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Increase in water column denitrification during the last deglaciation: the influence of oxygen demand in the eastern equatorial Pacific

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Abstract. Here we present organic export production and nitrogen isotope results spanning the last 30 000 years from a core recovered off Costa Rica (Ocean Drilling Program (ODP) Site 1242) on the leading edge of the oxygen minimum zone of the Eastern Tropical North Pacific. Marine export production reveals glacial-interglacial variations with low organic matter (total organic carbon and total nitrogen) contents during warm intervals, twice more during cold episodes and double peaked maximum during the deglaciation, between ∼15.5–18.5 and 11–13 ka B.P. When this new export production record is compared with four nearby cores from within the Eastern Pacific along the Equatorial divergence, good agreement between all the cores is observed. The major feature is a maximum of export during the early deglaciation. As for export production, water-column denitrification, represented by sedimentary δ^{15}N records, along the Eastern tropical North and South Pacific between 15° N and 36° S is also coherent over the last deglaciation. Each of the nitrogen isotope profiles indicate that denitrification increased abruptly at 19 ka B.P to a maximum during the early deglaciation, confirming a typical Antarctic timing. It is proposed that the increase in export production and then in subsurface oxygen demand lead to an intensification of water-column denitrification within the oxygen minimum zones in the easternmost Pacific at the time of the last deglaciation. The triggering mechanism would have been primarily linked to an increase in preformed nutrients contents feeding the Equatorial Undercurrent driven by the resumption of overturning in the Southern Ocean and the return of nutrients from the deep ocean to the sea-surface. An increase in equatorial wind-driven upwelling of sub-surface nutrient-rich waters could have played the role of an amplifier.

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1 Introduction

The extent of intermediate water suboxia and open ocean denitrification varies significantly with climate with a positive feedback between the production of N_2O, a strong greenhouse gas, during denitrification and warming. Increased oxygenation of intermediate waters during glacial intervals has been attributed to both enhanced oxygen supply during water mass formation (ventilation) and decreased oxygen demand due to lower export production in the subsurface (Galbraith et al., 2004; Ganeshram et al., 1995, 2000; Altabet et al., 1995, 2002). Higher glacial wind speeds and lower temperatures increase modeled horizontal oxygen supply to the oxygen minimum zones (OMZ) (Meissner et al., 2005). Co-located records of export productivity and the extent of denitrification indicate that oxygen demand due to local export is not or only partially responsible (Ganeshram et al., 1995, 2000; Kienast et al., 2002; Thunell and Kepple, 2004; Hendy and Pedersen, 2006; Martinez et al., 2006; Robinson et al., 2007; De Pol-Holz et al., 2007) for the observed changes in suboxia and denitrification along the eastern Pacific margins. However, export in regions outside of suboxic zones, provided they are upstream in terms of ocean circulation, may have played an important role in drawing down subsurface oxygen concentrations. Net oxygen demand on such a large scale, is related to the preformed nutrient content of the low latitude thermocline. If low latitude export productivity is higher overall, then suboxia at the terminus of intermediate water flow paths will intensify. Glacial-interglacial changes in the preformed nutrients are hypothesized to drive changes in both Equatorial export productivity and water column suboxia and denitrification in the eastern Pacific (Brunelle et al., 2007; Loubere, 2002; Loubere et al., 2007; Robinson et al., 2007; Sarmiento et al., 2004; Toggweiler et al., 1991). Recent modeling efforts suggest that an increase in preformed nutrients, associated with intensified Southern Ocean overturning circulation during Antarctic Warm Periods, explains

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mid-stadial increases in N_2O concentrations observed in ice core records (Schmittner et al., 2007). Ultimately, suboxia intensity and extent will be modulated by the strength of the poleward undercurrent which flows in the thermocline. Kienast et al. (2002) have suggested that a weaker flow of undercurrent waters during the last glacial was responsible for a decrease in the advection of heavy nitrates along the northeastern American margins.

