

High resolution planktic foraminiferal record of the last 13,300 years from the upwelling area off Chile

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Abstract

A high resolution sedimentary record spanning the last deglacial and Holocene periods was obtained by studying the deep-sea sediment core GIK 17748-2 retrieved from 2545 m water depth in the Valparaíso Basin (Chilean continental slope, Southeast Pacific — 32°45.00'S; 72°02.00'W). AMS-¹⁴C measurements and oxygen-isotope analyses of the planktic foraminifera species *Globigerina bulloides* and *Neogloboquadrina pachyderma* (dex.) indicate an age of 13.3 AMS-¹⁴C kyr B.P. at the base of the core (383 cm) and sedimentation rates ranging between 9 and 92 cm/kyr. Foraminiferal assemblages and accumulation rates were analysed in order to investigate variations in paleoceanography and paleoproductivity in the southern Peru–Chile Current during the last 13 kyr. Changes in foraminiferal assemblages indicate a sequence of three major hydrographic regimes at the site of the core: (1) deglacial sediments are characterised by variable faunal compositions generally reflecting strong upwelling and high productivity. (2) During the early and middle Holocene upwelling and, thus, productivity decreased, as indicated by an elevated relative abundance of *N. pachyderma* (dex.), and the importance of the Subtropical Surface Water of the Peru–Chile Countercurrent increased, as indicated by higher relative amounts of *N. dutertrei*. (3) For the last 3 kyr, variable faunal assemblages indicate variable competing environmental conditions characterised on one hand by increased upwelling, reflected by an elevated relative abundance of *N. pachyderma* (sin.), and on the other hand, by warmer conditions, deduced from a higher relative abundance of *N. dutertrei*, probably due to more frequent and more intense El Niño events. In addition, hints for slightly cooler conditions between 11.4 and 10.7 kyr B.P. might be related to a Younger Dryas event in this region. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

From a marine geological point of view, the southern part of the Peru–Chile Current (PCC) is

among the least studied regions of the world ocean. Compared to other Eastern Boundary Currents (EBC), the PCC stands out as the EBC with the longest N–S extension and a strong continuous upwelling regime resulting in a very high biological productivity ($> 200 \text{ gC m}^{-2} \text{ yr}^{-1}$) (Berger et al., 1987). In addition, the Southeast Pacific off Chile is episodically heavily influenced by El Niño events, during which warm surface waters reach the South

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American west coast, resulting in strongly reduced primary production (Wallace and Vogel, 1994).

To explain glacial/interglacial variations of atmospheric CO₂ concentrations known from ice core records (Barnola et al., 1987), a higher marine productivity has been proposed for glacial times (Berger et al., 1989). Nowadays, 50% of the global ocean export production are produced within only 15% of the ocean area, namely in upwelling areas and in the coastal seas (Berger et al., 1989). Thus, for the reconstruction of paleoproductivity and its relation to climate through the Late Quaternary climatic cycles, these regions are of greatest importance.

Glacial/interglacial variability of climate–ocean interactions can be traced by studying the flux and faunal composition of planktic foraminifera through the last climatic cycles (Oberhänsli, 1991; Peterson et al., 1991; Kennett and Venz, 1995). Planktic foraminifera can reveal detailed information about surface ocean conditions in terms of water mass distribution, sea surface temperatures and productivity. In addition, the accumulation of benthic foraminifera is also closely related to surface water productivity (Herguera and Berger, 1991).

In the modern Peru–Chile Current, the planktic foraminiferal assemblage is dominated by *Neoglobobulimina papyroderma* (dex.), followed by *Globobulimina bulloides* and *N. papyroderma* (sin.) (Bandy and Rodolfo, 1964; Boltovskoy, 1976; Hebbeln et al., submitted). Analyses of surface sediments from the Chilean continental slope between 27°S and 42°S reveal these three species account together for an average 80% of the total assemblage in this region (Hebbeln et al., submitted).

