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PRODUCTIVITY CHANGES IN THE MAGDALENA MARGIN OF MEXICO, BAJA CALIFORNIA PENINSULA, DURING THE PAST 50,000 YEARS

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The biological pump in the ocean plays an important role in the global carbon cycle. A substantial portion of carbon is exported and preserved on continental margins, areas that support 10 to 15% of the total production of chlorophyll across the ocean with a contribution of more than 40% of the global organic carbon export to the ocean floor. Reconstruction of past primary productivity (PP) in areas of high biological activity is important to understand how climate change affects the global carbon cycle in different timescales. Burial rates of organic carbon (Corg) and biogenic opal (BSi) were measured in a core couplet GC31/PC08 from the Magdalena margin, SW of the Peninsula of Baja California, in order to estimate changes in PP during the last 50,000 years. During the late Holocene (period between 3,000 years ago and today), the burial rate of BSi and Corg was lower than in the marine isotope stages 2 and 3 (occurred in the periods 29,000 to 14,000 and 57,000 to 29,000 years ago, respectively), including the last glacial maximum (27,000 to 18,000 years ago), suggesting that PP was greater in the latter two stages than in the most recent part of the record. In the marine isotope stage 3, the burial rate of BSi and Corg showed important oscillations coupled with DO cycles (rapid climate fluctuations that occurred in Greenland during the last glacial period with a quasi-periodically recurrence time of 1,470 years) indicating that PP in the region responds to millennial-scale global climate forcing. Our study in Baja California suggests that, in coherence with evidences from other sites along the northeast Pacific margin, the variability of the Oxygen Minimum Zone (OMZ) in the northeast Pacific is more largely controlled by changes in productivity rather than by ventilation changes of the water column, as it was the prevalent view.

Keywords: oceanic paleoproductivity, paleoclimate, global climate change, carbon export, carbon-silica burial rates, millennial cycles, marine isotope stages.

1. INTRODUCTION

The continental margin of the Baja California Peninsula is one of the four areas of the world characterized by high biological productivity in the surface and an underlying oxygen minimum zone. Along the southwestern coast of the Peninsula, upwelling intensity is greatest from April to June, changing with the local wind conditions and sea bottom topography (Zaitzev *et al.* 2003). Coastal upwelling along the west coast of Baja California changes the local properties of surface water by decreasing its temperature, enriching the water column with nutrients and hence increasing biological productivity.

The intensity of the oxygen minimum zone (OMZ) along the eastern border of the North Pacific is a function of two primary variables: 1. Ocean circulation and 2. Oxygen consumption (Wyrtki 1962). Ventilation is the process that transfers surface conditions (high oxygen concentrations) to subsurface waters (*e.g.*, by ocean circulation) (Van Scoy and Druffel 1993). Currently, the ventilation of the OMZ in the northeastern Pacific reflects the balance between the contribution of North Pacific Intermediate Water (NPIW, relatively rich in oxygen from the northern Pacific) and the Subtropical Subsurface Water (SSW, deficient in oxygen, from the southern Pacific). A relative change in the input and/or concentration of oxygen in some of these water bodies influences the intensity of the OMZ. Additionally, oxygen consumption occurs throughout the water column by oxidation of organic matter and after its deposition on the ocean floor. The higher the rate of export of labile (easy to decompose) organic matter from surface waters, the greater the deficiency of oxygen in the underlying intermediate water. In the northeastern Pacific, large changes in primary productivity occurred in the past which may have had a substantial impact on the intensity of the OMZ (Ganeshram and Pedersen 1998). Growing evidence suggest that there have been different oxygenation conditions in the past along the northeastern Pacific continental margins (*e.g.*, California and Baja California; Cannariato and Kenneth 1999, Cannariato *et al.* 1999, Stott *et al.* 1999, Ortiz *et al.* 2004, Hendy *et al.* 2004, Hendy and Pedersen 2005, McKay *et al.* 2005, Dean *et al.* 2006, Hendy and Pedersen 2006, Sánchez and Carriquiry 2007a, b, Nederbragt *et al.* 2008). These studies concluded that subsurface ventilation and/or upwelling and export production, and concomitantly the local and regional primary production, varied markedly along the northeastern Pacific continental margins during the Quaternary (the period between 2.6 million years ago and the present).

Based on the $\delta^{13}C$ isotopic gradient of benthic foraminifera that live at different depths in the sediment, Stott *et al.* (2000) estimated a decrease in the rate of oxidation of organic carbon equivalent to an increase in dissolved oxygen content of 15-20 μm/kg. This coincided with a change in the regime shift of the Pacific Ocean that occurred during 1976/1977, which involved a reduction in the number of upwelling events and an increase in ocean surface temperature by 1.5-3.0ºC. Thus, it is not necessary to invoke changes in ocean circulation and ventilation to explain changes in the OMZ of the northeastern Pacific. As a result, the new paleoceanographic evidences suggest that decreases in primary productivity caused by a deepening of the nutricline caused changes in the OMZ producing oceanographic conditions that were similar to El Niño (Ortiz *et al.* 2004). Measurements of organic carbon and trace metal concentration (Cd, Mo) in two cores from the Magdalena margin revealed millennial scale oscillations very similar to those observed in Greenland ice cores (Ortiz *et al.* 2004, Dean *et al.* 2006). This evidence convincingly suggests the operations at millennial timescale of teleconnections between the global climate and the intensity of the OMZ and/or productivity along the west coast of North America.

Recently, Schmittner *et al.* (2007) proposed that the variation of the OMZ in the Pacific Ocean can be explained by changes in the formation/subduction rates of the North Atlantic Deep Water. Through the ocean conveyor system, when the North Atlantic becomes too cold (*e.g.*, glacial conditions) there is a reduced nutrient release to the Pacific Ocean's surface resulting in decreases in primary productivity with a concomitant reduction in the exported productivity. Since there is less organic matter to be oxidized during these periods, subsurface oxygen levels in the water column start increasing concomitantly. Water column denitrification also decreases accordingly because of the increased levels of oxygen. The effect of reduced consumption of oxygen caused by lowered exported productivity at millennial timescales dominates at low latitudes.

