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Quaternary Research 65 (2006) 519 – 525

QUATERNARY RESEARCH

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Short Paper

Paleoproductivity evolution off central Chile from the Last Glacial Maximum to the Early Holocene

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Received 14 February 2005
Available online 12 September 2005

Abstract

A geochemical and paleontological reconstruction of paleoproductivity, upwelling intensity and sea surface temperature (SST) off central Chile at 35°S (GeoB3359-3) reveals marked changes from the Last Glacial Maximum (LGM) through the Early Holocene. Surface-water productivity was determined by the interaction between the atmospheric (the Southern Westerlies) and oceanographic (the Antarctic Circumpolar Current, ACC) systems from the LGM through early Termination I (TI). The northward shift of the climate zones during the LGM brought the ACC, as the main macronutrient source, closer to the GeoB3359-3, SST lowered, and surface water productivity and accumulation rates of biogenic components enhanced. With the poleward return of the Southern Westerlies and the ACC, the subtropical high-pressure system became the dominant atmospheric component southward till 35°S during the late TI and Early Holocene and caused surface water productivity to increase through enhanced upwelling.

Keywords: Deglaciation; Diatoms; Holocene; Last Glacial Maximum; Paleoproductivity; Peru-Chile Current; Sea-surface temperatures; Upwelling

Introduction

The present-day surface oceanography in the SE Pacific along the mid-latitude Chilean coast is dominated by an oceanographic component, the Peru-Chile Current (PCC) and by an atmospheric one, the Southern Westerlies (Shaffer et al., 1995; Strub et al., 1998; Fig. 1). The PCC branches from the Antarctic Circumpolar Current (ACC) at approximately 40°–45°S and builds one of the world's most productive eastern boundary current systems. Upwelling-favorable winds occur up to 36°–38°S off Chile, while south of 38°S onshore-blowing, the Southern Westerlies generally prevent coastal upwelling (Strub et al., 1998). Although favorable conditions for intense phytoplankton proliferation presently characterize surface waters in the SE Pacific, satellite-derived information reveals strong north–south variations (Thomas, 1999).

Paleoceanographic research in the southern PCC relates changes in surface water productivity during the Last Glacial Maximum with changes in water masses and wind systems. Two main scenarios for paleoproductivity changes have been proposed. The marine downcore record in the southernmost PCC show that paleoproductivity changes were driven by the N–S migration of the Southern Westerlies and the ACC (Lamy et al., 1999; Hebbeln et al., 2002). In this scenario, paleoproductivity was highest during the LGM and decreased afterwards. Therefore, paleoproductivity variations most likely reflect the displacement of the nutrient source, the ACC (Hebbeln et al., 2002). Based on cores collected off northern Chile between 24° and 33°S, Mohtadi and Hebbeln (2004) recently suggested an additional player in the regional paleoceanography. They demonstrated that surface waters were less productive in the SE Pacific during the LGM than during Termination I, followed by the lowest paleoproductivity during the Holocene. In addition to the effect of the Southern Westerlies, this new scenario proposed that paleoproductivity variations off northern Chile during the Late Quaternary

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0033-5894/$ - see front matter
doi:10.1016/j.yqres.2005.07.003