Sediments from within the Eastern Tropical Pacific (ETP) directly record changes in preformed nutrient concentrations and suboxia. The ETP houses both the equatorial upwelling system as well as two large regions of open ocean suboxia underlying the eastern boundary current upwelling systems centered off Peru and Mexico. Nutrients subducted in the thermocline in the Subantarctic Zone of the Southern Ocean as Subantarctic Mode Water (SAMW) are the dominant fuel for productivity in the low latitude oceans, with the exception of the North Pacific (Sarmiento et al., 2004). Variations in preformed nutrient content of SAMW are likely felt in a direct way in the EEP, because SAMW feeds into the Equatorial Undercurrent (EUC) that then shoals eastward across the Pacific. Upwelling delivers EUC waters to the surface in the equatorial cold tongue. Throughout the equatorial cold tongue, radiocarbon-poor surface waters indicate their distal origins as SAMW (Toggweiler et al., 1991).

Localized oxygen demand in the eastern equatorial Pacific (EEP) is thought to drawdown O_2 in the EUC waters that enter the poleward undercurrents (Lukas, 1986). Glacial-interglacial sedimentary nitrogen isotope records from the SE and NE Pacific margins indicate that the extent of water column denitrification was quite low during the last glacial period and increased significantly upon deglaciation (Altabet et al., 1995, 2002; De Pol-Holz et al., 2006; Galbraith, 2006; Galbraith et al., 2004; Ganeshram et al., 2000, 2002; Robinson et al., 2007). Galbraith et al. (2004) proposed a single physical mechanism, implicating lower oxygen supply during interglacial periods through a combination of reduced oxygen solubility, due to warming of surface waters in the Antarctic Ocean, and reduced circulation of intermediate water masses, then assuming no change between during their advection from the high (Antarctic Ocean) to the low latitudes (Suboxic zones). We discuss here the hypothesis that the deglacial maximum in suboxia and water column denitrification is related to the increase in oxygen demand in the EEP and this in turn results from an increase in the preformed nutrient content of SAMW (Loubere, 2002; Loubere et al., 2007; Spero and Lea, 2002; Robinson et al., 2005, 2007).

2 Material and methods

In this study, we compare regional trends in export productivity in the EEP with ETP margin records of water column denitrification, with the addition of new export and nitrogen isotope data from ODP Site 1242, located on the Costa Rica margin, underlying the leading edge of the suboxic OMZ. Site 1242 is located at 7°51.352′N, 83°36.418′W in a shallow basin at 1364 m water depth within the structurally complex intersection between Cocos Ridge and the Mesoamerican trench (Fig. 1). The site is in a graben on the crest of the Cocos Ridge. The sediments consist of lithologically homogenous hemipelagic olive-brown clayey silts, with minor amounts of well-preserved biogenic components (Mix et al., 2003). Geochemical analyses presented here at Site 1242 were measured every 4 cm in the upper 4.5 m, i.e. every 0.3 ka on average.

The age model, from Benway et al. (2006), is based on a $\delta^{18}O$ record on benthic foraminifers compared with both benthic $\delta^{18}O$ and radiocarbon dates from a co-located core (ME0005A-43JC). Sedimentation rates over the studied interval range between 4 and 15 cm ka^{-1}. Nitrogen isotope ratios ($\delta^{15}N$, ‰) and total nitrogen contents (TN, wt %) were determined on dried, ground bulk sediment, using a Carlo-Erba CN analyser 2500 interfaced directly to a Micromass-Isoprime spectrometer using ∼20–30 mg aliquots of homogenized bulk sediment. The precision of the isotopic analyses based on replicates of international standards and samples is better than ± 0.2‰. Nitrogen isotope values are reported in delta (δ) notation where: $\delta^{15}N = ((^{15}N/^{14}N_{sample}/^{15}N/^{14}N_{standard}) - 1)\times 1000$, and the standard is atmospheric N_2. Organic carbon (TOC or Corg, wt %) measurements were carried out using a LECO C-S 125 analyser after treatment of the sediment with hydrochloric acid to remove calcium carbonate, where precision were better than ± 5%.

A comparison of TOC and TN at Site 1242 suggests that a small amount of the nitrogen may come from an inorganic source (certainly mostly ammonium), as indicated by the positive intercept of TN when plotting TOC against TN (TN = 0.0747 TOC + 0.075; $r^2 = 0.909$; not shown). Ammonium is generally fixed within clay lattices (Müller, 1977). However, due to the large amount of TOC in core 1242, the isotopic composition of total nitrogen mostly reflects that of organic matter rather than inorganic N which constitutes only a small fraction of total N in these sediments.