Despite the large amount of high quality data that have been generated along the northeastern margin of the Pacific, the relative importance of surface productivity on the changes of oxygen content of intermediate water masses has not been completely assessed. For instance, the climatic event of the Bolling/Allerød (B/A, a warm and moist interstadial period that occurred during the final stages of the last glacial period, from c. 14,700 to 12,700 years before the present) was either weak and/or very intense in some places, depending on the proxies used. Moreover, the nature of the teleconnections between millennial cycles in Greenland and processes controlling the biogeochemistry and circulation over the northeastern Pacific continental margin remains a large area of debate. This study presents new data from biogenic opal of a sediment core composite GC31/PC08 collected from the southwestern margin of Baja California, where previous work has shown millennial scale fluctuations in climate over the last 50,000 years (Ortiz *et al.* 2004, Dean *et al.* 2006, Marchitto *et al.* 2007, Sánchez and Carriquiry 2007a, b).

1.1. Sedimentary proxies for reconstructing export productivity changes

Two proxies used as indicators of primary productivity are presented in this paper. The first is the accumulation rate of Corg in the sediment. The sediments in productive ocean regions usually contain high concentrations of Corg (Berger 1989). Less clear is the quantitative relationship between Corg content of the sediment and the amount of exported carbon from the ocean's surface. This is because only a small fraction of Corg produced in the surface water reaches the sediment (Suess 1980). The decomposition of Corg is affected by a number of factors, including the rate of oxidation occurred in the water column during its travel to the seafloor, the burial rate of that exported carbon that reaches the seafloor, and under certain conditions the oxygen content of bottom waters and the penetration of oxygen in interstitial water (Hedges and Keil 1995, Hartnett *et al.* 1998, Sott *et al.* 2000, Holsten *et al.* 2004). The Corg that is preserved in the sediment is usually the most refractory component of the particle flux of planktonic organic matter (Canfield 1994, Hedges and Kiel 1995) which weakens the quantitative connection to the primary productivity existing at the sea surface.

Other factors that complicate the interpretation of buried Corg are that fine sediments are typically richer in organic matter than the coarser sediments (Hedges and Kiel 1995, Nederbragt *et al.* 2008). Thus, variations in the content of Corg may be the result of changes in the source of the particles due to changes in bottom currents (Berger *et al.* 2004) or by hauling minerals (Nederbragt *et al.* 2008). Because of the larger surface-to-volume ratio of fine-grained sediments and clay minerals that tend to absorb more organic matter than coarse sediments, a wrong interpretation could be reached with regard Corg fluxes to the ocean's floor. Hence, when grain size differences are suspected to exist in a sedimentary record, a grain-size normalization is commonly performed to achieve the correct interpretation.

The other proxy for primary productivity is the content of biogenic opal (BSi) in the sediments, which is commonly associated with oceanic regions characterized by high primary productivity resulting from upwelling systems with high deposition and preservation (*e.g.*, burial) rates of BSi (*e.g.*, Sánchez and Carriquiry 2007a). Because the ocean is undersaturated with respect to silicic acid, the BSi is dissolved in its path along the water column to the sediment-water interface. A small residual fraction of settling BSi escapes dissolution. Oceanic sites with sediments rich in BSi are clearly related to regions with high surface production of BSi that also have the tendency of supporting blooms of diatoms, especially dominated by the large and robustly silicified species (*e.g.*, Calvert and Price 1983, Nelson *et al.* 1995, Pondaven *et al.* 2000, Ragueneau *et al.* 2000). In fact, BSi is one of the most widely used proxies in reconstructions of paleoproductivity and in conjunction with other proxies such as Corg, this multiproxy approach can give a consistent scenario of past changes in export productivity (*e.g.*, Hendy *et al.* 2004, Hendy and Pedersen 2005, McKay *et al.* 2005, Sánchez and Carriquiry 2007a, Nederbragt *et al.* 2008).

2. MATERIALS AND METHODS

The sediment cores (GC31 and PC08) of this study were collected from the open slope of the northeastern Mexican Pacific (see Figure 1), within the OMZ, also known as the Magdalena margin (Ortiz *et al.* 2004). Two complementary cores, a gravity (GC31) and a piston (PC08) core, were raised from a depth of 700 m, at 23°28' N and 111°36' W. The combined length of both cores was ~15 m. Oxygen concentration at the site was <3 mmol kg^{-1} (clearly suboxic). The sedimentation rate at the site of GC31/PC08 was assessed from 52 individual ^{14}C datings of planktonic and benthic foraminifera (van Geen *et al.* 2003, Marchitto *et al.* 2007), and 21 tie-points were established with the Hulu Cave record that was ^{230}Th-dated (Wang *et al.* 2001, Marchitto *et al.* 2007). The calculated sedimentation rate in this site was determined to be ~30 cm ka^{-1} (Van Geen *et al.* 2003). The cores were sampled every 5 cm (resolution ~170 years); each sample had a thickness of 1 cm, which integrated ~30 years.

2.1. Biogenic components

2.1.1. Total organic carbon (C_{org})

C_{org} as content of sediment was determined using a LECO elemental analyzer. Prior to analysis, carbonates were removed from the sample by acid treatment with 10% HCl. C_{org} content was estimated as weight percent. The analytical precision of elemental C content was <0.5%.

2.1.2. Biogenic opal (BSi)

The content of biogenic opal (BSi) in sediment was analyzed by the alkaline extraction method (Mortlock and Froelich 1989). The silica is measured after dilution of the samples using the 'molybdate blue' spectrophotometric method (Strickland and Parsons 1972). Some samples were analyzed in duplicate, yielding an analytical precision of this extraction method of <2%. The obtained concentration of dissolved silica is later converted to BSi and expressed as percentage by weight.