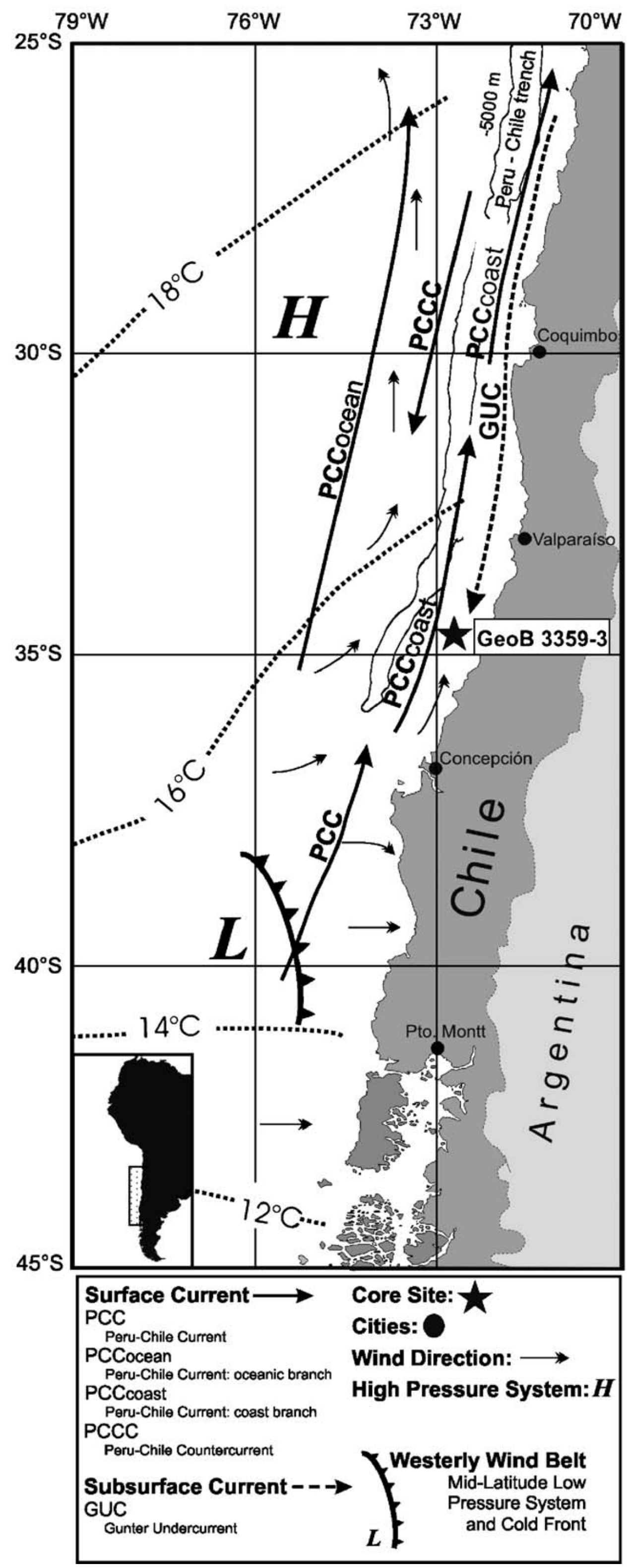

Figure 1. Modern oceanographic and atmospheric conditions in the SE Pacific (Shaffer et al., 1995; Strub et al., 1998). Annual mean sea-surface temperatures at 0 m water depth were taken from Levitus and Boyer (1994). Location of GeoB3359-3 is shown as a black star.

were also affected by the subtropical high pressure belt in the SE Pacific.

The core site investigated here, GeoB3359-3, is located at ~35°S in the SE Pacific, beneath the most intense present-day coastal upwelling and chlorophyll filament activity (Thomas, 1999). Its location fills a spatial gap in the paleoceanographic record along the Chilean margin (e.g., Lamy et al., 1999, 2002, 2004; Hebbeln et al., 2002; Mohtadi and Hebbeln, 2004; Mohtadi et al., 2004), and allows us to describe the evolution of paleoproductivity, upwelling intensity, and SST at 35°S off Chile from the LGM through the early Holocene. We discuss our observations in the context of the Southern Westerlies and the subtropical high-pressure belt, the main forcing for paleoproductivity changes in the southern part of the PCC.

Material and methods

Gravity core GeoB3359-3 was collected beneath the main present-day upwelling area off Chile (35°13.0′S, 72°48.5′W, water depth 678 m, core length 368 cm: Hebbeln et al., 2001; Fig. 1). For the present work, samples were taken at 5-cm intervals allowing analyses to be performed on an average time interval of approximately 225–240 yr. The total organic carbon (TOC) as well as the total carbon (TC) contents was obtained following the method described by Müller et al. (1994). Calcium carbonate was calculated as the difference between TC and TOC, and expressed as calcite ($CaCO_3$ = (TC − TOC) × 8.33). We applied the alkenone paleothermometry method to estimate SST. The procedure of alkenone analysis follows Kim et al. (2002). Sample preparation and counting procedure for diatoms were described by Romero and Hebbeln (2003). Biogenic opal was determined with a sequential leaching technique (Müller and Schneider, 1993). Accumulation rates were calculated by multiplying the content or concentration of the particular parameter, sediment dry bulk density, and sedimentation rate. The age model is based on five ^{14}C Accelerator Mass Spectrometry (AMS) dates determined on mixed planktonic foraminiferal tests (Table 1) at the Leibniz laboratory for age determinations and isotope research at the University of Kiel (Nadeau et al., 1997). The continuous time scale was obtained by linear interpolations between the age control points after converting the ^{14}C ages into calendar years using Calib 4.4.1 (Stuiver et al., 1998).