At present, Site 1242 is located under the warm, relatively low-salinity waters of the intertropical convergence in the Panama Basin. Biological productivity is relatively low compared to other continental margin settings (Pennington et al., 2006). Off Costa Rica, nitrate is completely consumed annually in the surface waters overlying Site 1242, indicating that the N isotope record at this site should reflect the N isotopic composition of the upwelled water, as no net isotopic fractionation occurs when all nitrates are used (Fig. 1). In this region, subsurface O_2 concentrations at ∼150–200 m average 5–6 µmol/l on an annual basis with some seasonal variations according to hydrostation data from the World Ocean Atlas database (http://www.nodc.noaa.gov/). The threshold oxygen level below which suboxia and then denitrification can take place is not absolutely determined and some authors

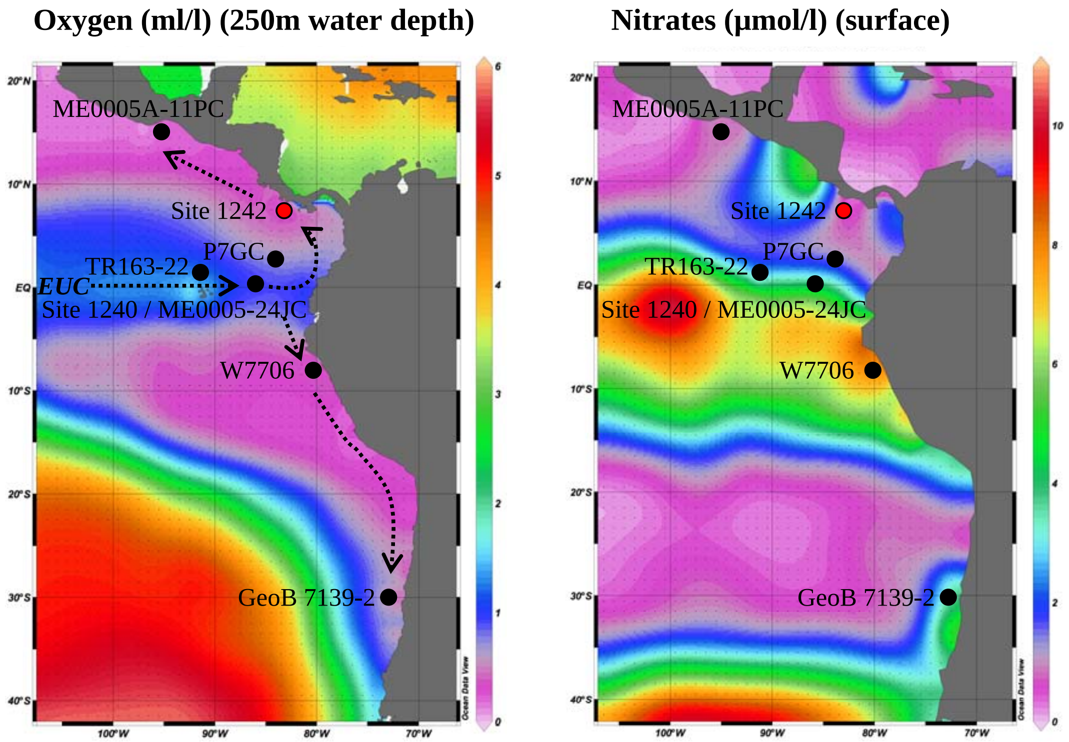

Fig. 1. Sub-surface dissolved oxygen concentrations at 250 m water depth and surface nitrate concentrations (Garcia et al., 2006). Locations of ODP Site 1242 (this study) as well as additional sites (TR163-22, ODP Site 1240, ME0005-24JC, P7GC, W7706, GeoB 7139-2) discussed in the text are marked with a black dot. Sub-surface current EUC (Equatorial Undercurrent) is also indicated by an arrow.

proposed based on field observations that it ranges between 2 and 10 µmol/l (see Codispoti et al., 2005). Oxygen concentration within the OMZ (between 300 and 700 m) over Site 1242, fall into this range. Water column denitrification imparts a strong isotopic signature on the sub-surface nitrate pool due to the faster reaction rate of the lighter isotope, ^{14}N, during nitrate reduction. The remaining nitrate pool is enriched in ^{15}N. The extent of denitrification is reflected in the isotopic composition of nitrate that is upwelled and that signal is transferred to the organic matter produced during photosynthesis and eventually buried on the seafloor. Sitting on the leading edge of the OMZ, Site 1242 should provide a minimum estimate of the denitrification changes, without overprinting by regional productivity features.