Studies of planktic foraminiferal assemblages collected in sediment traps deployed off Coquimbo, Chile (ca. 30°S), indicate that a seasonal succession of species occurs during the year (Marchant et al., 1998). High fluxes of planktic foraminifera occur between August and January, compared with low fluxes during the remaining part of the year. Comparing the foraminifera collected during El Niño conditions with those collected during normal conditions shows a shift in species composition. Most obvious are the much higher numbers of *N. dutertrei* under El Niño conditions, which replace most of the *N. papyroderma* (sin.) flux found under normal conditions.

Here we present the first detailed reconstruction of paleoenvironmental conditions in the southern PCC deduced from planktic foraminifera assemblages. This reconstruction spans the last 13.3 AMS-¹⁴C kyr including the end of the deglaciation and the Holocene. The objective of this study is (1) to establish a high resolution sequence of paleoceanographic events in the southern Peru–Chile Current during the last 13 kyr, (2) to compare deglacial and Holocene environmental conditions by planktic foraminiferal assemblages and (3) to analyse the intensity of upwelling and productivity in the Peru–Chile Current during the deglaciation and the Holocene.

2. Regional and oceanographic setting

The Valparaíso Basin is a 50 × 50 km² wide, flat area on the Chilean continental margin off Valparaíso (Fig. 1). It is located between 2400 m and 2600 m water depth. A small transverse ridge divides the basin in a northern and a southern part. The upper slope rises steeply towards the coast and is cut by two large canyons, which both end in the northern part of the basin.

The oceanography off Chile north of 45°S is controlled by the Peru–Chile Current (PCC, also known as Humboldt Current) (Fig. 1). This current originates from the Antarctic Circumpolar Current (ACC) transporting Subantarctic Surface Water eastward across the Pacific Ocean. Approaching the South American continent at 40°–45°S, the ACC splits into two branches (Boltovskoy, 1976; Martens, 1981): the Cape Horn Current (CHC) flows poleward and the PCC flows equatorward. The PCC extends to few degrees south of the equator before turning west becoming the South Equatorial Current (SEC) (Pickard and Emery, 1982).

Off the Chilean coast, the PCC can be divided into an oceanic and a coastal branch separated occasionally by the poleward flowing Peru–Chile Countercurrent (PCCC, Subtropical Surface Water) (Shaffer et al., 1995; Strub et al., 1998) (Fig. 1). These surface water masses are underlain by the Gunther Undercurrent (GUC, Equatorial Subsurface Water), which is mainly located between 100 m and 400 m water depth over the shelf and the continental