Results

We describe the paleoproductivity and SST variations at 35°S off Chile for the time span between 23,500 and 7000 cal yr B.P. on a three-period basis: the Last Glacial Maximum, Termination I, and the Early Holocene.

Table 1
Age control points for gravity core GeoB3359-3

Lab no.	Interval [cm]	Depth [cm bsf]	Age [^{14}C yr B.P.]	Error (1σ) [yr]	2σ [cal yr B.P.]	Age[a] [ΔR = yr][b] [cal yr B.P.]	Analyzed material
KIA8224	138–143	140.5	13,190	130	14,272–15,727	15,000	Mixed planktic forams
KIA8225	168–178	173.0	14,270	90	16,038–17,040	16,539	Mixed planktic forams
KIA8226	243–248	245.5	16,070	90	18,022–19,220	18,621	Mixed planktic forams
KIA8227	278–283	280.5	18,650	150/140	20,829–22,335	21,582	Mixed planktic forams
KIA8229	353–363	358.0	20,070	120/110	22,533–23,963	23,248	Mixed planktic forams

[a] To convert uncorrected ^{14}C ages into calendar ages, the CALIB REV4.4.1 program was used (Stuiver et al., 1998).
[b] Regional ^{14}C reservoir ages (ΔR) are assumed to be 400 yr (Lamy et al., 2004).

The Last Glacial Maximum (LGM)

Full glacial conditions off central Chile were characterized by the highest accumulation rates (AR) of $CaCO_3$ and opal for the whole studied period (between 1.3 and 1.6 g cm^{-2} (10^3 yr)$^{-1}$, Fig. 2). The AR of C_{org} paralleled well those of $CaCO_3$ and opal. The rapid decrease of the AR of all biogenic components after ~21,500 cal yr B.P. relates to ^{14}C dates (Fig. 2). Sediment composition was strongly dominated by lithogenics throughout.

The diatom AR was the lowest for the whole study period (Fig. 3). Basically, two main distinct floral assemblages occurred: (a) an upwelling-associated assemblage (mainly spores of *Chaetoceros* spp.), and (b) a non-upwelling related assemblage, composed of benthic, freshwater, and Southern Ocean diatoms (Fig. 3). Contribution of non-upwelling diatoms reached its highest during the LGM, while upwelling diatoms ranged from 45 to 60%. Alkenone-derived SST reveals a narrow range of variation between 11.3° and 13°C with the lowest SST at 23,100 cal yr B.P. (Fig. 3).

Termination I (TI)

$CaCO_3$ and C_{org} were high between 18,500 and 15,000 cal yr B.P. (Fig. 2). During the second half of TI, the $CaCO_3$ AR decreased while C_{org} increased. The opal AR dimin-