3 Discussion

3.1 Export productivity and denitrification in the Eastern Equatorial Pacific

At Site 1242, total organic carbon (TOC) contents are high all along the time interval 0–30 ka B.P., varying between 2.2 and 3.8 wt %. Total nitrogen (TN) contents follow the same pattern as the TOC profile, and vary between 0.24 and 0.38 wt %. Both records present glacial-interglacial variations with low organic matter contents during warm intervals, twice more during cold episodes and double peaked maximum during the deglaciation, between ∼15.5–18 and 11–13 ka B.P. A significant contribution of terrestrial organic matter is excluded at this site. The C/N ratio is too low (ranging between 9 and 10.5) and is indicative of marine organic matter (Meyers, 1997). The sedimentary organic matter variability at Site 1242 more likely reflects changes in local export production and/or in dilution by one of the major sedimentary components (silicoclastic and biogenic carbonate material). A rough estimate of past organic carbon export fluxes, using conventional method of calculating mass accumulation rates (sedimentation rates × dry bulk density × TOC %) is quite similar, in terms of temporal variability, to the changes in TOC and TN content. However, this approach can only be used as a first approximation because it is highly dependant on age model constraints. Moreover, mass accumulation rates of sedimentary components should be interpreted with caution because of the potential influence of lateral sediment redistribution during syn- and post-depositional processes on the seafloor (Francois et al., 2004). A recent compilation of accumulation rate calculations using the conventional method based on core chronologies (as we used here) and the Thorium-230 normalized method in the Panama Basin demonstrated that sediment focusing is highly

