay in the reduction of BWO at the 700-m site could also be consistent with the suggestion that ventilation of intermediate waters of the North Pacific within the lower portion of the OMZ was temporarily enhanced between 11 and 9 ka relative to shallower depths [*van Geen et al.*, 1996]. The stronger influence of Subtropical Subsurface Water supplied by the

Equatorial Undercurrent at the shallower of the two sites today [*Kienast et al.*, 2002] suggests that other differences in hydrography could have decoupled the decline in BWO concentrations at the two open margin sites during deglaciation. Consideration of the potential role of the flux of organic matter in triggering the generation of coarse laminations suggests, however, that there is an equally plausible scenario under which water column oxygen levels did not necessarily change appreciably between 12.9 and 10.0 ka but productivity gradually increased to the point where diagenetic bands were formed at 430 m depth on the open margin, then at 700 m, and finally inside Soledad Basin. Similar factors may explain why the pattern of laminations of two records from the Gulf of California that have been carefully dated appear to be different as well (Figure 1).

4.3. Comparison With Other Sites Along the Margin of North America

[27] Other available records of laminations provide some additional constraints on what must have been major reorganizations of circulation in the North Pacific during deglaciation. It is useful in this context to consider open margin sites and semi-enclosed basins separately. Only open margin sites south of 24°N show preservation of laminations within the core of the OMZ during the Holocene (Figure 1). Because the productivity of the California Current appears to be higher north of Baja California based on satellite chlorophyll measurements [*Thomas et al.*, 2001], this suggests that ventilation of the OMZ from the north has been sustained throughout the Holocene. In contrast, preserved laminations and geochemical proxies indicate that particularly reducing conditions prevailed at several open margin sites to the north during the Bolling-Allerod [*van Geen et al.*, 1996; *Mix et al.*, 1999; *Zheng et al.*, 2000b], but evidently not off southern Baja California. Faunal assemblages of benthic foraminifera at (bioturbated) ODP Site 1017 at a depth of 955 m on the open California margin, northwest of Santa Barbara Basin [*Cannariato and Kennett*, 1999], and at ODP Site 1019 further north [*Mix et al.*, 1999] also indicate a more pronounced OMZ during the Bolling-Allerod than during most of the Holocene. The available open margin records therefore clearly show that rather different distributions of productivity and/or ventilation along the western margin of North America prevailed during these two relatively warm climate intervals.

[28] The precise set of conditions that distinguish the Holocene and the Bolling-Allerod are difficult to determine without independent records of ventilation and productivity. One can speculate that if ventilation of the northeast Pacific OMZ during the LGM and at the onset of deglaciation originated in the Southern Ocean [*Lund and Mix*, 1998], then open margin sediment off southern Baja California may have remained bioturbated during the Bolling-Allerod because BWO concentrations were higher than at the northern sites where laminations were preserved. The diminishing role of a southern source of intermediate waters during early deglaciation is difficult to reconcile, however, with the preservation of laminations before or at the Bolling-Allerod at 420 m depth off Mazatlan and at 818 m depth in the Gulf of California (Figure 1). If instead ventilation during the LGM and throughout deglaciation continued to originate in the North Pacific as it does today [*Keigwin*, 1998], and therefore BWO concentration off Baja California always were lower than at the northern sites, then the lack of coarse laminations off southern Baja California during the Bolling-Allerod may indicate instead that productivity was locally not sufficient to trigger the formation of visible patterns in underlying sediment.