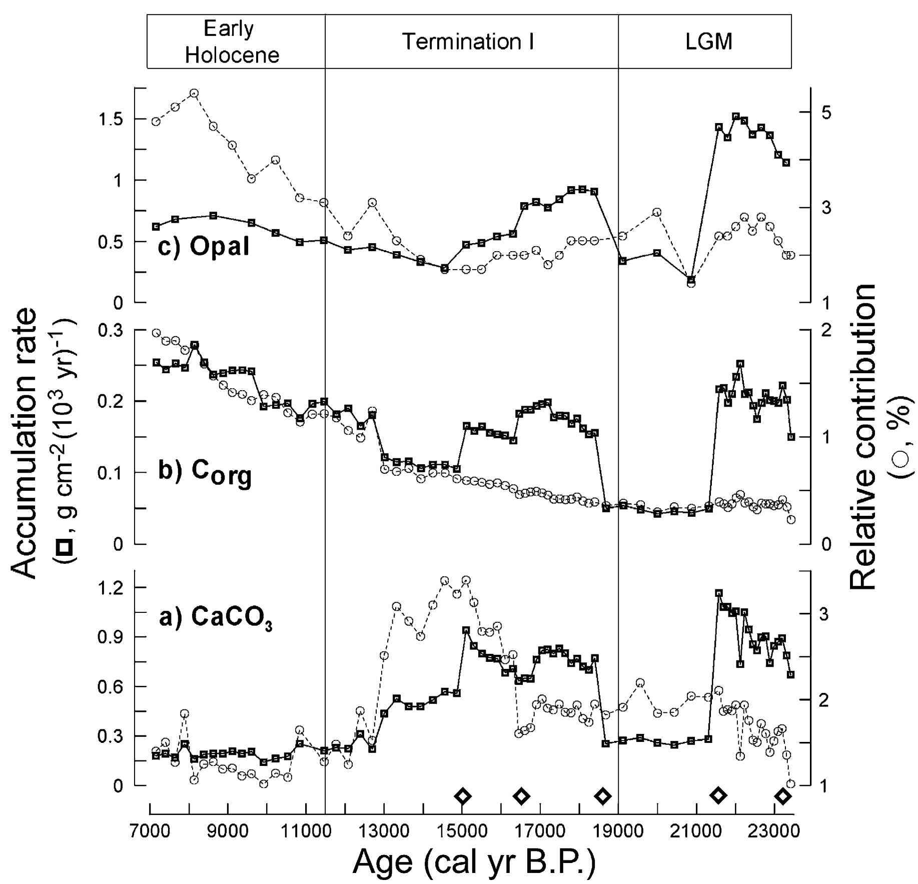

Figure 2. Downcore variations of biogenic bulk components at GeoB3359-3 in the SE Pacific for the time period between ca. 23,500 and 7000 cal yr B.P. Accumulation rates of biogenic bulk components are given as g cm^{-2} (10^3 yr)$^{-1}$ (left axis) and relative contribution expressed as percentage (right axis). Open diamonds represent age control points.