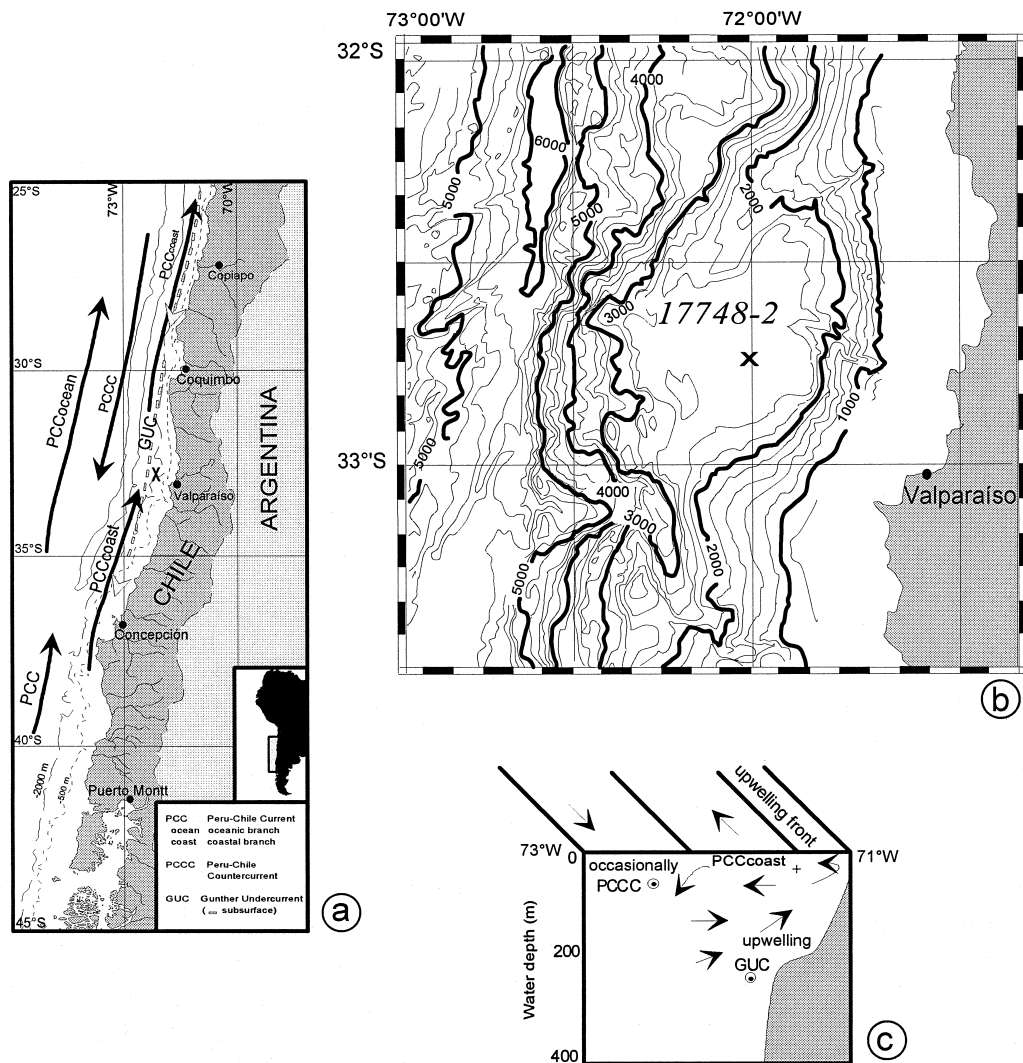


Fig. 1. (a) Ocean surface and subsurface currents in the Southeast Pacific off the Chilean coast (compiled after Shaffer et al., 1995 and Strub et al., 1998) and the location of the core site. (b) Bathymetry of the Valparaíso Basin and again the core site (after Von Huene and Shipboard Scientific Party, 1995). (c) Schematic profile at 33°S showing a typical coastal upwelling situation in the Peru–Chile Current (see text).

slope. Between 400 m and 1200 m water depth, Antarctic Intermediate Water (AAIW) flows equatorward underlain by sluggishly poleward flowing Pacific Deep Water (PDW).

Perennial southerly winds result in Ekman-drift induced upwelling of cool, nutrient-rich waters along the Chilean coast (Brandhorst, 1963). Due to the continuous and intense coastal upwelling, the PCC

belongs to the most important high productivity regions in the world ocean (Berger et al., 1987). Although the winds are upwelling-favourable throughout the year (Strub et al., 1998), the physical and the biological settings display distinct seasonal patterns. Off Valparaíso, primary productivity is highest during the austral winter (Thomas et al., 1994) when sea surface temperatures are lowest.

During this time, the wind direction shifts from predominantly southeasterly to southwesterly directions. The particle flux in the PCC reflects this seasonal pattern with highest fluxes in late winter (September), intermediate fluxes until January and low fluxes between January and July (Hebbeln et al., in press).

3. Material and methods

The gravity core GIK 17748-2 was taken from the southern part of the Valparaiso Basin on the continental slope off Valparaiso, Chile (32°45.00'S; 72°02.00'W, 2545 m water depth, core length 383 cm) (Fig. 1) by the German RV SONNE (cruise SO 80) (Stoffers and Shipboard Scientific Party, 1992). The recovered sediment consists mainly of light brown to olive silty clays with three distinct dark sandy turbidites. For this study, the core was sampled at 5 cm intervals in two sample sets.