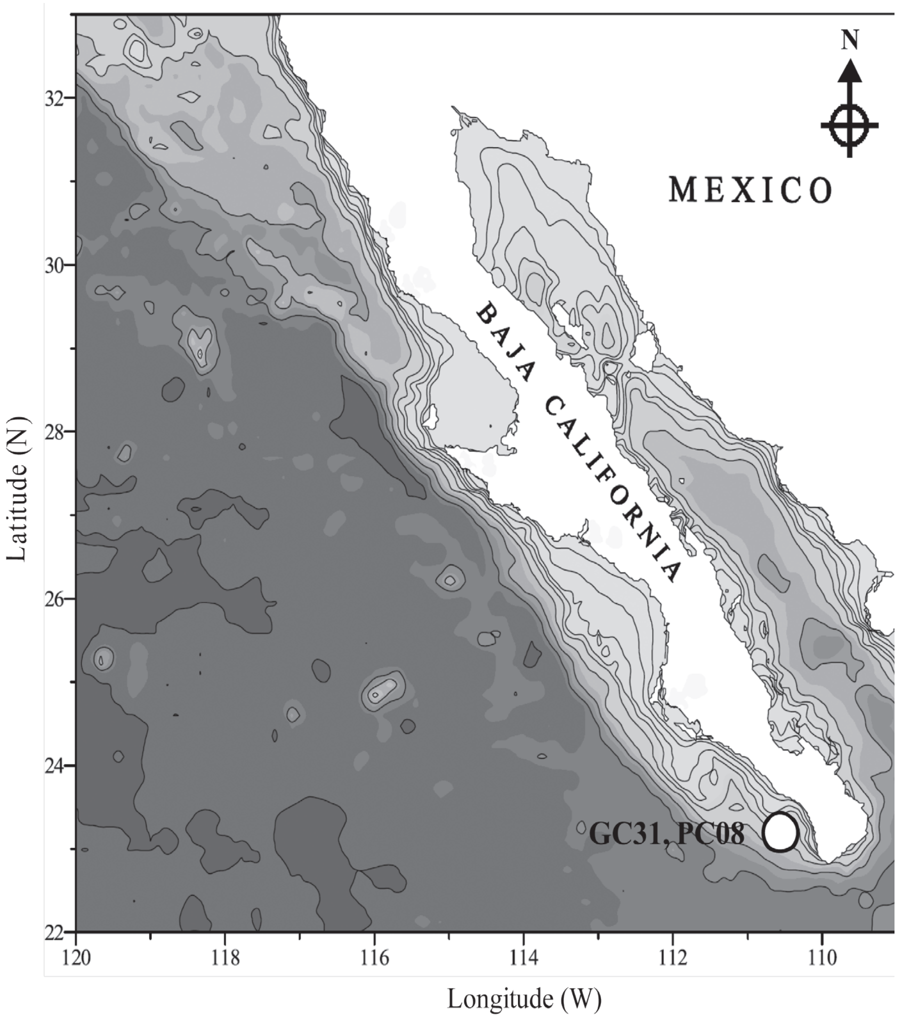

FIGURE 1. Bathymetric map and location of sediment cores GC31/PC08 in the Magdalena margin, Baja California Sur, Mexico.

2.1.3. Accumulation rate

Accumulation rates (AR) for biogenic components were calculated from the density of dry sediment taken from Dean *et al.* (2006). The sedimentation rate (cm ky^{-1}) and the percentages of biogenic components were multiplied by the density of dry sediment to estimate the accumulation rates (mg cm^{-2} ky^{-1}) for each biogenic component. Because the sedimentation rate's slope is practically a straight line, the assumed constant sedimentation rate in this site is very realistic (Ortiz *et al.* 2004).

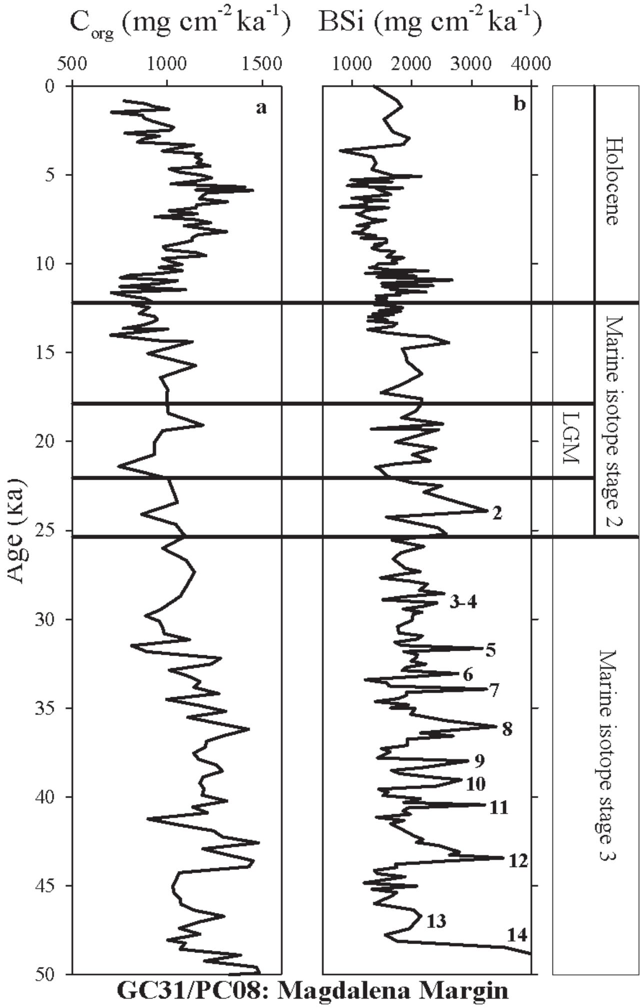

FIGURE 2. Burial rate of (a) Corg (mg cm-2 ka-1) and of (b) BSi (mg cm-2 ka-1) in the Magdalena margin, at 700 m depth. Labels in the diagram (b) indicate interstadial events 2–14.

3. RESULTS

3.1. Sedimentation rate of C_{org} and BSi

C_{org} flux in the cores GC31-PC08 from Magdalena margin displays high variability (500 to 1500 mg cm^{-2} ky^{-1}) during the last 50 Ka (see Figure 2a). Average C_{org} flux during the Holocene was from 1062 ± 155 mg cm^{-2} ky^{-1}and decreased to 700 mg cm^{-2} ky^{-1}during the late Holocene (see Figure 2a). During the marine isotope stage

2 (MIS-2), the C_{org} flux was slightly lower (932 ± 120 mg cm^{-2} ky^{-1}) but similar to the last glacial maximum (22-18 ky) (963 ± 143 mg cm^{-2} ky^{-1}). C_{org} flux during the MIS-3 was slightly higher (1150 ± 159 mg cm^{-2} ky^{-1}. In general, it can be said that the C_{org} burial rate was relatively higher during the warm periods than during the cold periods of the MIS-3 (see Figure 2a).