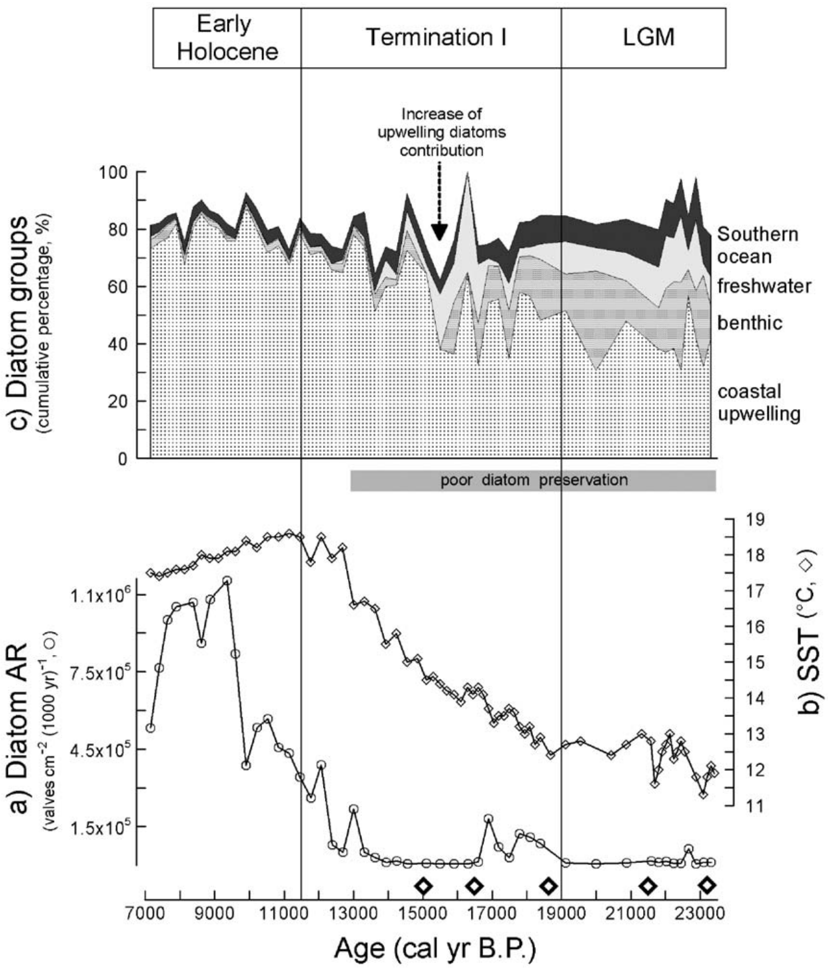

Figure 3. Downcore variations of (a) diatom accumulation rate (AR) (valves g cm^{-2} $(10^3\ yr)^{-1}$), (b) alkenone-derived SST (°C), and (c) relative contribution of group of diatoms (coastal upwelling, dotted; benthic, dark grey; freshwater, light grey; and Southern Ocean, black) at GeoB3359-3 in the SE Pacific for the period between ca. 23,500 and 7000 cal yr B.P. Open diamonds represent age control points.

ished after 16,500 cal yr B.P. and its values remained below 0.5 g cm^{-2} $(10^3\ yr)^{-1}$ till the end of TI. The relative contribution of C_{org} and opal increased toward the end of TI, while that of $CaCO_3$, though low throughout, had a maximum between ~16,500 and 13,000 cal yr B.P.

The diatom AR remained below 3×10^5 valves cm^{-2} $(10^3\ yr)^{-1}$ until 12,300 cal yr B.P. and increased thereafter (Fig. 3). The contribution of the upwelling-associated diatoms rapidly increased at ~15,500 cal yr B.P., while that of freshwater, benthic and southern ocean diatoms reached its lowest values later (Fig. 3). An abrupt change in the preservation of valves is observed at ~13,000 cal yr B.P.: valves are better preserved than those from the LGM and early TI. The alkenone-derived SST started to increase around 18,700 cal yr B.P. and reached its maximum close to the end of TI (Fig. 3).

The Early Holocene

Opal and C_{org} became the main biogenic sediment components during the Early Holocene, while $CaCO_3$ reached its lowest values for the whole study period (Fig. 2). The diatom AR continued to increase and reached the highest AR between ~9500 and 7600 cal yr B.P. (Fig. 3). The contribution of upwelling-related *Chaetoceros* spores exceeded 70%. The alkenone-derived SST decreased ~1.5°C since late TI.

Discussion and conclusion

The strong paleoproductivity variations along the Chilean coast during the late Quaternary have been associated to different mechanisms and forcing processes. Our multi-parameter record shows that the off-shore paleoproductivity at 35°S responded to the same mechanisms during the LGM that were influential to the south (Lamy et al., 1999; Hebbeln et al., 2002). The equatorward shift of the Southern Westerlies during the LGM transported cold water masses and macronutrients of the ACC closer to the site GeoB3359-3, causing the decrease of SST and the increase of the AR of the biogenic components (Figs. 2 and 3). A similar pattern

