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Biogeochemistry of surface sediments off Concepción (~36°S), Chile: El Niño *vs.* non-El Niño conditions

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Abstract

We compared the signals of several water column properties (upwelling intensity, sea level anomaly, temperature, nutrients, dissolved oxygen, chlorophyll-*a*, and surface sediments) of the continental shelf off Concepción (36°S) during the 1997–1998 El Niño with those of a normal year (2002–2003). We found that the primary hydrographic effect of El Niño 1997–1998 was a reduction in the input of nutrient-rich, oxygen-poor Equatorial Subsurface Water over the shelf. This affected the biology of the water column, as evidenced by the reduced phytoplankton biomass. Surface sediment properties (biogenic opal, organic carbon, bulk δ^{15}N) observed during El Niño 1997–1998 reflected a reduced export production and the sediments failed to show the water column seasonality that occurs under normal conditions. In addition, weakened denitrification and/or upper water column fertilization could be inferred from the sedimentary δ^{15}N. Although diminished, export production was preserved in the surface sediments, revealing less degraded organic matter in the upwelling period of the El Niño year than in the normal year. We suggest that the fresher organic material on the seafloor was probably associated with a severe reduction in the polychaete *Paraprionospio pinnata*, which is considered to be the most important metazoan remineralizer of organic carbon at the sediment–water interface in the study area.

Keywords: El Niño 1997–1998; Upwelling index; Sea level anomaly; Organic carbon; Biogenic opal; Chile

1. Introduction

The coastal region off central Chile (30–40°S) undergoes wind-driven upwelling events, intensified between 35°S and 38°S (Strub et al., 1998). In the area off Concepción (36.5°S 72.3°W), changes in wind stress induce well-defined seasonality in oceanographic conditions, phytoplankton biomass, and primary production (Ahumada et al., 1983). Upwelling involves mainly Equatorial Subsurface Water (ESSW) and occurs during austral

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spring, summer, and early fall (*i.e.*, September–May). The ESSW flows poleward in association with the Peru–Chile Undercurrent (Morales et al., 1996; Leth and Shaffer, 2001) and is characterized by low temperature, high salinity, low dissolved oxygen, and high-nutrient concentrations (Brink et al., 1983). During non-upwelling periods, relatively cold, fresher, nutrient-depleted Subantarctic Water can be found to depths of 120 m (Strub et al., 1998; Blanco et al., 2002), and phytoplankton biomass and primary production are lower than during upwelling (Morales et al., 2001; Grunewald et al., 2002). This well-defined seasonality promotes rapid changes in the water column primary production that are preserved as chlorophyll-*a* (Chl-*a*) variability in the surface sediments (Graco et al., 2001, 2006).

The strong seasonality is perturbed by the El Niño Southern Oscillation (ENSO). Modified circulation patterns and water properties typically attributed to El Niño (EN, warm ENSO phase) include enhanced poleward transport of warm and saline surface water, higher sea levels and sea surface temperatures (SST), and a depressed thermocline and nutricline, thereby reducing primary productivity (Blanco et al., 2001, 2002; Carr et al., 2002). Changes in sea level and thermocline depth have been associated with a decrease or even a reversal of local upwelling-favorable winds during EN (Blanco et al., 2002). Coastal winds, however, continued to be strongly equatorward and, therefore, upwelling-favorable during the 1997–1998 and 1982–1983 EN (Fonseca, 1985; Thomas et al., 2001; Carr et al., 2002). In spite of the wind pattern, the nutrient supply to the upper layer was reduced since upwelling originated from above the nutricline, thus affecting phytoplankton biomass, species composition, and primary production (Thomas et al., 2001; Carr et al., 2002).

During EN 1997–1998, surface Chl-*a* concentrations decreased along the coast when maximum SST anomalies were observed (Thomas et al., 2001; Carr et al., 2002; Escribano et al., 2004). Although the seasonally upwelling-favorable winds remained relatively unchanged between 18 and 40°S (Escribano et al., 2004), the upper boundary of the oxygen minimum zone (OMZ) off Concepción was deeper than the normal depth of 40 m in May, August, and November 1997, allowing greater oxygenation of the otherwise suboxic bottom waters that impinge on the seafloor (Gutiérrez et al., 2000; Neira et al., 2001a; Escribano et al., 2004; Sellanes and Neira, 2006).