The BSi sedimentation rate, like the C_{org}, displayed considerable variability during the last 50 Ka (see Figure 2b). During the MIS-3, there were several events of maximum levels of BSi concentration, balanced by a similar number of events containing minimum levels of BSi. During the Holocene, the average BSi flux was 1475 ± 352 mg cm^{-2} ky^{-1}. During the MIS-2, the average BSi flux was 1828 ± 404 mg cm^{-2} ky^{-1} and particularly during the LGM, the average BSi was 1908 ± 413 mg cm^{-2} ky^{-1}. BSi values in the period of 50 to 25 Ka (MIS-3) showed a range very similar to the DO cycles recorded in the Greenland's ice core record.

4. DISCUSSION AND CONCLUSIONS

The comparison of the different components: C_{org}, BSi, abundance of benthic foraminifera and the DSR-factor 3 (the latter two from Ortiz *et al.* 2004) in the GC31/PC08 cores respond in time and magnitude (except C_{org}) to $\delta^{18}O$ variations in the GISP2 ice core (see Figure 3). The sedimentation rate of C_{org} during some intervals during the MIS-3 had limited response to millennial-scale 'DO' oscillations (see Figure 3c). The rate of burial of C_{org} in the Magdalena margin during the Holocene was 1062 ± 155 mg cm^{-2} yr^{-1}, which is similar to the modern C_{org} flux in Soledad basin (824 mg cm^{-2} yr^{-1}). During the warmer periods of the MIS-3, the average burial rate of C_{org} was 25% higher, reaching the maximum value of 1450 mg cm^{-2} yr^{-1} which is similar to the maximum values observed during the Holocene. During the cold periods of the MIS-3, the average burial rate of C_{org} was slightly lower than that of the Holocene. The MIS-2 and LGM, periods of similar conditions to the cold events of the MIS-3, presented C_{org} burial rates in the order of 932 ± 120 mg cm^{-2} yr^{-1}, and 963 ± 143 mg cm^{-2} yr^{-1}, respectively. These C_{org} fluxes were very similar to the Holocene's, but significantly lower than those of the warm events of the MIS-3.

BSi flux calculations agree well with the C_{org} comparisons between periods of contrasting climatic conditions during the last 50,000 yrs. Particularly for the MIS-3, the burial rate of BSi fluctuates in synchrony with the millennial scale climate oscillations observed in the $\delta^{18}O$ of the Greenland ice core (GISP2). These new observations suggest that fluctuations in the intensity of the OMZ in the northeastern tropical Pacific were caused by changes in productivity and, by a lesser degree, by the formation of the NPIW (North Pacific Intermediate Water which implies

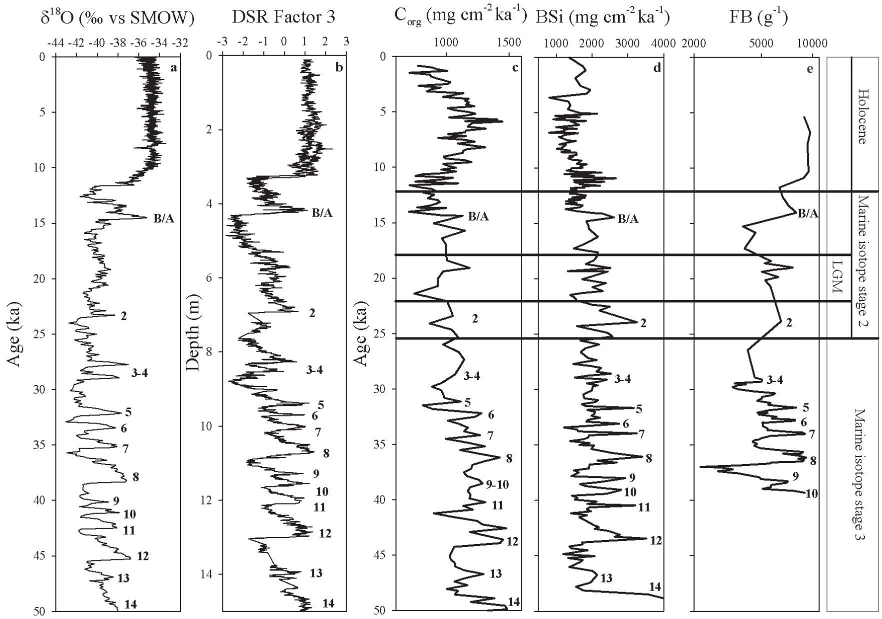

FIGURE 3. (a) d18O of the Greenland ice core (GISP2; Grootes and Stuiver, 1997), (b) of DSR-Factor 3 (Ortiz *et al.*, 2004), (c) burial rate of Corg (mg cm-2 ka-1), (d) BSi (mg cm-2 ka-1) and (e) flow of benthic foraminifera (Ortiz *et al.*, 2004) in the Magdalena margin, at 700 m depth. Numeric labels in the diagrams correspond to interstadial events 2–14.

"renewed" ventilation). This is in agreement with recent evidence that these millennial-scale events of high productivity should produce a more pronounced OMZ, which is more oxygen deficient, as will be further discussed.

The preservation of sedimentary C_{org} is an empirical relationship that is related to primary productivity, C_{org} flux along the water column, sedimentation rate, the rate of degradation of C_{org} and the background concentration of oxygen in the water column. The mechanisms that control the sedimentary organic carbon preservation remain unclear and continues to be debated (*e.g.*, Hartnett *et al.* 1998, Hendy *et al.* 2004, McKay *et al.* 2005, Sánchez and Carriquiry 2007a, Nederbragt *et al.* 2008).