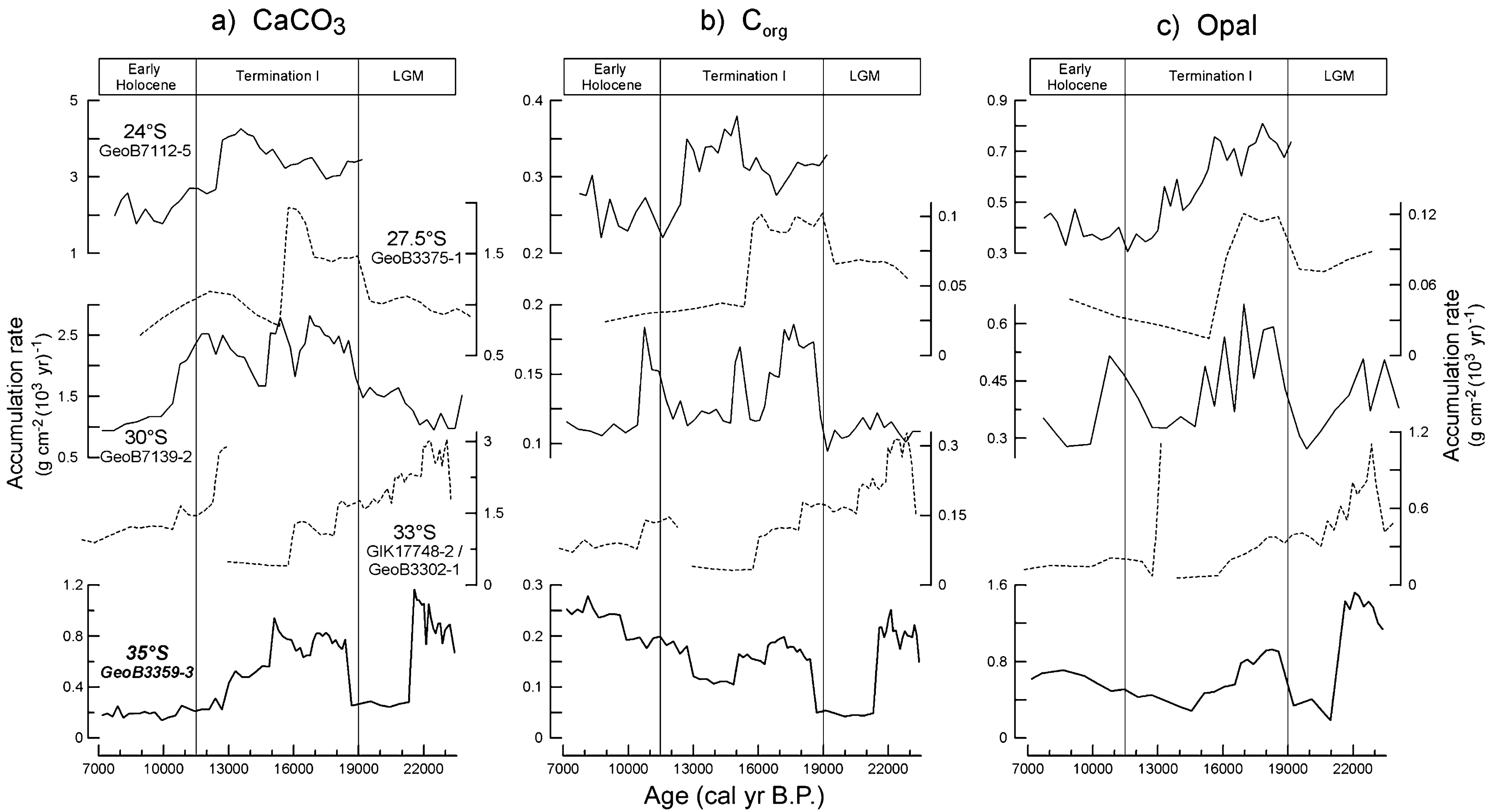

Figure 4. Accumulation rate (g cm^{-2} (10^{3} yr)$^{-1}$) of biogenic bulk components a) calcium carbonate, b) organic carbon, and c) opal] in five cores from the SE Pacific for the period between ca. 23,500 and 7000 cal yr B.P. Note the different scales for each panel. Data and core description of GeoB7112-5, GeoB3375-1, GeoB7139-2 and GIK17748-2/GeoB3302-1 are available in Mohtadi and Hebbeln (2004).

around LGM has been recorded further north along the Chilean coast, where maximum AR were reached later during TI (Fig. 4; Mohtadi and Hebbeln, 2004). In spite of low SST, a less intense upwelling is expected at 35°S due to the downwelling effects associated with the northward-displaced Southern Westerlies. Additionally, the increased continental rain in the Andes increased the terrigenous input at 35°S prior to TI (Lamy et al., 1999), and, hence, enhanced the dissolution of siliceous components.