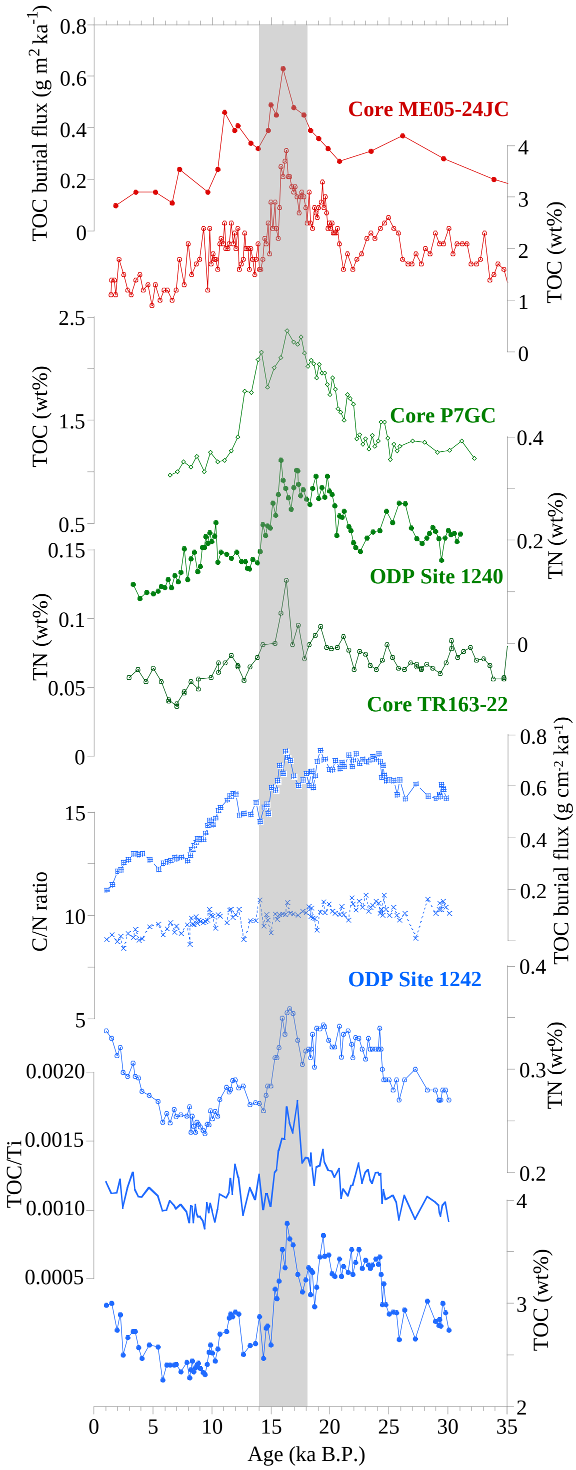

Fig. 2. Downcore profiles of TOC/Ti, TOC (wt %) and TN (wt %) contents, of C/N ratio, and of burial fluxes of TOC (in g cm^2 ka^{-1}) at ODP Site 1242 (in blue). Downcore profiles of TOC (wt %), TN (wt %), and TOC burial fluxes for additional sites (in green and blue) referred in the text and localized in Fig. 1. The shaded area highlights the interval of organic export maximum in the Eastern Equatorial Pacific during the deglaciation.

variable both spatially and temporally (Kienast et al., 2007). This work demonstrates that the conventional method systematically overestimates fluxes by a factor of 2–6 compared to fluxes normalized to ^{230}Th, particularly during the last glacial period when large terrigenous silicoclastic and hydrothermal inputs dominate the sediment composition (Kienast et al., 2007). These findings are certainly valid for Site 1242, and serve to explain the overall high organic carbon accumulation rates found off Costa Rica compared to the lowest measured in the Equatorial Pacific given that these two sites have comparable organic carbon contents (Kienast et al., 2006; Fig. 2).

Off Costa Rica, calcium carbonate contents are low (∼12% on average over the last 30 ka, not shown; see also Mix et al., 2002) and sedimentation is dominated by terrigenous silicoclastic material. Siliciclastics are, therefore, the main sedimentary fraction diluting the organic carbon contents of the sediment. Normalization of organic carbon to the concentration of a refractory element (as Titanium (Ti), or Aluminium (Al) found in the silicoclastic sediment may then correct for variable dilution effects and has the potential to give a good estimate of organic material input to the sediment over time (see Calvert and Pedersen, 2007; Hendy et al., 2004; Kienast et al., 2006). We used the Ti content, commonly and easily measured by XRF core-scanning, as an estimate of the terrigeneous fraction. Not surprisingly at Site 1242, Corg/Ti and Corg records look similar with only subtle differences. For instance, the Corg/Ti curve shows a large peak between 15 and 18 ka, indicative of higher export of organic carbon, whereas the raw organic carbon content profiles shows high values in the oldest part of the glacial (18–25 ka). This change in the shape of the profile is certainly the result of removing the dilution effect (Fig. 2). In addition, the Corg/Ti ratio perfectly covaries with the ^{230}Th-Corg profile of Kienast et al. (2006) of one core located offshore in the Equatorial Pacific. We are thus confident that our Corg/Ti profile provides a good estimate of past export production off Costa Rica.

We compare our results from Site 1242 with TOC and TN content from 4 nearby sites between 90° W and the Costa Rica margin (TR163-22, ODP Site 1240, ME0005-24JC, P7GC; see Figs. 1 and 2) in order to make a broader regional interpretation. All five cores show good agreement across the glacial-interglacial transition (Pedersen et al., 1991; Farrell et al., 1995; Kienast et al., 2006; Robinson et al., 2009), and with ^{230}Th-normalized organic carbon flux estimates from ME0005A-24JC (Kienast et al., 2006; Fig. 2) and from Site 1240 (Pichevin et al., 2009) which are more reliable estimation of marine primary export production (François et al., 2004). Since this method of normalization estimates absolute vertical organic fluxes for each measurement, a larger export during the deglaciation increasing significantly and abruptly at ∼18 ka with a peak centered at ∼16 ka B.P. in the EEP is clearly evident (Kienast et al., 2006). The exact timing of the productivity peak is rather difficult to determine because of the scarcity of high resolution ^{230}Th normalized accumulation rates of Corg over the last 30 ka available in the literature for this area. A combination of the different records from the EEP all together indicate that export production from across the EEP display a regionally coherent pattern of change over the last 30 ky, with higher overall export during the glacial interval, a maximum during the deglaciation, especially during the early deglaciation, and low export in the Holocene. Given, that the observed changes in water column denitrification highlighted here are direct evidence for changes in water column oxygenation, one could posit that the preservation of sinking organic matter may lead to variation not directly related to export. In addition, the deep North Pacific appears to have been less well oxygenated during the glacial (Jaccard et al., 2009). However, the regional organic carbon data presented here are in agreement, despite potential differences in oxygenation. Preservation is thus not an important control on organic matter accumulation. Additional support for a broadly regional, significant increase in export during with the deglaciation comes from Th-normalized opal accumulation records in the EEP (Bradtmiller et al., 2006). The various opal records show different patterns of change on the glacial-interglacial scale, both between themselves and when compared to the records here, yet most show a sharp increase in export associated with the deglaciation (Bradtmiller et al., 2006).