The goal of this study is to evaluate whether the water column properties that developed under EN 1997–1998 (upwelling intensity, sea level anomaly, temperature, nutrients, dissolved oxygen, Chl-*a*) were preserved as distinct signatures of biogenic opal, organic carbon, and δ^{15}N in the surface sediments on the continental shelf off Concepción. By comparing the 1997–1998 EN to the normal conditions of 2002–2003, we tested the hypothesis that the sedimentary signal of water column seasonality is lost during EN years.

2. Materials and methods

The study site is located on the continental shelf off Concepción in central Chile (Station 18; 36°30.8′S; 73°07.7′W) at 88 m depth. Station 18 (Sta. 18) is one of the fixed time-series stations routinely sampled by the Center for Oceanographic Research in the eastern South Pacific (FONDAP COPAS Center; Fig. 1). Water column and sediment samples were taken every three months between May 1997 and May 1998 (EN). Between September 2002 and December 2003 (non-EN), the water column was sampled nearly every two months and sediments were collected on a monthly basis. Field work was carried out onboard the R/V *Kay Kay* (Universidad de Concepción).

We used the El Niño 1 + 2 index, based on the SST anomalies calculated along the west coast of South America between 0° and 10°S and 80°W and 90°W (*i.e.*, EN 1 + 2 region) to characterize EN 1997–1998. The Coastal Upwelling Index, available from the Pacific Fisheries Environmental Laboratory (http://www.pfeg.noaa.gov), was used to estimate offshore transport at 36.5°S; 72.5°W. Sea level (SL) anomalies at Talcahuano (36.7°S; 73.1°W) were obtained from the University of Hawaii Sea Level Center (http://ilikai.soest.hawaii.edu/uhslc/datai.html). Anomalies were corrected for atmospheric pressure and computed by subtracting the mean annual cycle of the sea level variation estimated for 1975 through 1995.

Water column temperature, salinity, and dissolved oxygen were measured using a Seabird model 25 CTDO. Surface (0.5 m) and bottom (87 m) water samples for dissolved oxygen and nitrate were collected using Niskin bottles. Oxygen was measured in triplicate by a modified Winkler method using a DOSIMAT 665 (Methrom) for titration and a photoelectric cell for end-point detection (Williams and Jenkinson, 1982). Water samples were immediately filtered through GF/F filters (Whatman), stored in acid-cleaned plastic vials, and kept

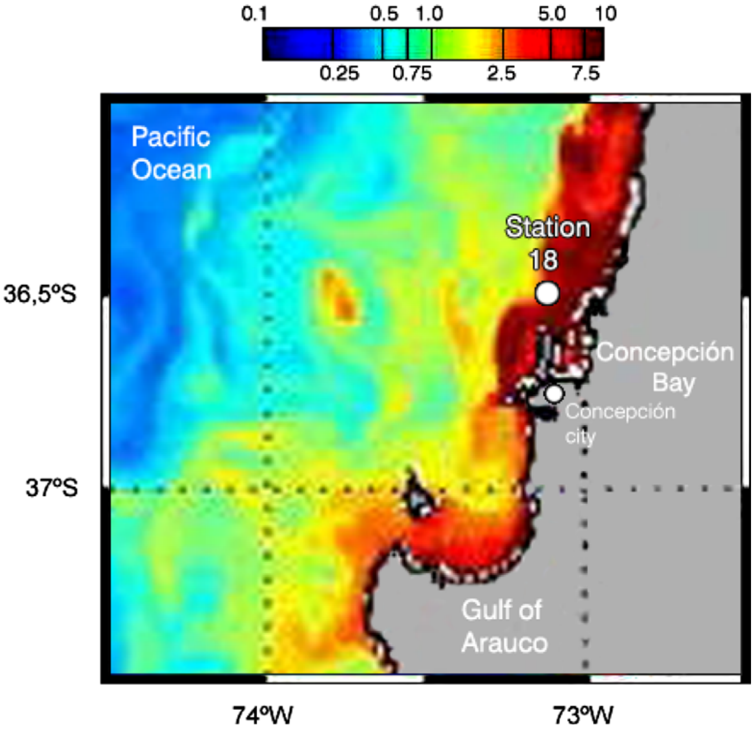

Fig. 1. Location of sampling Station 18 on the continental shelf off central Chile. Surface water chlorophyll-*a* concentration (mg m^{-3}) for February 19 (2006), based upon satellite imagery from high resolution SeaWiFs (Sea-viewing Wide Field-of-view Sensor).

frozen (−20 °C) for nutrient analyses. Nitrate was analyzed using either a Bran and Luebbe TRAACS 800 or an Alpkem Flow Solution 4 autoanalyzer. No replicates of nitrate measurements were made, but the historical error is ±0.04 μM. Chlorophyll-*a* (mg m^{-3}) (36.5–37.5°S; 72–73°S) was obtained from the Giovanni Ocean Color Time-Series Multi-Parameter Intercomparison System from NASA (http://reason.gsfc.nasa.gov/OPS/Giovanni/mpcomp.ocean.2.shtml).