One sample set was sieved through a 63 μm sieve. The remaining coarse fraction was oven dried at 50°C and dry sieved in three fractions (63–150 μm , 150–212 μm and > 212 μm), which all were weighted. Of the three size fractions, only the two larger fractions were used for the foraminifera investigations. The sieved samples were subsequently divided with a microsplitter to a sample size of approximately 200 individuals of foraminifera. All specimens were individually picked and identified using the planktic foraminifera species concepts by Kennett and Srinivasan (1983) and Hemleben et al. (1989). The abundances of planktic and benthic

foraminifera were recorded in all samples by counting all individuals > 150 μm . For *N. pachyderma*, the relative abundances of right- (dex.) and left- (sin.) coiling individuals were determined and both forms were treated as individual species.

The stable oxygen isotopes ($\delta^{18}\text{O}$) of the near surface living planktic foraminifera *G. bulloides* (Fairbanks et al., 1982) and of the deeper dwelling species *N. pachyderma* (dex.) (Boltovskoy, 1981) were analysed using a Finnigan MAT 251 mass spectrometer with an automated carbonate preparation device at the University of Bremen. 10 to 15 tests (> 212 μm , mostly between 212 μm and 250 μm with a few shells up to 400 μm) (50–200 μg) of each species and sample were picked for each measurement. The isotope $^{18}\text{O}/^{16}\text{O}$ ratios are expressed in the standard δ notation relative to the PDB (Pee Dee Belemnite) standard. Precision of our determinations is about $\pm 0.07\text{‰}$ PDB. Age control is provided by eight ^{14}C analyses. For these datings, 10 mg carbonate (> 3000 tests of planktic foraminifera, *G. bulloides* and *N. pachyderma* (dex.)) were picked and analysed using the accelerated mass spectrometer (AMS) facility at the University of Groningen, The Netherlands. Following standard procedures, the AMS-dates are corrected for ^{13}C and for a reservoir age of 400 years (Bard et al., 1987) (Table 1). All ages are given in AMS- ^{14}C kyr.

The second sample set was ground for carbonate content determinations. Carbon analyses of the sediment were conducted with an elemental analyser (Hereaus CHN-O-Rapid). Total carbon (TC) contents were measured on untreated samples and organic carbon (TOC) contents on HCl-treated samples. Car-

Table 1
AMS- ^{14}C measurements of deep-sea core GIK 17748-2

Depth (cm)	Lab. ident.	^{14}C -age (kyr B.P.) uncorr.	^{14}C -age (kyr B.P.) reservoir corr. (– 400 years)
63–78	GrA-1095	4160 \pm 40	3760
98–103	GrA-1096	7290 \pm 40	6890
128	GrA-3805	9650 \pm 79	9650
153–158	GrA-1097	10 920 \pm 50	10 520
183–188	GrA-1098	11 600 \pm 50	11 200
228–238	GrA-3827	11 380 \pm 130	11 380 ^a
273–278	GrA-3806	12 750 \pm 100	12 750 ^a
333–348	GrA-1099	13 290 \pm 60	12 890

^aSamples have not been used for the age model.

bonate contents were calculated according to the formula $\text{CaCO}_3 = (\text{TC} - \text{TOC}) * 8.333$, with the factor resulting from the stoichiometric composition of CaCO_3 . The relative error of the carbonate determinations is $< 5\%$. Accumulation rates of carbonate components and of foraminiferal numbers are calculated according to the equations given by Van Andel et al. (1975) and by Thiede et al. (1982).