What factors may facilitate an increase in the rate of burial of C_{org} during the warmer periods of the MIS-3? The very well dated core couplet GC31/PC08 allowed for precise determinations of sedimentation rate in the Magdalena margin. The sedimentation rate for the Holocene, the MIS-2 and LGM was 30 cm ky^{-1} (0.30 mm yr^{-1}), and slightly decreased to 25 cm ky^{-1} during the MIS-3 (0.25 mm yr^{-1}). The similarity in the sedimentation rate suggests that there is no artifact introduced by sedimentation rate and that the accumulation rate of C_{org} was the result of changes in primary productivity and C_{org} flux along the water column (*e.g.*, Hedges and Keil 1995, Hartnett *et al.* 1998).

Hartnett *et al.* (1998) suggest that the burial and preservation of C_{org} in the continental margin is mainly related to the oxygen's exposure time (estimated to be 3 months), considering that the oxygen's penetration depth (into the sediment; see Hartnett *et al.* 1998 for details) is very shallow (<2 mm). In the margin of Magdalena, the oxygen exposure time was 45 days (with <2 mm) and an oxygen penetration depth of <1 mm; the calculated time is very similar to Hartnett's *et al.* (1998). Thus, the exposure time to oxygen explains very little in terms of preservation and accumulation of C_{org} in the Magdalena margin. Canfield (1994) suggested that the efficiency of C_{org} burial decreases with increases in primary productivity, and the rain of C_{org} due to the mixing of labile and refractory C_{org} that increases the oxidation of C_{org}. Indeed, Berelson and Stott (2003) found that the efficiency of C_{org} burial for the past 100 years was lower than in the present in the central California margin, and concluded that the burial of C_{org} efficiency was not related to the exposure time to oxygen.

Recently, the age distribution of the settling particles and their exposure time to oxygen in bioturbated marine sediments was modeled for the continental shelf and slope. The results indicated that the biodifusive mixture of particles and the preferential degradation of organic matter under conditions of oxygenation predicts an inverse relationship between the burial efficiency and the exposure time to oxygen in marine sediments, and differs from a simple relationship between oxygen penetration and the rate of sedimentation (Meile and Van Cappellen 2005).

Under the current scenario, the concentration of oxygen in the OMZ depends on the balance between the relative contribution of the intermediate waters from the "North Pacific subsurface water' which is relatively rich in oxygen, and the oxygen-poor 'subsurface waters of the equatorial Pacific". Thus, any change in the mixing contributions of the two sources would directly impact the condition of the OMZ of the northeastern Pacific. The North Pacific intermediate water (NPIW) that is formed in the Okhostk Sea and the Gulf of Alaska (You 2003, Shcherbina *et al.* 2003), and travels along the North Pacific subtropical gyre, was suggested to explain the ventilation of the water column and the presence of bioturbated intervals during cold periods or stadials (LGM, and the stadials of the MIS-3) along the northeastern Pacific and Gulf of California. In contraposition, laminated sediments formed during the Holocene and the interstadials of the MIS-3, indicating low oxygen levels in the water column (Duplessy *et al.* 1988, Keigwin and Jones 1990, Kennett and

Ingram 1995, Van Geen *et al.* 1996, Behl and Kennett 1996, Keigwin 1998, Zheng *et al.* 2000).

Better ventilation in the northeastern Pacific during the last glacial has been inferred from the $\delta^{13}C$ values of benthic foraminifera that suggest the presence of a "young" intermediate water mass in the northwestern Pacific, low in nutrients (Duplessy *et al.* 1988, Keigwin 1998, Stott *et al.* 1999, Keigwin 2002). ^{14}C data on benthic and planktonic foraminifera in sediment cores from the west Pacific suggest an increase in ventilation between 17 and 13 ka, and during the Younger Dryas, as well as a decrease in ventilation during the Bolling/Allerød (Duplessy *et al.* 1989). Nonetheless, Keigwin (2002) indicate similar ventilation conditions during the Holocene and last glacial maximum and suggests that the possible source of ventilation was the Gulf of Alaska, or the Southern Ocean. In Santa Barbara Basin, ventilation increased during the last glacial maximum and the Younger Dryas (this event was a brief period of cold climatic conditions and drought that occurred between approximately 12.8 and 11.5 Ka ago) (Ingram and Kennett 1995), which contrasts with data from the open California margin that show, ambiguously, a decrease in ventilation between 11 and 9 Ka (Van Geen *et al.* 1996), and increased ventilation in the early Holocene (11-8 ka) and Bolling/Allerod, while the OMZ was intensifying (Mix *et al.* 1999). In fact, McKay *et al.* (2005) shows that ventilation in the water column, compared to Vancouver Island for the period between 16 and 12.6 Ka (including the B/A) was very similar to the present.

Age differences between benthic-planktonic foraminifera used to infer changes in ventilation have the limitations that it considers a constant reservoir age of surface water and plankton. However, the concentration of atmospheric ^{14}C, the ocean-atmosphere exchange, and the changes in the circulation may influence the reservoir age estimate, as the diagenesis of methane influences the $\Delta^{14}C$ and ^{13}C (*e.g.*, Keigwin, 2002). Overall, the collected evidences from countless sedimentary records seem to indicate that the ventilation of the water column remained unchanged over the last 25 ka, and the observed changes in the OMZ of the Northeast Pacific are therefore caused by changes in primary productivity and not ventilation.

The high productivity in the Pacific NW is suggested as a new driving mechanism for the low levels of O_2 observed at intermediate depths along the western margin of North America. Near the site of NPIW formation, O_2 consumption took place by an increase in respiration of C_{org} in response to the high productivity of the period from 14.7 to 12.9 Ka (Crusius *et al.* 2004). Off Vancouver Island, C_{org} fluxes were significantly higher, relative to the Holocene, suggesting the activation of an upwelling system as the atmospheric and oceanic circulation was restored from a glacial to interglacial mode (McKay *et al.* 2005). Thus, the consumption of oxygen by high productivity on the sites of formation of North Pacific intermediate water, in these time-intervals, suggest the presence of the NPIW poor in oxygen and not due to decreased ventilation at intermediate depths, which is supported by ^{14}C estimates. In fact, Galbraith *et al.* (2007) indicate a rapid acceleration of export production during the deglaciation (18-15 ka) in the Pacific Northwest derived from an increased supply of nutrients, leading to increased sequestration of CO_2 at intermediate depths.