Sediment samples were collected with a mini-multicorer (inner diameter 9.5 mm) (Barnett et al., 1984). Only undisturbed cores with clear overlying water were used. The sediment tops (0–1 cm) for EN 1997–1998 and 2002–2003 samples were kept frozen (−20 °C) until analysis. Organic carbon, total nitrogen, and $\delta^{15}N$ were determined on freeze-dried, homogenized sediments after acidification with 1 N HCl in excess to remove carbonates (Byers et al., 1978; Froelich, 1980) with a Heraus-CHN elemental analyzer according to Hedges and Stern (1984) and Nieuwenhuize et al. (1994). Acetanilide was used as a standard and precision was 2% for carbon and 0.3% for nitrogen determinations. Sedimentary $\delta^{15}N$ was obtained using a PDZ Europa 20-20 mass spectrometer connected to an elemental analyzer at the University of California Davis Stable Isotope Facility with an analytical precision of ±0.2‰.

Biogenic opal in the sediments is an indicator of export production (*i.e.*, mainly diatoms) and was measured following the method of Mortlock and Froelich (1989). Briefly, this consisted of a single extraction of silica with an alkaline solution at 85 °C for 6 h and measuring the dissolved silicon concentration in the extract by molybdate-blue spectrophotometry at 812 nm. No replicates of biogenic opal were made, but the historical error is between 0.3% and 0.5%.

The quality of sedimentary organic matter was evaluated by determining 15 protein amino acids using HPLC (Pantoja and Lee, 1999) and calculating the degradation index (DI) proposed by Dauwe and Middelburg (1998). DI is directly related to the reactivity of the organic material and varies from negative to positive depending on the source. Fresh organic material such as phytoplankton, bacteria, and material in sediment traps have a DI between 1 and 1.5, whereas the DI of degraded and refractory organic mater is <0 (Dauwe et al., 1999). Error in the determination of protein amino acids is ±7.2%.

3. Results

3.1. Local oceanographic changes

Local oceanographic changes recorded at Sta. 18 during EN 1997–1998 were compared with those observed during the "normal" conditions of September 2002–December 2003 (Fig. 2). Although there was evidence of a moderate El Niño in 2002–2003 in the central equatorial Pacific (*i.e.*, regions EN 4, EN 3.4), the propagation detected in the eastern Pacific and along the west coasts of the Americas was weak (McPhaden, 2004). Indeed, the weak EN 1 + 2 anomalies (<0.6) that occurred at the beginning of the upwelling period (November 2002) (Fig. 2a) were *ca.* 6–7 times lower than the anomalies for the same months during EN 1997–1998 (3.7–4.1) (Fig. 2b). Positive upwelling indices characterized the upwelling periods between November and April (with maximum strength in January) in both 2002–2003 and 1997–1998 (Fig. 2a,b). Thus, we consider the 2002–2003 upwelling period off Concepción to be "normal" and the 1997–1998 to be an upwelling period during an El Niño year.

The highest SL anomalies (6.9–9.9 cm) were detected between July and December 2002 (Fig. 2c); lower (3.1 cm, 0.3 cm) and even negative values (−1.4 cm, −0.5 cm) were observed from January to April 2003, indicating a shallow thermocline. The shallowest thermocline (lowest SL anomaly; −1.4 cm) was associated with maximum upwelling in January (Fig. 2c). The lowest and most negative SL anomalies, recorded in January (−4.8 cm), February (−6.3 cm), and March (0.2 cm) 1998, were similar or even greater than those recorded during the 2002–2003 upwelling period (Fig. 2d). The highest SL anomalies occurred in May–June (10.9–5.9 cm) and October–November 1997 (13–9.3 cm), and represented the deepest thermocline due to the EN (Fig. 2d).