4. Results and discussion

4.1. Chronology

Comparison with samples from a boxcorer taken at the same site showed that the uppermost 13 cm of the sediment column are missing in core 17748-2 (Stoffers and Shipboard Scientific Party, 1992). Thus, the real sediment surface with a pre-set age of 0 yr is set to -13 cm for core 17748-2. Onboard magnetic susceptibility measurements revealed three turbidites in 9–16 cm, 47–54 cm and 160–175 cm core depth, respectively (Fig. 2) (Stoffers and Shipboard Scientific Party, 1992). AMS-dates immediately above

and below the older turbidite clearly show, that this event had no considerable erosional effect on the sedimentary sequence. The same is assumed for the two younger turbidites.

The chronostratigraphy for this core is based on AMS- ^{14}C measurements on planktic foraminifera shells (Table 1). Two of the AMS dates (11.38 kyr and 12.75 kyr B.P.) suffered from a poor gas quality during the measurement resulting in a relatively large uncertainty. Therefore they were rejected, although they fit within the age sequence. Thus, an age model was developed based on the six good AMS data with ages between dated points obtained by linear interpolation (thereby excluding the turbidite layers from the sequence). The estimated age of the oldest retrieved sediments (383 cm core depth) is 13.3 kyr B.P. The Pleistocene–Holocene boundary, assumed to be at 10 kyr B.P. (Berger, 1982), is placed at ~ 140 cm depth.

The oxygen isotope curves of the two planktic foraminifera species *G. bulloides* and *N. pachyderma* (dex.) show an almost continuous change from higher to lower values reflecting the deglaciation.

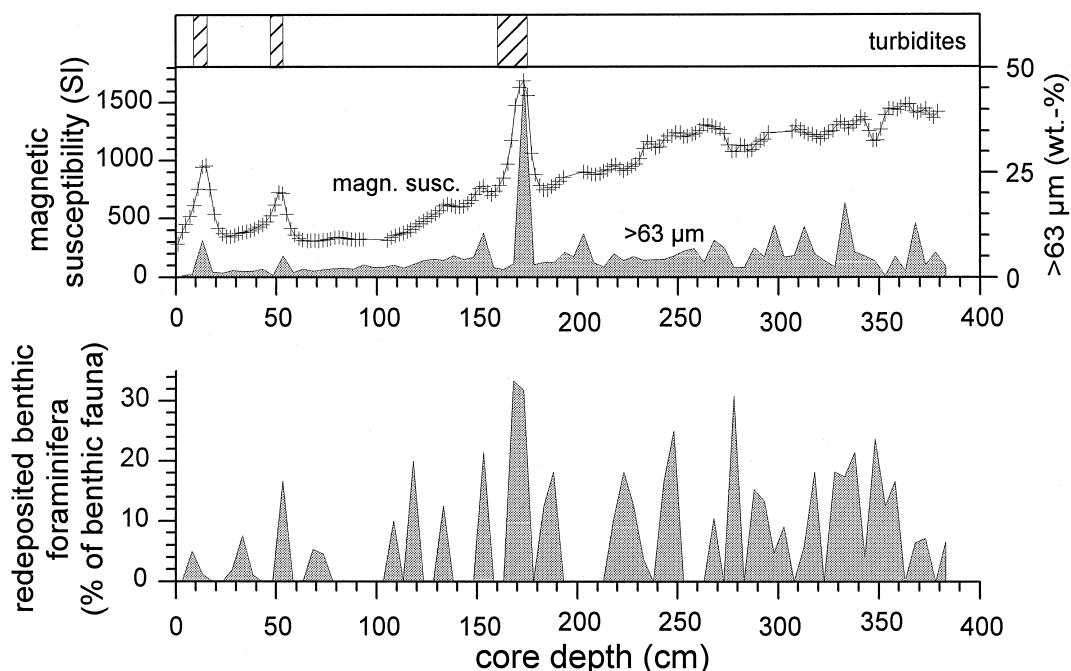


Fig. 2. Magnetic susceptibility (from Stoffers and Shipboard Scientific Party, 1992) and $> 63 \mu\text{m}$ records of core 17748-2 indicating three distinct turbidites. Relative abundance of redeposited benthic foraminifera ($> 150 \mu\text{m}$) throughout the core (see text).

tion and the onset of the Holocene (Fig. 3). Throughout the core, the $\delta^{18}\text{O}$ data of *G. bulloides* and *N. pachyderma* (dex.) exhibit a total range of 2.2‰ and 1.6‰, respectively (Fig. 3).