The sedimentary record of Santa Barbara Basin shows alternation of laminated and bioturbated sediments that have been associated with changes in the oxygenation of the water column and sediment, as well as on the presence/absence of benthic foraminifera species (*e.g.*, Cannariato *et al.* 1999). Nederbragt *et al.* (2008) show high burial rates of C_{org} under both, oxic conditions (>2 ml l^{-1} O_2) (*e.g.*, Younger Dryas) and dysoxic conditions (2 to 0.2 ml l^{-1} O_2) (laminated sediments). These results support the evidence of the oxygen level control by variation in the intermediate water ventilation, and not by changes in productivity in surface waters in this basin.

Mix *et al.* (1999) suggest that the Southern Ocean may be an important source of variability in the North Pacific. The expansion of the OMZ in the Gulf of California precedes the expansion occurring in the California margin during the deglaciation, but coincides with changes in ice cover and winds around Antarctica. These observations reinforce the importance of Southern Ocean as a primary modulator of climate in the Northern Hemisphere (Hendy *et al.* 2004). Marchitto *et al.* (2007) reconstructed the activity of ^{14}C at intermediate depth in the northeast Pacific, finding that this activity decreased sharply during the deglaciation, suggesting the arrival of a very old water mass originating in the Southern Ocean. Thunell and Kepple (2004) indicate that denitrification of the water column in the Gulf of Tehuantepec is sensitive to changes in ventilation and circulation in the subsurface water of oxygen deficient as well as variations in the intensity of upwelling (*i.e.*, marine productivity).

Besides Santa Barbara Basin, the northeastern Pacific sedimentary records that extend into the marine isotope stage 3, with millennial or sub-millennial resolution are very scarce. Hendy *et al.* (2004) followed a multiproxy approach in a sediment core collected from the active upwelling cell of Point Conception, California. The results suggest that marine productivity in this region was not simply linear between warm and cold climatic oscillations (*e.g.*, glacial - interglacial), except for the marine isotope stage 3 where the upwelling cell and the resulting productivity remained active during warm events (interstadials) and inactive during cold events (stadials). Productivity increased dramatically during the Bolling warming interval, while in the Allerød and Younger Dryas were much less productive. The response of productivity resulted from a complex interaction of local winds and a more vigorous subsurface flow. Thus, export production and ventilation of intermediate water played an important role in the development of California margin OMZ (Hendy and Pedersen 2005).

Low latitude paleoproductivity records from the northeast Pacific margin are restricted to the subtropical latitude of the Gulf of California, with a time scale limited to the last 25 ka, and the open margin of Magdalena with a timeline that extends to 50 ka, consisting of millennial and sub-millennial resolution. Ortiz *et al.* (2004) suggest that productivity changes recorded in the Magdalena margin during MIS-3 were balanced similarly to the modern conditions of La Niña that favored a shallow nutricline and consequently high productivity during warm climate intervals alternating with El Niño-like conditions, with a deep nutricline and low productivity intervals during cold periods. The concentrations of C_{org}, cadmium and molybdenum were measured in the same core studied by Dean *et al.* (2006). The accumulation of C_{org}, Cd and Mo generally corresponded to warm periods with the exception of B/A, which is weakly expressed on the Baja California margin. The new data provide evidence of teleconnections between global climate and the intensity of the OMZ and/or productivity along the northeastern Pacific margin.

The sedimentary record of Pacific and Indian oceans documenting millennial scale fluctuations in dissolved oxygen levels and denitrification are consistent with the oscillation of temperature in the North Atlantic. Schmittner *et al.* (2007) have recently modeled the oxygen and nitrogen cycles explaining how the changes in subduction of deepwater in the North Atlantic can cause the synchronic variations in the OMZ of the Pacific and Indian Ocean. Cold periods in the North Atlantic are associated with reduced nutrients release to the surface of the Pacific and Indian Oceans. As a result, export production decreased and the subsurface respiration of organic matter was reduced leading to an increase in the concentration of oxygen and less denitrification at lower latitudes.

Generally, the flux of BSi in the range of Magdalena indicate that during some marine isotope stages, as is the case of MIS-3, primary productivity associated with diatoms (mainly) fluctuated in synchrony with the 'D-O' cycles in Greenland. Our study in Baja California suggests that, in coherence with evidences from other sites along the northeast Pacific margin, the variability of the Oxygen Minimum Zone (OMZ) in the northeast Pacific is more largely controlled by changes in productivity rather than by ventilation changes of the water column, as it was the prevalent view. The low C_{org} preservation during some millennial-scale events would suggest a decrease in productivity and/or increase of ventilation of the water column, which contrasts with the increase in the flux of BSi and in the abundance of benthic foraminifera. Ocean circulation changes responsible for increasing the oxygen content of the water column is the most likely controlling factor explaining the divergence of the paleoproductivity proxies during these events.

REFERENCES

Behl, R.J., and J.P. Kennett. 1996. Brief interstadial events in the Santa Barbara Basin, NE Pacific, during the past 60 kyr. *Nature* 379: 243–246.

Berelson, W.M., and L.D. Stott. 2003. Productivity and organic carbon rain to the California margin seafloor: modern and paleoceanographic perspectives. *Paleoceanography* 18(1): 1002 (1029/2001PA000672).

Berger, W.H. 1989. Global maps of ocean productivity. In W.H. Berger, V. Smetacek, and G. Wefer (eds.), *Productivity of the Ocean: Present and Past.* John Wiley, Hoboken, NJ, pp. 429–455.

Berger, W.H., A. Schimmlemann, and C.B. Lange. 2004. Tidal cycles in the sediments of Santa Barbara Basin. *Geology* 32: 329–332.

Calvert, S.E., and N.B. Price. 1983. Geochemistry of Namibian Shelf sediments. In E. Suess and J. Thiede (eds.), *Coastal Upwelling*. Plenum Publishing Corporation, New York, pp. 337–375.

Canfield, D. 1994. Factors influencing organic carbon preservation in marine sediments. *Chemical Geology* 114: 315–329.

Cannariato, K.G., and J.P. Kennett. 1999. Climatically related millennial-scale fluctuations in strength of California margin oxygen-minimum zone during the past 60 k.y. *Geology* 27: 975–978.