The *in situ* sea surface temperature (SST) pattern at Sta. 18 was different for the two periods analyzed (Fig. 2e,f). During EN 1997–1998, SST ranged between 13.5 °C and 15.5 °C, with an abrupt increase between November 1997 and March 1998 (from 13.7 to 15.5 °C; Fig. 2f). SST in 2002–2003, on the other hand, oscillated around 13 °C with maxima (>14.5 °C) in December 2002, April 2003 (Fig. 2e), and December 2003; SST maxima are probably a local combination of high insolation and upwelling relaxation as previously reported by Arcos and Navarro (1986). If we compare the upwelling periods of both analyzed intervals, it is evident that the SST in 2002–2003 was at least 1 °C lower than during EN 1997–1998 (Fig. 2e,f).

Bottom water temperatures were below 11.4 °C throughout 2002–2003 but they never dropped below that value in 1997–1998 (Fig. 2e,f).

Surface nitrate concentrations were <5 μM during the 2002–2003 upwelling period, increasing to higher concentrations (>15 μM) at the end of austral autumn and winter (*i.e.*, May and June, 2003) (Fig. 2g). In contrast, surface nitrate concentrations were low (0.02–2.20 μM) throughout the entire 1997–1998 upwelling period (Fig. 2h). Higher bottom water nitrate concentrations (>20 μM) occurred in 2002–2003 (Fig. 2g) than in 1997–1998 (Fig. 2h).

Surface oxygen concentrations were similar in both years (Fig. 2i,j), ranging between 200 and 300 μM. In contrast, bottom water oxygen (BWO) concentrations showed a marked seasonal pattern in 2002–2003 (Fig. 2i), with the highest concentrations in early spring before the onset of upwelling (63 μM in September 2002, 45 μM in September 2003). The lowest values (13 μM) were recorded in the 2002–2003 upwelling period (Fig. 2i), whereas higher BWO concentrations (>22 μM; Fig. 2j) characterized the EN 1997–1998 upwelling period.

In general, Chl-*a* from the Giovanni Ocean Color Time-Series was 3 times higher in 2002–2003 than in 1997–1998 (Fig. 2k,l). However, the pattern of two maxima during the upwelling period was maintained.

3.2. Biogeochemical response of surface sediments to EN 1997–1998

Biogenic opal in the sediments was highest (11.3%) at the onset of the upwelling period in early summer (December 2002) and lowest (<5%) in austral winter (Fig. 3a). During EN 1997–1998, on the other hand, opal concentrations varied little and ranged between 7.5% and 9% without a seasonal maximum (Fig. 3a,b).