4.2. Sedimentation rates

The calculated sedimentation rates range from 92 cm/kyr during the deglaciation (188–383 cm, 11.2–

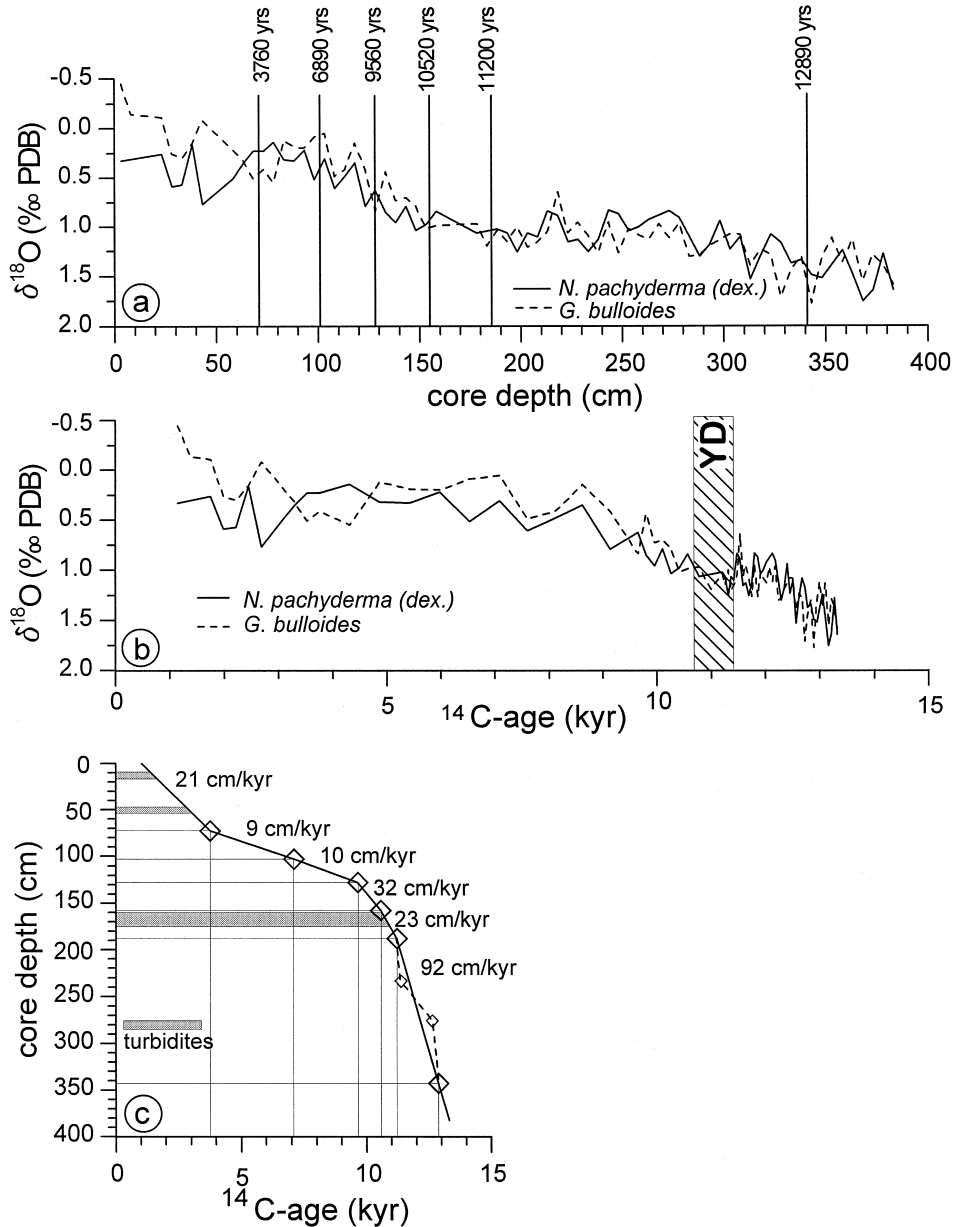


Fig. 3. (a) Stable oxygen isotope records of *N. pachyderma* (dex.) and *G. bulloides* and AMS ^{14}C -datings in core 17748-2 vs. core depth. (b) Resulting chronology for the oxygen isotope records. The hatched bar marks the Younger Dryas interval. (c) Resulting age model for core 17748-2 based on 6 AMS- ^{14}C measurements. Two additional AMS-dates (~ 235 cm and ~ 275 cm) are not used for the age model (see text). For the calculation of the sedimentation rates, the depth intervals occupied by the turbidites have been excluded.

13.3 kyr) to lower values on the order of 10–30 cm/kyr during the Holocene (0–158 cm, <10.6 kyr) (Fig. 3). These average Holocene sedimentation rates provide a temporal resolution of approximately 160 to 500 years at a sample spacing of 5 cm. The high sedimentation rates during the deglacial are most likely due to resedimentation processes caused by the postglacial flooding of the continental shelf. This is indicated by higher and more variable coarse fraction contents and by increased contents of redeposited benthic foraminifera (Fig. 2).