The extent of water column denitrification, as represented by sedimentary δ^{15}N in ETP margin sediments, appears to have been regionally coherent as well. Along the margin of the Americas, between 15° N and 36° S from southern Mexico to southern Chile, denitrification was weak during the last ice age and increased abruptly at ∼18 ka B.P to a maximum at ∼15 ka, with a slight decrease around 13–14 ka (Fig. 3; Site 1242 off Costa Rica: this study; Core GeoB 7139-2: De Pol-Holz et al., 2006; Core ME5A-11PC: Hendy and Pedersen, 2006, and see also Thunell and Kepple, 2004). A careful examination of the timing of δ^{15}N maximum reached off Southern Mexico (Hendy and Pedersen, 2006), Costa Rica (this study), Peru (Higginson and Altabet, 2004) and Chile (De Pol-Holz et al., 2006, 2007; Robinson et al., 2007; Martinez et al., 2006) is in fact difficult to assess and gives slightly different values: 15–15.5 ka off Costa Rica and Southern Mexico, 15.7–16.2 ka off Peru, 14.3–16.5 off Chile, whereas all this profiles show clearly a similar Antarctic timing. The age-model of all the cores is based on a combination of radiocarbon and oxygen isotope on benthic foraminifera, except off Peru where it is based on alkenones ^{14}C measurements because of the paucity or the absence of carbonate tests (Higginson and Altabet, 2004), and could be the main cause explaining these subtle differences, together with possible local processes. We can then assume that the denitrification profiles are all synchronized with a maximum occurring ∼15–16.5 ka. Besides, in both the Chilean and the Costa Rica records, δ^{15}N and thus local denitrification remains relatively steady with elevated values throughout the last 10 ka,