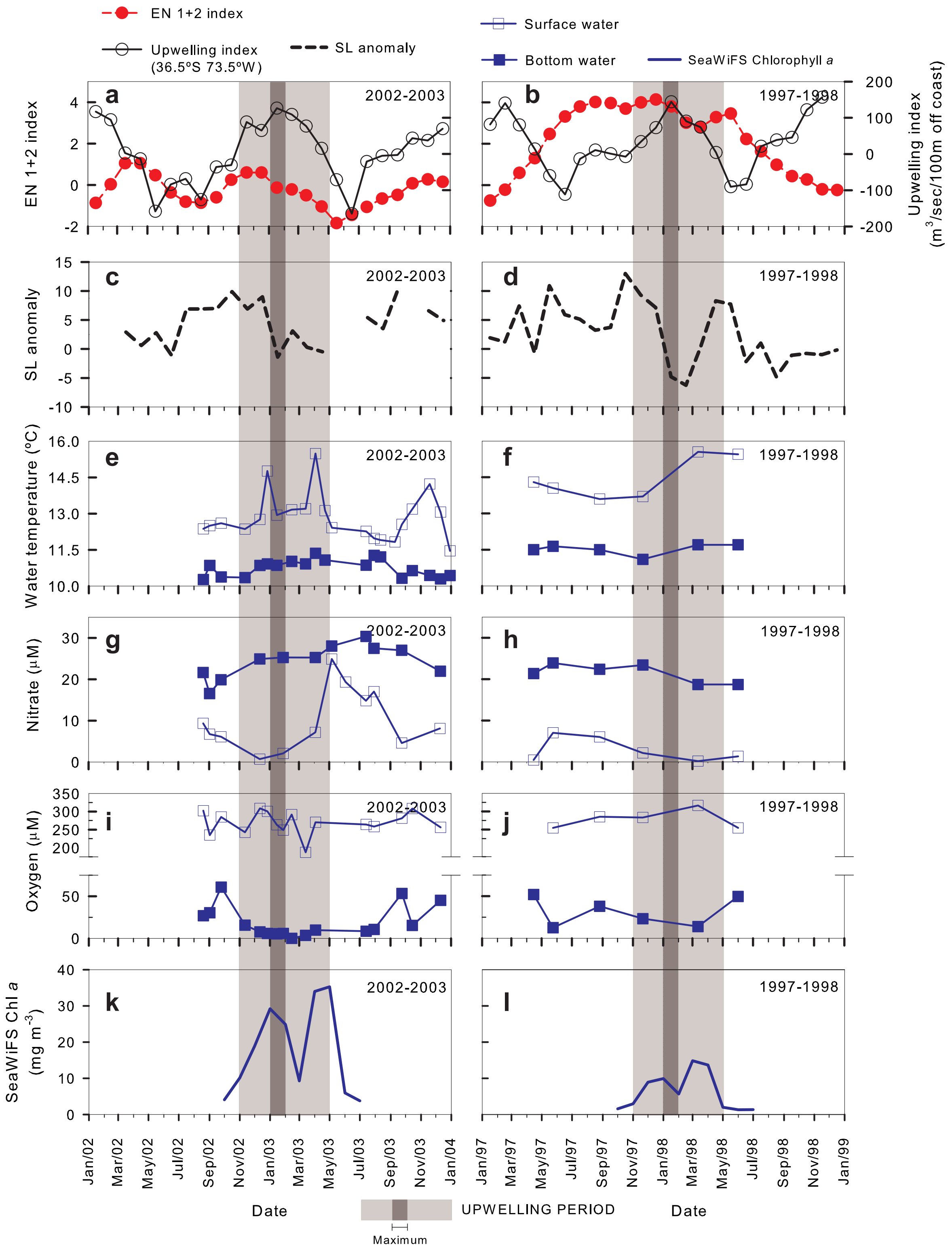

Fig. 2. El Niño 1 + 2 index, upwelling index ($m^3/s/100$ m off coast), sea surface level (SL) anomaly (cm), *in situ* temperature (°C), nitrate (µM), and dissolved oxygen concentrations (µM) from surface and bottom waters at Station 18 from September 2002 to January 2004 (a, c, e, g, i) and during EN 1997–1998 (b, d, f, h, j). SeaWiFS surface chlorophyll-*a* (mg m^{-3}) at Sta. 18 from the 2002–2003 and 1997–1998 upwelling periods (k, l). The shaded area shows the upwelling period and the dark shading its maximum intensity.