Cannariato, K.G., J.P. Kennett, and R.J. Behl. 1999. Biotic response to late Quaternary rapid climate switches in Santa Barbara Basin: ecological and evolutionary implications. *Geology* 27: 63–66.

Crusius, J., T.F. Pedersen, S.K. Kienast, L. Keigwin, and L. Labeyrie. 2004. Influence of northwest Pacific productivity on North Pacific Intermediate Water oxygen concentrations during the Bølling-Allerød interval (14.7 2.9 ka). *Geology* 32: 633–636, doi:10.1130/G20508.1.

Dean, W.E., Y. Zheng, J.D. Ortiz, and A. van Geen. 2006. Sediment Cd and Mo accumulation in the oxygen-minimum zone off western Baja California linked to global climate over the past 52 kyr. *Paleoceanography* 21, doi:10,1029/2005 PA001239.

Duplessy, J.C., N.J. Shackleton, R.G. Fairbanks, L. Labeyrie, D. Oppo, and N. Kallel. 1988. Deep water source variations during the last climate cycle and their impact on the global deepwater circulation. *Paleoceanography* 3: 343–360.

Duplessy, J.C., M. Arnold, E. Bard, J. Juillet-Leclerc, N. Kallel, and L. Labeyrie. 1989. AMS 14C study of transient events and of the ventilation rate of the Pacific Intermediate Water during the last deglaciation. *Radiocarbon* 31: 493–502.

Galbraith, E.D., S.L. Jaccard, T.F. Pederson, D.M. Sigman, G.H. Haug, M. Cook, J.R. Southon, and R. Francois. 2007. Carbon dioxide release from the North Pacific abyss during the last deglaciation. *Nature* 449 (7164): 890-U9, doi:10.1038/nature 06227.

Ganeshram, R.S., and T.F. Pedersen. 1998. Glacial-interglacial variability in upwelling and bioproductivity off NW Mexico: Implications for Quaternary paleoclimate, *Paleoceanography* 13(6): 634–645, doi:10.1029/98PA02508.

Grootes, P.M., and M. Stuiver. 1997. Oxygen 18/16 variability in Greenland snow and ice with 10^{-3}- to 10^{-5}-year time resolution. *Journal of Geophysical Research* 102: 26455–26470.

Hartnett, H.E., R.G. Keil, J.I. Hedges, and A.H. Devol. 1998. Influence of oxygen exposure time on organic carbon preservation in continental margin sediments. *Nature* 391: 572–574.

Hedges, J., and R. Keil. 1995. Sedimentary organic matter preservation: an assessment and speculative synthesis. *Marine Chemistry* 49: 81–115.

Hendy, I.L., and T.F. Pedersen. 2005. Is pore water oxygen content decoupled from productivity on the California Margin? Trace element results from Ocean Drilling Program Hole 1017E, San Lucia slope, California. *Paleoceanography* 20: PA4026, doi:10.1029/2004PA001123.

Hendy, I.L., and T.F. Pedersen. 2006. Oxygen minimum zone expansion in the eastern tropical North Pacific during deglaciation. *Geophysical Research Letters* 33: L20602, doi:10.1029/2006GL025975.

Hendy, I.L., T.F. Pedersen, J.P. Kennett, and R. Tada. 2004. Intermittent existence of a southern Californian upwelling cell during submillennial climate change of the last 60 kyr. *Paleoceanography* 19(3), doi:10.1029/2003PA000965.

Holsten, J., L.D. Stott, and W. Berelson. 2004. Reconstructing Benthic Carbon Oxidation Rates Using d13C of Benthic Foraminifers. *Journal Foraminiferal Research* 53: 117–132.

Ingram, B.L., and J.P. Kennett. 1995. Radiocarbon chronology and planktonic-benthic foraminifera 14C age differences in Santa Barbara Basin sediments, Hole 893A. *Proc. Ocean Drill. Program Sci. Results* 146: 19–27.

Keigwin, L.D. 1998. Glacial-age hydrography of the far northwest Pacific Ocean. *Paleoceanography* 13: 323–339.

Keigwin, L.D. 2002. Late Pleistocene–Holocene paleoceanography and ventilation of the Gulf of California. *Journal of Oceanography* 58: 421–432.

Keigwin, L.D., and G.A. Jones. 1990. Deglacial climatic oscillations in the Gulf of California. *Paleoceanography* 5: 1009–1023.

Kennett, J.P., and B.L. Ingram. 1995. A 20,000-year record of ocean circulation and climate change from the Santa Barbara Basin. *Nature* 377: 510–514.

Marchitto, T.M., S.J. Lehman, J.D. Ortiz, J. Flückiger, and A. van Geen. 2007. Marine radiocarbon evidence for the mechanism of deglacial atmospheric CO_2 rise. *Science* 316: 1456–1459.

McKay, J.L., T.F. Pedersen, and J. Southon. 2005. Intensification of the oxygen minimum zone in the Northeast Pacific during the last deglaciation: ventilation and/or export production? *Paleoceanography* 20, doi:10.1029/2003PA000979.

Meile, C., and P. van Cappellen. 2005. Particle age distributions and O2 exposure times: Timescales in bioturbated sediments. *Global Biogeochemistry Cycles* 19, GB3013, doi:10.1029/2004GB002371.

Mix, A.C., D.C. Lund, N.G. Pisias, P. Boden, L. Bornmalm, M. Lyle, and J. Pike. 1999. Rapid climate oscillations in the northeast Pacific during the last deglaciation reflect Northern and Southern Hemisphere sources. In P.U. Clark *et al.* (eds.), *Mechanisms of Global Climate Change at Millennial Time Scales*, Geophys. Monogr. Ser., AGU, Washington, DC, Vol. 112, pp. 127–148.

Mortlock, R.A., and P.N. Froelich. 1989. A simple method for the rapid determination of biogenic opal in pelagic marine sediments. *Deep-Sea Research* Part A 36: 415–1426.

Nederbragt, A.J., J.W. Thurow, and P.R. Bown. 2008. Paleoproductivity, ventilation, and organic carbon burial in the Santa Barbara Basin (ODP Site 893, off California) since the last glacial. *Paleoceanography* 23, PA1211, doi:10.1029/2007PA001501.