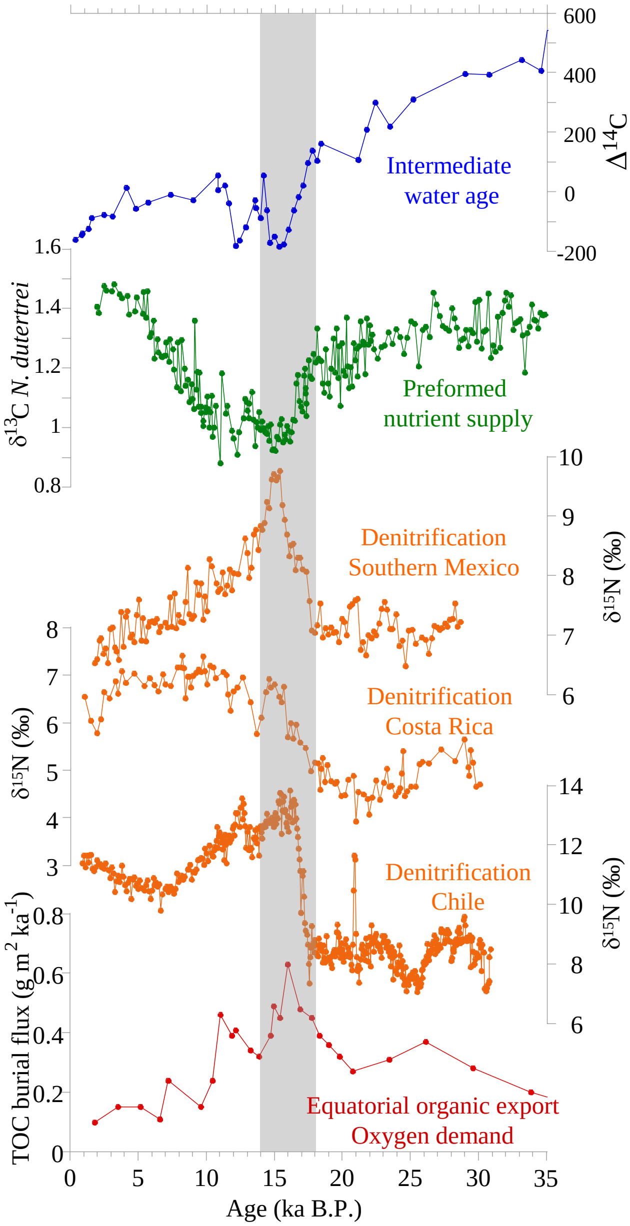

Fig. 3. Downcore profiles of organic export flux representative of the EEP as represented by ^{230}Th normalized TOC flux at Site ME005A-24JC (from Kienast et al., 2006), of δ^{15}N representative of water-column denitrification off Costa Rica (ODP Site 1242, this study), off Chile (Core GeoB7139-2 from De Pol-Holz et al., 2006), off Southern Mexico in the Gulf of Tehuantepec (Core ME0005A-11PC from Hendy and Pedersen, 2006), of planktonic foraminiferal δ^{13}C (*N. dutertrei* from Site 1240; Pena et al., 2008), and of and radiocarbon composition of benthic foraminifera from offshore Baja California in the northeast Pacific (from Marchitto et al., 2007). The shaded area highlights the interval of the deglaciation characterized by higher export production synchronous with higher water-column denitrification, driven by higher nutrient supply in the EEP and an increase in the influx of old and nutrient-rich bottom waters toward the surface.

whereas the records off Peru and Southern Mexico (Gulf of Tehuantepec) indicate a decrease during this time interval (Higginson and Altabet, 2004; Hendy and Pedersen, 2006). Such a Holocene δ^{15}N decrease toward glacial values is not specific of the southern Mexican margin but has already been observed in other records within, proximal or even distal to denitrifying areas (Higginson and Altabet, 2004; Pride et al., 1999; Martinez et al., 2006; Hendy and Pedersen, 2006; Kao et al., Kienast et al., 2008; Pichevin et al., 2009). This feature could result from an overprinting of the denitrification signal by local changes in nutrient utilization by phytoplankton at the sea-surface during photosynthesis related to upwelling activity and/or by the influence of variable local or regional biological (N_2 fixation, nutrient utilization rates) and hydrologic conditions (depth and strength of undercurrents for instance) (De Pol-Holz et al., 2009; Hendy et al., 2004; Ren et al., 2009).

3.2 Enhanced nutrient supply during the deglaciation

The deglacial increase in export production in the EEP appears to be coincident with the increase in denitrification inferred from the nitrogen isotope records, although the productivity and denitrification profiles do not always present the same pattern. There are differences in timing between the age of the productivity and the denitrification maxima. Nevertheless, the deglacial increase in export production (and then oxygen demand) and denitrification starts at about the same time (Fig. 3). This observation fits with the hypothesized increase in subsurface oxygen demand leading to an intensification of the oxygen minimum zone in the easternmost Pacific. In order for the increase in export in the EEP to be causally related to the increase in water column denitrification on the margin there must have been a net increase in oxygen demand along the flow path of SAMW, not merely a local (Altabet et al., 1995; Ganeshram et al., 2000; Galbraith et al., 2004; Meissner et al., 2005). The EEP is directly connected to SAMW, the primary source of nutrients to the low latitudes, via the EUC. However, the increase in export could be the result of either intensified upwelling or enhanced nutrient content of EUC waters.

The good covariance between higher marine export production and decreased alkenones- or Mg/Ca-based sea-surface reconstructions at sites ME5A-24JC (Kienast et al., 2006) and 1242 (Klinkhammer et al., 2009) respectively in the EEP and the ETP would lend support to the hypothesis of increased wind-driven upwelling activity during the deglaciation (Kienast et al., 2006; Bush and Philander, 1998), although it is not so clear for the Holocene period. There are however some other studies which did not describe a cooling associated with the deglaciation in this area of the EEP, but rather an Antarctic-type deglacial pattern starting at ∼19 ka B.P. (Koutavas et al., 2002; Lea et al., 2006; see also Kiefer and Kienast, 2005 for a synthesis). Since lower SST in the EEP may also result from colder source waters in the Austral Ocean without invoking large changes in upwelling activity, the understanding of the relationships between SST and productivity is then not straightforward.