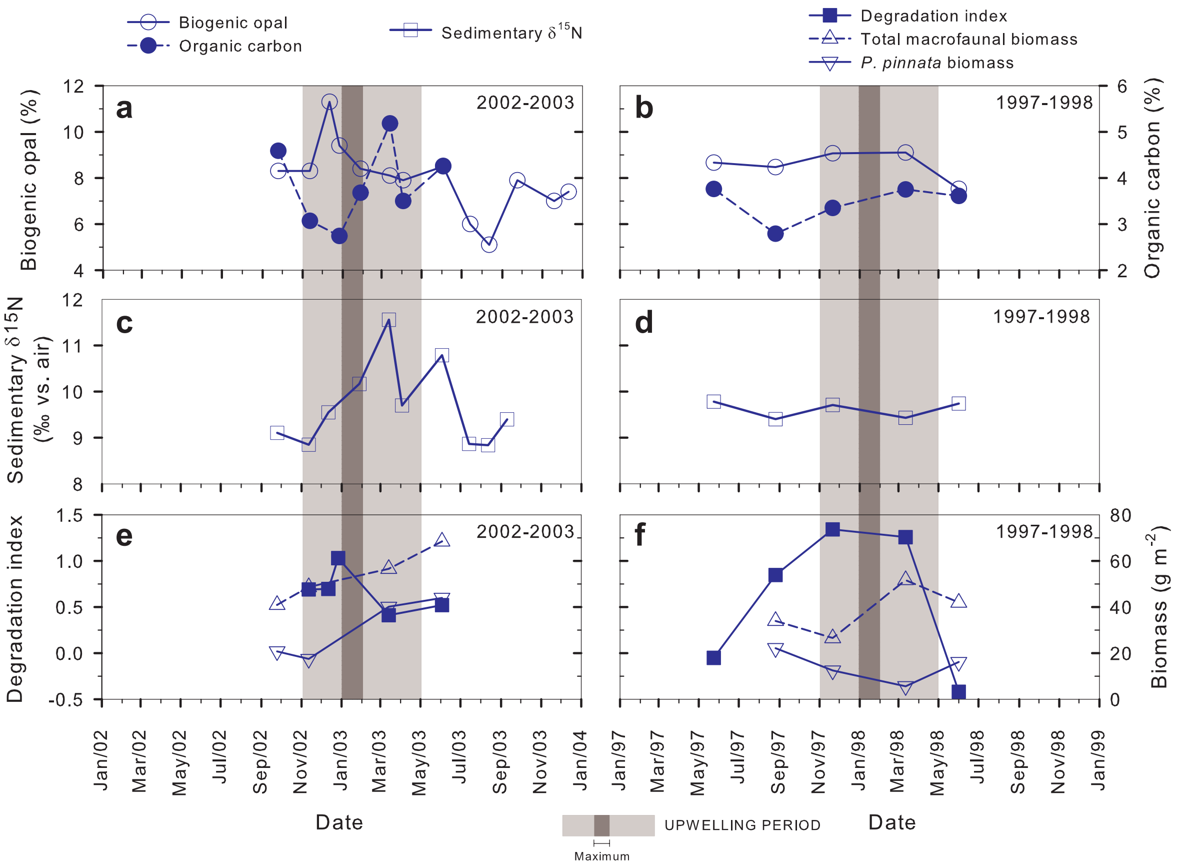

Fig. 3. (a, b) Proxies for export production represented by biogenic opal (%) and organic carbon (%); (c, d) bulk $\delta^{15}N$ (‰); (e, f) degradation index, biomass of total macrofauna and *Parapronospio pinnata* ($g\,m^{-2}$) from the sediments collected at Station 18 from September 2002 to January 2004 and during the 1997–1998 EN. Macrofauna data from Sellanes et al. (2007). Shaded area as in Fig. 2.

Organic carbon concentrations ranged between 2.7% and 5.2% in 2002–2003 with the maximum value in March 2003 after the opal peak (Fig. 3a). In contrast, the entire EN period recorded lower overall organic carbon values (2.8–3.8%); a slight increase of 1% (Fig. 3b) occurred during maximum upwelling.

Our time series station off central Chile is located near two important rivers that supply terrestrial detritus to the adjacent sediments: to the north of our sampling site, the Itata River and to the south, the Bío-Bío River. Although, the decreased organic carbon and biogenic opal contents of the EN 1997–1998 upwelling sediments may be explained by dilution with clastic terrigenous material transported by rivers, river discharges at this time of the year (late spring, summer) are minimal and were similar in both 2002–2003 and 1997–1998 upwelling periods (Dirección General de Aguas Chile, www.dga.cl).

Sedimentary $\delta^{15}N$ in 2002–2003 (Fig. 3c) showed marked fluctuations and ranged between 8.8‰ and 11.6‰, with minimum values at the beginning of the upwelling period. In contrast, $\delta^{15}N$ values during EN 1997–1998 were rather stable between 9.5‰ and 10‰ (Fig. 3d).

When analyzing the quality of organic matter in the surface sediments, the degradation index (DI) indicated less degraded organic matter for the upwelling period of the EN year (DI >1.2; Fig. 3f) than for the normal year (Fig. 3e). The decrease in DI values during the 2002–2003 upwelling period was accompanied by an increase in both total benthic macrofauna and *Parapronospio pinnata*, the dominant species (Fig. 3e) (Sellanes et al., 2007). During the EN 1997–1998 upwelling period, however, the total macrofauna was lower and a marked decreased in *P. pinnata* biomass was detected (Fig. 3f).

4. Discussion

4.1. Water column

The analysis of our results shows that upwelling did take place from November through April in both EN (1997–1998) and non-EN (2002–2003) years (Fig. 2a,b). However, a deepening of the thermocline was evident in May–June and October–November 1997 (Fig. 2d).

Low bottom water temperatures (<11.4 °C), high bottom water nitrate concentrations (>20 μM), and low BWO (<22.3 μM) during the 2002–2003 upwelling period (Fig. 2e,g,i) describe the usual seasonal intrusion of cold, high-nutrient, low-oxygen ESSW (typically located between 100 and 300 m water depth) onto the continental shelf (Ahumada, 1989; Morales et al., 1996; Strub et al., 1998; Blanco et al., 2001). Higher bottom temperatures (>11.4 °C) and oxygen concentrations (>25 μM) observed in May, August, and November 1997 (Fig. 2f,j) have been interpreted as the main effects of EN 1997–1998 in the area, attributable to a deepening of the thermocline and the OMZ upper boundary off central Chile (Gutiérrez et al., 2000; Neira et al., 2001a; Escribano et al., 2004).