[29] The presence of laminations in deeper sections of the piston cores from southern Baja California and other locations along the western margin of North America suggests that patterns of productivity and ventilation during the warm interstadials of marine-isotope stage 3 may have been different again from the conditions that prevailed during the Bolling-Allerod or the Holocene. Both PC10 at 430 m and PC08 at 700 m contain coarse laminations that precede the LGM. The end of the preservation of these sequences can be estimated from the available radiocarbon dates. There is considerable uncertainty in the timing of preservation of laminations in PC10 because of the dramatic drop in sedimentation rate before and during the LGM (Figure 8). The local bathymetry suggests that sedimentation at the site of PC10 (430 m) could indeed have been reduced when sea level was particularly low (Figure 4). An estimated age for the end of preservation of laminations at this site of 57 ka is calculated by extrapolating from the oldest measurable calendar age of 42.4 ka, measured 320 cm above the deposition of the last pre-glacial dark band, assuming a constant sediment rate of 22 cm/kyr (Figure 8). The onset of bioturbation in PC08 at 700 m depth is much better constrained. In this core, the age of the oldest dated interval at 35 ka, located 30 cm above the last dark band deposited before the LGM, can be increased with confidence by 1 kyr based on the average sedimentation rate of 30 cm/kyr. The onset of bioturbation in PC08 at 36 ka is essentially identical to the timing of the onset of glacial bioturbation (Figure 1) in core NH15P within the OMZ off Mazatlan [*Ganeshram et al.*, 1995] and a shift to less reducing conditions indicated by the benthic fauna at (bioturbated) open margin ODP Site 1017 [*Cannariato and Kennett*, 1999]. Combined with the observation of several sequences of laminations in deeper sections of a number of cores from within the OMZ of central California (Figure 1), this suggests that conditions in open margin sediments before the LGM may occasionally have been more widely reducing than during either the Bolling-Allerod or the Holocene.

[30] How do conditions recorded on the open margin relate to the records of laminations in Santa Barbara Basin? There is, first of all, a significant difference in how closely conditions in Santa Barbara (or Santa Monica) Basin reflect conditions on the open margin compared to the two semi-enclosed basins cored off southern Baja California during the 1999 R/V *Melville* cruise. The difference is the extent to which oxygen is consumed within these basins. The effect is illustrated with hydrographic data collected in October-November 1999 for internal consistency, but has of course been noted previously for Santa Barbara Basin [e.g., *Sholkovitz and Gieskes*, 1971; *Reimers et al.*, 1990]. Comparison of density profiles inside

and outside Santa Barbara Basin indicates an effective sill depth of 450 m, which is consistent with the bathymetry of the region (Figure 6). Interpolation of water column properties outside the basin to the density of bottom water inside the basin indicates that, in contrast to the southern Baja California basins, a considerable amount of oxygen and nitrate is consumed within Santa Barbara Basin, and a measurable amount of phosphate and silicate is added to the water column from the decomposition of plankton (Figure 7). The difference could be due to a longer residence time of water below the sill depth within Santa Barbara Basin, which is on the order of a year [*van Geen et al.*, 1995, and references therein] or, more likely, because of higher productivity off coastal Southern California compared to southern Baja California. In either case, the implication is that whereas the pattern of laminations recorded in Santa Barbara Basin may well have been modulated by large-scale processes such as changes in productivity of the California Current or changes in ventilation of the OMZ outside the basin [*Behl and Kennett*, 1996; *Cannariato and Kennett*, 1999a; *Cannariato et al.*, 1999; *Hendy and Kennett*, 1999; *Stott et al.*, 2000a], the main reason the bottom of this basin is so delicately poised relative to these changes in terms of preservation of laminations or bioturbation is because of oxygen consumption within the basin. Drawdown of BWO within Santa Barbara Basin could therefore explain why both the Holocene and the Bolling-Allerod are recorded as laminated sections inside the basin whereas several nearby open margin sites clearly indicate more reducing conditions during the Bolling-Allerod [*Cannariato and Kennett*, 1999; *Zheng et al.*, 2000b].