The relative abundance of redeposited benthic foraminifera was estimated on the relative abundance of four species of benthic foraminifera, which are known to live in the PCC in distinctly shallower waters than the retrieval depth of this core (2545 m). These species are *Bolivina* sp. (lives shallower than 1500 m, Bandy and Arnal, 1960; Ingle et al., 1980), *Cassidulina laevigata* (lives shallower than 1500 m, Ingle et al., 1980), *C. subglobosa* (lives shallower than 1500 m, Ingle et al., 1980) and *Nonion* sp. (restricted to the shelf, Bandy and Arnal, 1960; Ingle

et al., 1980). Thus, a minimum estimate of the relative abundance of redeposited shells is obtained, given that shells of other species have also most likely been redeposited. However, redeposition is unequivocal only for these four species.

The record of redeposited benthic foraminifera indicates that redeposition is a common process in the Valparaíso Basin (Fig. 2). However, in the upper 160 cm of the core, the contribution of redeposited shells is rather low (3% on average, disregarding the turbidite layers). Thus, we assume that this part of the core reflects an only slightly altered hemi-pelagic flux signal. In contrast, in the lower part of the core, the average contribution of redeposited shells amounts to 9%. In combination with the very high sedimentation rates, this is an indication of a substantial contribution of reworked sediments.

4.3. Carbonate content and dissolution

The carbonate content varies between 2 and 18% (Fig. 4). It is generally much lower in the upper