Available Chl-*a* data for EN 1997–1998 point to a threefold decrease in phytoplankton biomass with respect to 2002–2003 (Fig. 2k,l). Chlorophyll-*a* values during the upwelling period were *ca.* 30 mg m^{-3} (2002–2003) and *ca.* 10 mg m^{-3} (1997–1998); the latter values are much higher than those of the non-upwelling months (*ca.* 2 mg m^{-3} in September–October 2002, 1.4 mg m^{-3} in May–June 2003; Fig. 2k). Farías et al. (2004) reported a twofold reduction in water column primary production when comparing data from the ending phase of EN 1997–1998 (March 1998) with non-EN years (March 1999 and 2000).

4.2. Surface sediments

Sedimentary biogenic opal concentrations (Fig. 3a,b) were within the range of those reported for surface sediments in this (COPAS Workshop, 2003) and adjacent areas (Romero and Hebbeln, 2003). Organic carbon concentrations (Fig. 3a,b) were similar to values reported previously for the same station (*ca.* 2% to *ca.* 6%; Thamdrup and Canfield, 1996; Glud et al., 1999; Schubert et al., 2000). Export production (as reflected by organic carbon and biogenic opal) (Fig. 3a) during 2002–2003 responded to the hydrographic seasonality and the supply of nutrients during upwelling (Fig. 2). Increased surface sediment opal concentrations (Fig. 3a) and phytoplankton biomass during late spring–early summer (Fig. 2k) were followed by increased sedimentary organic carbon (Fig. 3a). Both proxies agree with reports of high spring–summer surface sediment Chl-*a* in the area (COPAS Workshop, 2003; Muñoz et al., 2007).

Because the sedimentation rate at this site is 0.18 cm yr^{-1} (Muñoz et al., 2007), a 1-cm section would correspond to roughly 6 years of sedimentation. Therefore, the most plausible explanation for the water column–benthic coupling (also observed previously by Graco et al., 2006) was the presence of a seasonally recurrent (end of summer) flocculent layer which was previously reported by Thamdrup and Canfield (1996) and Graco et al., 2006) for the same sampling site (Sta. 18) during non-El Niño years following the phytoplankton spring bloom. Thamdrup and Canfield (1996) reported a ~2 cm flocculent layer above the surface sediment collected in March 1994 (*i.e.*, non-El Niño year), and recently, Graco et al. (2006) observed that this layer was present during the austral summer of non-El Niño years (1999–2000) and absent during the summer of El Niño years (1997–1998). Thus, the observed increase in biogenic opal and C-org during the productive season could be the result of the concentration of flocculent material above the seafloor (composed of filamentous bacteria, diatom detritus, fecal pellets, and clay minerals; Graco et al., 2001). Unlike the 2002–2003 period, a loss of the seasonal signal in export production delivered to and imprinted on the sediments could be inferred for the EN 1997–1998 upwelling period (Fig. 3b), which we propose to be associated with the absence of the flocculent layer. Although the overall lower organic carbon values in the EN sediments may also be linked to reduced preservation due to higher aerobic degradation rates, we suggest that the factor determining the observed sediment values is the reduction in water column phytoplankton production (based on Chl-*a*; Fig. 2l) and not the higher bottom water oxygen concentrations. Also, the higher degradation index (Fig. 3f), indicating less degraded material during the EN 1997–1998 upwelling period, is not consistent with less preservation.