[31] Local consumption of oxygen may also explain certain differences in the timing of transitions to more reducing conditions in Santa Barbara Basin relative to other sites. Considering the new southern Baja California records, the transition to an intensified OMZ appears to have started at 13 ka and lasted about 3 kyr (Figure 9). This timing is somewhat surprising because it indicates that conditions became sufficiently reducing before the Younger Dryas cold interval when many of the other records in the region indicate a temporary return to relatively oxic conditions (Figure 1). The only other open margin record of laminations within the upper OMZ (NH15P) also does not show an interruption during the Younger Dryas, which suggests that only deeper sites were affected by a return to cold conditions. This interpretation is not consistent with the data from Santa Barbara Basin, which also has a shallow sill, where instead the full range in response of bottom proxies such as the bioturbation index and benthic faunal assemblages from oxic to more reducing conditions spans only a few hundred years starting at $\sim$11 ka [*Behl and Kennett*, 1996; *Cannariato et al.*, 1999a]. This discrepancy might have suggested an effect of surface forcing, i.e., productivity, on conditions in the bottom of Santa Barbara Basin were it not for the fact that the response of surface proxies, such as faunal assemblages of planktonic foraminifera and their oxygen isotopic composition, in Santa Barbara Basin during deglaciation also spans several thousand years [*Hendy et al.*, 2002]. For reasons that are therefore not clear at this point, it appears as though bottom proxies from Santa Barbara Basin create the appearance of very rapid climate change at the onset of the Holocene, whereas conditions on the open margin may have been evolving more gradually. *Stott et al*. [2000b] also suggested that the OMZ of the northeast Pacific may have evolved more gradually than suggested by some of the Santa Barbara Basin records.

[32] Despite the uncertainties in dating for some of the sequences of laminations deposited before the LGM, some general observations can be drawn from the combined set of open margin and basin records. The basic pattern suggests four distinct sets of oceanographic conditions along the western margin of North America prevailed during the past 60 kyr: (1) very cold climate conditions corresponding to the LGM and earlier stadial intervals when laminations were not preserved anywhere along the margin; (2) present interglacial conditions when laminations are preserved within the OMZ on the southern part of the open margin but not the northern margin, (3) warm climate conditions corresponding to the Bolling-Allerod when laminations were formed and occasionally preserved off northern and central California but not off southern Baja California, and (4) warm interstadials preceding the LGM when particularly reducing conditions resulted in the preservation of laminations along the entire open margin. These features add some nuance to the bimodal pattern of climate change that frequently has been invoked in the interpretation of the records that have been recovered from Santa Barbara Basin [*Hendy and Kennett*, 2000].

5. Conclusions

[33] Bioturbation has been inhibited within the OMZ on the open Pacific margin of southern Baja California throughout the Holocene and prior to 36 ka. Unlike other sites with a pronounced seasonal cycle in the nature of sediment deposition, a minimum flux of organic matter reaching the sediment may be required off Baja California to produce diagenetic evidence of the lack of bioturbation in the form of light/dark coarse laminations. This might explain why the intensification of the OMZ off southern Baja California over the course of deglaciation does not appear to be simultaneous at different locations. On the other hand, the asynchronous timing could indicate different regional responses of the OMZ to deglaciation. Relatively low productivity may have prevented the formation of the banding pattern characteristic of inhibited bioturbation off southern California during the Bolling-Allerod, a period during which other locations along the margin of North America indicate a particularly intense OMZ. Although the Bolling-Allerod and Holocene were both recorded as particularly reducing intervals in Santa Barbara Basin, the available suite of open margin records indicates that conditions of OMZ intensity and productivity were quite different on the open margin during these two periods. When laminations were preserved during the warm interstadials that preceded the LGM, conditions on the open margin appear to indicate a pronounced OMZ over a wider area of the western margin of North America than today or during the Bolling-Allerod.

[34] The value of the Santa Barbara Basin record of laminations and its close link to interstadials recorded in Greenland ice is in no way diminished by our documentation of a complex relation between the preservation of laminations inside the basin and conditions on the open margin. The implication is that other approaches, possibly geochemical and faunal proxies of surface- and bottom-water conditions retrieved from the existing open margin records are needed to better understand the nature of the linkage between the intensity of the North Pacific OMZ and global climate. In this respect, further study of two silled basins off southern Baja California sites with very limited internal consumption of oxygen may be fruitful. Soledad Basin is more directly influenced by climatic signals from the tropics such as the El Nino-Southern Oscillation than Santa Barbara Basin. The Soledad Basin cores may therefore yield proxy records of these processes through the Holocene at unprecedented resolution.