There is strong evidence for enhanced nutrient content of subsurface EUC waters. Records of planktonic foraminfera δ^{13}C and a residual δ^{15}N, washed of the regional denitrification overprinting, suggest that the upwelling of relatively nutrient-rich water in EEP led to deglacial increases in export (Spero and Lea, 2002; Pena et al., 2008; Robinson et al, 2009). Such an increase in nutrient supply would have the larger effect on low latitude export and subsurface oxygen demand required to drive the change in the strength of the OMZ (Fig. 3). Based on δ^{13}C on benthic foraminifera, Pahnke and Zahn (2005) demonstrated that the conversion of intermediate and mode waters from the Southern Ocean and feeding the EUC increased significantly during from the last deglaciation and remained stable during the Holocene, thus increasing the intensity of the thermocline circulation. Additional data support these findings. The increase in preformed nutrients (low δ^{13}C values at Site 1240; Fig. 3) during the deglaciation was likely driven by the resumption of overturning and the return of nutrients (and CO_2) from the deep ocean to the surface ocean-atmosphere system (Spero and Lea, 2002; Pena et al., 2008; Marchitto et al., 2007; Robinson et al., 2009). Evidence for the release of sequestered deep waters comes from radiocarbon of intermediate and deep ocean benthic foraminifera (Marchitto et al., 2007; Schmittner et al., 2007) (Fig. 3).

Longer timescale records of δ^{15}N along the NE Pacific margin indicate that glacial-interglacial variations in the extent of denitrification have persisted for the last several million years, where cooler climate periods are associated with weak or negligible denitrification (Liu et al., 2008; Altabet et al., 1999). In the Equatorial Pacific, Pena et al's 500 ka B.P. δ^{13}C record of planktonic foraminifera indicates that preformed nutrients peaked during each of the 4 glacial terminations (Pena et al., 2008). This pulse of nutrients likely caused the peaks in export and oxygen demand that led to rapid intensification of suboxia during glacial terminations in general. However, export records indicate that this elevated input of nutrients was not sustained. This suggests an additional factor at work. Two alternative mechanisms to maintain suboxia through the interglacials exist: 1) a change in ventilation associated with the bimodal climate variability and the physical controls on oxygen supply (Meissner et al., 2005) or 2) Local fluctuations in export and oxygen demand. If indeed there was a step-like decrease in ventilation associated with the termination of the glacial period, one would then expect sedimentary δ^{15}N to be elevated relative to glacial values throughout the interglacial periods, as seen in the records from Chile and Costa Rica shown here. However, records from the Peru margin or from the Gulf of Tehuantepec off Southern Mexico show decreases to near glacial low values in the late Holocene (Higginson and Altabet, 2004; Hendy et al., 2006; Chazen et al., 2008). These records are from near shelf sediments and so may reflect local conditions rather than the broader regional situation. The deglacial peaks in oxygen demand (export production) and denitrification can thus be considered transient features and this climatic transition is a time when oxygen demand becomes more important than supply.

4 Conclusions

The regional comparison of export production records from the eastern equatorial Pacific with denitrification records from the eastern Pacific margins illustrates the influence of oxygen consumption and subsurface circulation in controlling thermocline oxygen concentrations. We show that the increase in water-column denitrification over the last deglaciation off Southern Mexico to Costa Rica and off Peru to Chile is at least partly the result of an increase in productivity at that time in the entire eastern Equatorial Pacific which leads to enhanced subsurface oxygen consumption. This signal was then transported downstream along the eastern tropical Pacific margins by undercurrents (EUC), certainly facilitated by a strengthening of intermediate water circulation. Fluctuations in export production in the eastern equatorial Pacific would have been by large changes in preformed nutrients inputs in the eastern equatorial Pacific. Further work with additional data, and especially modeling efforts, are needed to test numerically the real impact and viability of our hypothesis.

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