A pattern of seasonality (2002–2003) *vs.* stable values (1997–1998) could also be observed in the surface sediment $\delta^{15}N$ (Fig. 3c,d). Our sediment $\delta^{15}N$ data can be interpreted in two ways. One interpretation is that the $\delta^{15}N$ values for the 2002–2003 upwelling period are attributed to nutrient utilization (Holmes et al., 1996; Voss et al., 1996). Low values at the start of the 2002–2003 upwelling period (Fig. 3c) suggest a higher availability of upwelled nutrients (from the ESSW). As the upwelling process advances and as nitrate is utilized, the $\delta^{15}N$ in the sediments increases (Fig. 3c). This is supported by the decreased surface nitrate concentrations in the water column (Fig. 2g) concurrent with an increase in phytoplankton biomass (Fig. 2k) and pulses of sedimentary biogenic opal and organic carbon (Fig. 3a). The second interpretation is related to denitrification. Our sedimentary $\delta^{15}N$ values during both study periods (Fig. 3c,d) are over 8.5‰, and sediments enriched in ^{15}N are usually attributed to active water column denitrification (Altabet et al., 1999, 2002; Ganeshram et al., 2000). Water column depletion of O_2 and nitrate observed during upwelling at Sta. 18 between 20 and 80 m depth (COPAS Workshop, 2003) could result in enriched $\delta^{15}N$-nitrate due to denitrification. This, in turn, leads to overall increased $\delta^{15}N$ in the sediments (Fig. 3c) due to isotope enrichment of source nitrate in the water column superimposed on any fractionation by algal utilization. The rather stable $\delta^{15}N$ data during EN 1997–1998 would suggest diminished denitrification and/or reduced fractionation during nutrient uptake when compared with 2002–2003.

4.3. The effect of macrofauna activity on the preservation of the seasonal signal in the sediment

Rapid shifts in benthic faunal assemblages in the area off Concepción in response to changes in water column conditions were observed by Gutiérrez et al. (2000), Neira et al. (2001a), Sellanes and Neira (2006), and Sellanes et al. (2007). Total macrofaunal and *P. pinnata* biomasses increased throughout the entire 2002–2003 upwelling period (Fig. 3e); however, this was not the case in the EN 1997–1998 upwelling period (Fig. 3f), when a change in the benthic community took place. Large, deep-burrowing polychaetes (*e.g.*, *Cossura chilensis*, *Aricidea pigmentata*, *Mediomastus branchiferus*) replaced *P. pinnata* and, in addition, average total macrofaunal density was lower (*ca.* 20,000 ind m^{-2}) than during the 2002–2003 period (*ca.* 40,000 ind m^{-2}) (Sellanes et al., 2007).

P. pinnata is an interface-feeding, small body-sized polychaete that is well adapted to the organic-rich, oxygen-deficient environments found in the surface sediments (0–3 cm), and does not produce important bioturbation (Gutiérrez et al., 2000). It dominates the macrofaunal assemblage (>60%) off central Chile during non-EN years (Carrasco and Gallardo, 1994).

Low bottom oxygen conditions and high amounts of fresh organic matter reaching the seafloor off Concepción may lead to high pore water sulfide concentrations near the sediment surface (Gutiérrez et al., 2000). These conditions, in turn, increase the physiological costs of subsurface deposit-feeders and also reduce predation pressure on them (Neira et al., 2001b). Organisms living under suboxic conditions require physiological adaptations to survive (Childress and Seibel, 1998). In particular, *P. pinnata* has been described as the best-adapted polychaete inhabiting the suboxic conditions off central Chile due to its ability to reduce metabolic rates in basal functions (González and Quiñones, 2000; Levin, 2003).

It has been suggested that the dominance of tube-dwelling surface defecators such as *P. pinnata* would promote the remineralization of organic matter near the sediment–water interface, whereas the dominance of deep-dwelling subsurface deposit-feeders and non-local mixers would increase mineralization rates in subsurface sediments (Gutiérrez et al., 2000). In view of our results, we suggest that the presence of fresher organic material on the seafloor during the EN 1997–1998 upwelling period (Fig. 3f) when compared to 2002–2003 was probably associated with a severe reduction in *P. pinnata* biomass (compare Fig. 3e, f).

5. Concluding remarks

Although interpretations based on parameters measured at a single sampling station may be biased by spatial patchiness, we found consistent signatures of water column processes in surface sediments during both EN and non-EN periods. Our data show that the upwelling period during the EN 1997–1998 off Concepción was characterized by decreased phytoplankton biomass (Fig. 2l), reduced export productivity (*i.e.*, biogenic opal, organic carbon in surface sediments; Fig. 3b), weakened denitrification and/or upper water column fertilization, and a lack of water column seasonality resulting in a rather stable imprint of all parameters when compared to a normal year. On the other hand, less degraded organic material differentiates the surface sediments of the EN 1997–1998 upwelling period from those of 2002–2003. We attribute this difference to a change in benthic fauna activity related to a drastic reduction in the abundance of *P. pinnata*, the main metazoan remineralizer of organic carbon near the sediment–water interface.

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