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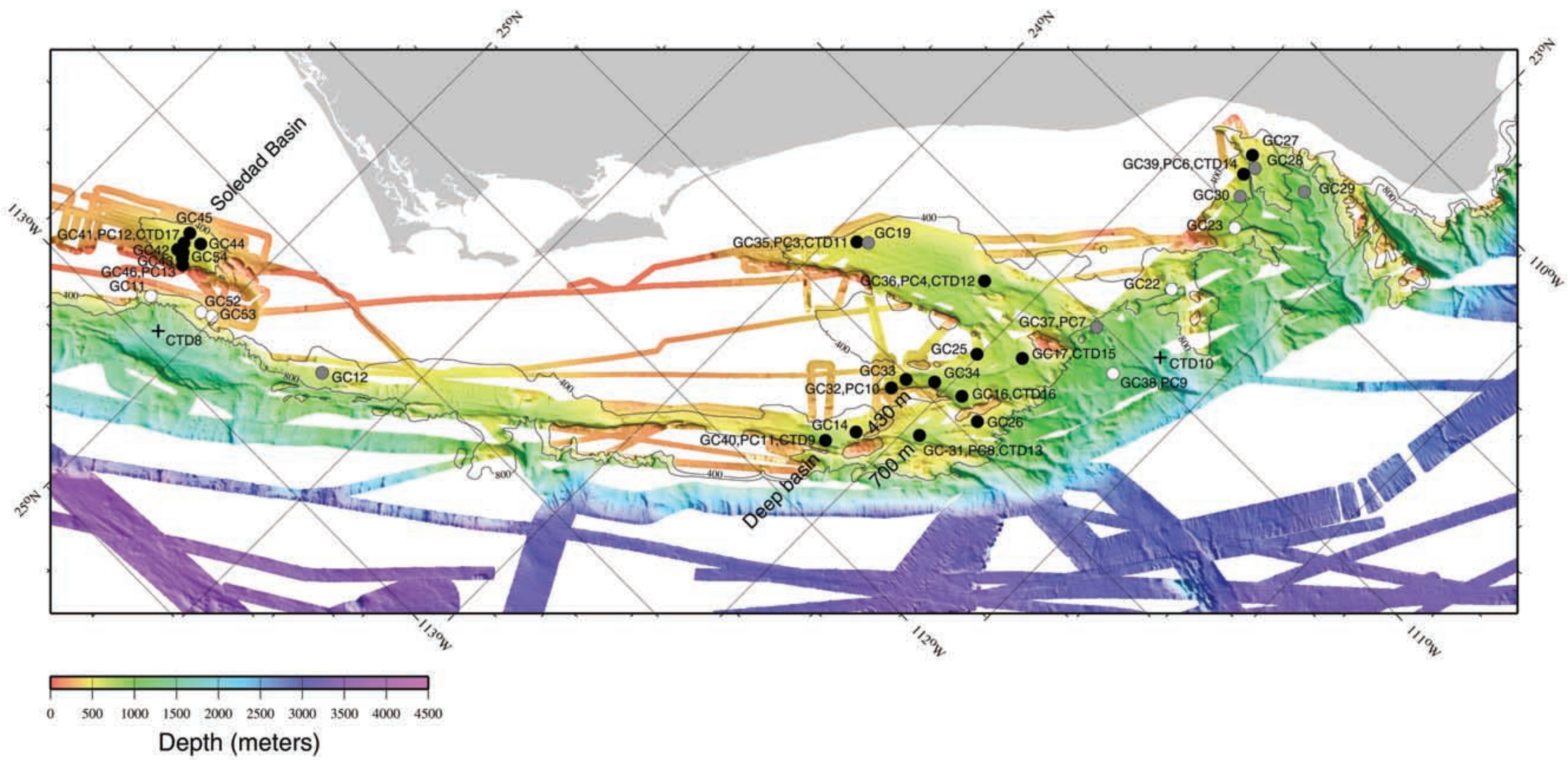

Figure 4. Detailed bathymetry of southern Baja California based on SeaBeam data (in color) and standard bathymetry for the area. Two isobaths at 400 and 800 m that delimit the core of the OMZ are shown. The map shows the location of all cores and CTD-Rosette casts collected in October-November 1999 south of 25.5°N (Table 1). The sites are labeled with the gravity core, piston cores and, where relevant, the CTD station numbers corresponding to each location.