The southward migration of the Southern Westerlies and the ACC between LGM and TI caused surface water masses to start warming (Fig. 3). The offset between the slow increase of SST and the stepwise increase of the relative contribution of upwelling diatoms suggests that favorable nutrient conditions at 35°S, rather than adequate temperature conditions, were decisive for diatom production. Similarly, a dominant temperature control has been ruled out for the shift in the dominance of planktic foraminifera from *Neogloboquadrina pachyderma* (sin.) to *N. pachyderma* (dex.) and the appearance of *N. dutertrei* off northern Chile around 16,000 cal yr B.P. (Mohtadi and Hebbeln, 2004).

Relatively high SST and the dominant contribution of upwelling diatoms during the late TI and the Early Holocene imply that the core site was beyond the direct influence of the Southern Westerlies. Instead, upwelling favorable winds of the subtropical high-pressure system were the dominant atmospheric component at 35°S (Mohtadi and Hebbeln, 2004). The rather low paleoproductivity during this time along the central-northern Chilean coast (Fig. 4) appears counterintuitive at first glance. This, however, agrees with the present-day highest productivities south of 35°S in the southern PCC (Thomas, 1999), where high nutrient-low chlorophyll waters of the ACC meet the strong, Fe-rich terrigenous input from southern Chile (Hebbeln et al., 2002).

The marked shift in the diatom assemblage at 15,700 cal yr B.P. clearly documents temporal and spatial changes at 35°S. The temporal trend at GeoB3359-3 is also reflected in the latitudinal trend of the qualitative and quantitative composition of the diatom thanatocoenosis preserved in Late Holocene sediments (Romero et al., 2001; Romero and Hebbeln, 2003). The dominance of spores of *Chaetoceros* spp. north of 36°S reflects predominant upwelling conditions along the central-northern Chilean coast. In contrast, south of 38°S, where the present-day productivity is higher than further north, freshwater, benthic, and southern ocean diatoms indicate strong terrigenous input and supply of ACC waters. Following an actualistic approach, the GeoB3359-3 diatom downcore record evidences the latitudinal pattern of the coastal upwelling occurrence off Chile and hence the whole oceanic (ACC) and atmospheric (Southern Westerlies) circulation systems during the last glacial/interglacial cycle.

Comparison of our data with those previously published for the Chilean coast shows some spatial and temporal variability in the development of the paleoproductivity off central and northern Chile. Generally, higher productivities between 24° and 35°S in the southern PCC occurred prior to Holocene times while during the early Holocene productivity dropped into much lower levels (Fig. 4). Regarding the latitudinal variation of biogenic components along the Chilean coast, the most striking feature is the low contribution of biogenic components at 35°S (Fig. 4). Opal and C_{org} show similar relative values at 35°S than further north, but calcium carbonate is up to six times lower GeoB3359-3 during the last glacial/interglacial cycle (Fig. 2; Mohtadi and Hebbeln, 2004). Although carbonate preservation is good for most of the Chilean coast, surface sediment samples at 35°–38°S are almost free of planktic foraminifera (Mohtadi et al., 2005). Most probably, the dissolution at the sediment water-interface of calcareous organisms affects the carbonate content. This hypothesis, however, requires detailed geochemical and hydrological investigations in the water column and in surface sediments from this area and remains speculative so far.

Our observations at 35°S fill a gap in the available marine paleoreconstruction for the southernmost PCC. The significance of our record lays on the fact that previous paleoceanographic reconstructions for the last glacial–interglacial cycle were spatially restricted to the northern coast off Chile between 24° and 33°S (Mohtadi and Hebbeln, 2004; Mohtadi et al., 2004) or southward (Lamy et al., 1999). We demonstrate that the surface-water productivity in the PCC at 35°S was strongly determined by the interaction between the atmospheric (the Southern Westerlies) and oceanographic (the ACC) circulation patterns from the LGM through early TI. The subtropical high-pressure system became the dominant atmospheric component southward down to 35°S along the Chilean coast during late TI and the Early Holocene.

Acknowledgments

M. Segl, B. Meyer-Schack, C. Hayn and M. Buëmann are acknowledged for their lab work. M. Mohtadi read an early version. M. A. Bárcena and an anonymous reviewer contributed with helpful comments. This study was supported by the German Bundesministerium für Bildung und Forschung (Project PUCK, 03G0156A). The data presented here are also available in digital format (www.pangaea.de/PangaVista). This is the RCOM Publication No. 0304.

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