Nelson, D.M., P. Treguer, M.A. Brzezinski, A. Leynaert, and B. Queguiner. 1995. Production and dissolution of biogenic silica in the ocean: Revised global estimates, comparison with regional data and relationship to biogenic sedimentation. *Global Biogeochemical Cycles* 9(3): 359–372.

Ortiz, J.D., S.B. O'Connell, J. DelViscio, W. Dean, J.D. Carriquiry, T.M. Marchitto, Y. Zheng, and A. van Geen. 2004. Enhanced marine productivity off western North America during warm climate intervals of the past 52 k.y. *Geology* 32: 521–524.

Pondaven, P., O. Ragueneau, P. Tréguer, A. Hauvespre, L. Dezileau, and J.L. Reyss. 2000. Resolving the "opal paradox" in the Southern Ocean. *Nature* 405: 168–172.

Ragueneau, O., P. Tréguer, A. Leynaert, R.F. Anderson, M.A. Brzezinski, D.J. DeMaster, R.C. Dugdale, J. Dymond, G. Fischer, R. François, C. Heinze, E. Maier-Reimer, V. Martin-Jézéquel, D.M. Nelson, and B. Quéguiner. 2000. A review of the Si cycle in the modern ocean: recent progress and missing gaps in the application of biogenic opal as a paleoproductivity proxy. *Earth Planetary Science Letters* 26: 317–365.

Sánchez, A., and J. Carriquiry. 2007a. Acumulación de C_{org}, N_{org}, P_{org} y BSi en la Margen de Magdalena, B.C.S., México durante los últimos 26 ka. *Ciencias Marinas* 33: 23–35.

Sánchez, A., and J. Carriquiry. 2007b. Flujos de carbono orgánico sedimentario a lo largo de la margen continental del Pacífico nororiental mexicano. In B. Hernández-De la Torre and G. Gaxiola-Castro (eds.), *Carbono en Ecosistemas Acuáticos de México.* INE, CICESE.

Schmittner, A., E.D. Galbraith, S.W. Hostetler, T.F. Pederson, and R. Zhang. 2007. Large fluctuations of dissolved oxygen in the Indian and Pacific Oceans during Dansgaard-Oeschger oscillations caused by variations of North Atlantic Deep Water subduction. *Paleoceanography* 22, PA3207, doi:10.1029/2006PA001384.

Shcherbina, A.Y., L.D. Talley, and D.L. Rudnick. 2003. Direct observations of North Pacific ventilation: brine rejection in the Okhotsk Sea. *Science* 302: 1952–1955.

Stott L.D., M. Nuemann, and D. Hammond. 1999. Intermediate water ventilation on the northeastern Pacific margin during the late Pleistocene inferred from benthic foraminiferal δ13C. *Paleoceanography* 15: 161–169.

Stott, L.D. W. Berelson, D. Gorsline, and R. Douglas. 2000. Increased dissolved oxygen in Pacific Intermediate waters due to lower rates of carbon oxidation in sediments. *Nature* 407: 367–370.

Strickland, J.D.H., and T.R. Parson. 1972. A Practical Handbook of Seawater Analysis *Journal Fisheries Research Canada Bulletin* 167: 263–266.

Suess, E. 1980. Particular organic carbon flux in the oceans - Surface productivity and oxygen utilization. *Nature* 288: 260–263.

Thunell, R.C., and A.B. Kepple. 2004. Glacial-Holocene d15N record from the Gulf of Tehuantepec, Mexico: Implications for denitrification in the eastern equatorial Pacific and changes in atmospheric N2O, *Global Biogeochem. Cycles* 18, GB1001, doi:10.1029/2002GB002028.

Van Geen A., R.G. Fairbanks, P. Dartnell, M. McGann, J.V. Gardner, and M. Kashgarian. 1996. Ventilation changes in the northeast Pacific during the last deglaciation. *Paleoceanography* 11: 519-528.

Van Geen A., Y. Zheng, J.M. Bernhard, K.G. Cannariato, J. Carriquiry, W.E. Dean, B.W. Eakins, J.D. Ortiz, and J. Pike. 2003. On the preservation of laminated sediments along the western margin of North America. *Paleoceanography* 18: 1098, doi:10.1029/2003PA000911.

Van Scoy, K.A., and E.R.M. Druffel. 1993. Ventilation and transport of thermocline and intermediate waters in the northeast Pacific during recent El Niños. *Journal of Geophysical Research* 98(C10): 18083–18088.

Wang, Y.J., H. Cheng, R.L. Edwards, Z.S. An, J.Y. Wu, C.C. Shen, and J.A. Dorale. 2001. A High-Resolution Absolute-Dated Late Pleistocene Monsoon Record from Hulu Cave, China. *Science* 294: 2345–2348.

Wyrtki, K. 1962. The oxygen minima in relation to ocean circulation. *Deep-Sea Research* 9: 11–23.

You, Y. 2003. The pathway and circulation of North Pacific intermediate water. *Geophysical Research Letters* 30, doi:10.1029/2003GL018561.

Zaitzev, O., R. Cervantes, O. Montante, and A. Gallegos. 2003. Coastal Upwelling Activity of the Pacific Shell of Baja California Peninsula. *Journal of Oceanography* 59: 489–502.

Zheng, Y., A. van Geen, R.F. Anderson, J.V. Gardner, and W.E. Dean. 2000. Intensification of the northeast Pacific oxygen minimum zone during the Bolling-Allerod warm period. *Paleoceanography* 15: 528–536.

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Exploring Mexico's northwest, the Baja California Peninsula, its surrounding oceans, its islands, its rugged mountains, and rich seamounds, one feels diminished by the vastness and the greatness of the landscape while consumed by a sense of curiosity and awe. In a great natural paradox, we see the region's harsh arid nature molded by water through deep time, and we feel that its unique lifeforms have been linked to this desert and sea for thousands of years, as they are now.

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This book offers a compilation of research efforts aimed at understanding this extraordinary region and preserving its complex richness. It is a synthesis of work done by some exceptional researchers, mostly from Mexico, who indefatigably explore, record, and analyze these deserts and these seas to understand their ecological processes and the role of humans in their ever-changing dynamics.

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