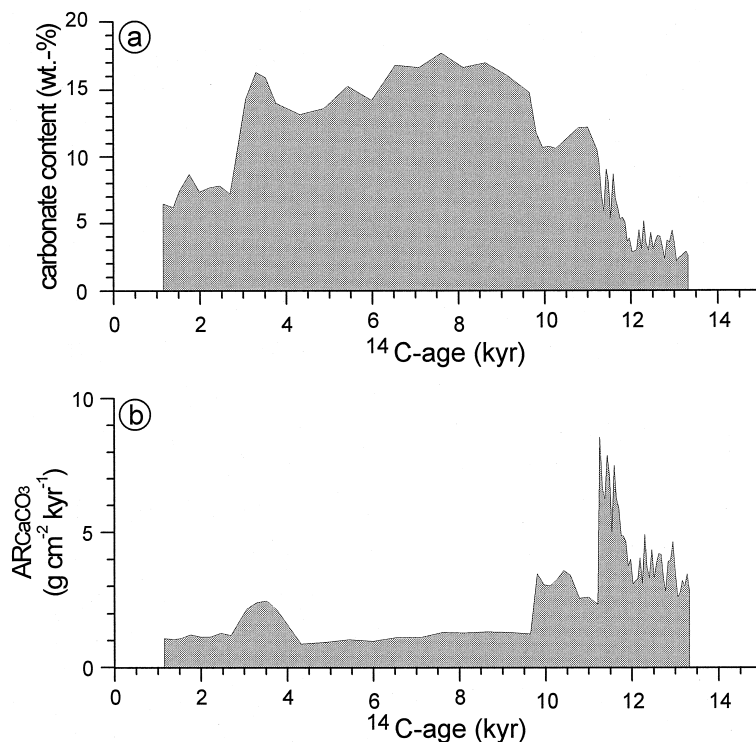


Fig. 4. (a) Carbonate content and (b) carbonate accumulation rate vs. age in core 17748-2.

(3–48 cm, 0.16–2.62 kyr B.P.) and lower part (228–383 cm, 11.64–13.32 kyr B.P.) of the core, varying between 2.6–8.7% and 2.3–6.8%, respectively. Between 48 cm and 228 cm, carbonate contents are consistently > 12%. The carbonate accumulation rate (AR $\text{CaCO}_3 \text{ g cm}^{-2} \text{ kyr}^{-1}$) is much higher (4–10 $\text{g cm}^{-2} \text{ kyr}^{-1}$) during the deglaciation than during the Holocene (1 $\text{g cm}^{-2} \text{ kyr}^{-1}$) (Fig. 4).

The analyses of surface sediments from the study region shows that the calcite compensation depth is at ~ 4500 m water depth, while the lysocline, where the onset of significant carbonate dissolution occurs, is at ~ 3700 m water depth (Hebbeln et al., submitted). These data are almost identical to results from the nearby Peru Basin (Weber et al., 1995). Thus, core 17748-2 has been collected from a depth (2545 m) clearly above that of the lysocline (~ 3700 m) and, therefore, it should not be seriously affected by carbonate dissolution. Even if the lysocline was shallower at some time during the Holocene than at present, it probably would not have been much closer to our core site. The total vertical shift of the lysocline through a full glacial/interglacial cycle has been estimated to ~ 1 km for the Western Pacific, with the present lysocline being near the minimum of the range, signifying maximum dissolution (Hebbeln et al., 1991). Furthermore, the preservation of the foraminifera shells is generally good as for example reflected by the high abundance of *G. bulloides* and *Globigerinita glutinata* (Fig. 5), which are relatively delicate forms sensitive to carbonate dissolution (Vincent and Berger, 1982). Thus, if the faunal composition is not significantly controlled by dissolution, the striking contrast in the carbonate content of the deglacial and Holocene sediments is most likely not due to variations in carbonate dissolution (Fig. 4). Instead, variability in the carbonate contents probably reflects changing dilution of the carbonate flux by lithogenic material as indicated by higher deglacial and rather constant Holocene carbonate accumulation rates (Fig. 4).

4.4. Foraminiferal time series

Large downcore variations in the absolute abundances of the total planktic and benthic foraminifera faunas (> 150 μm) and in the relative abundances of the dominant species indicate considerable past changes in the environmental conditions in this re-

gion. Absolute concentrations of planktic foraminifera show a distinct maximum (400–600 ind/g sediment) during the early Holocene (90–130 cm, 5.5–9.8 kyr B.P.) (Fig. 5).

After much lower concentrations (80 ind/g sediment) during the deglaciation (> 240 cm, 11.8–13.3 kyr B.P.), the increase to the high early Holocene values started already at 11.8 kyr, at a time when the sedimentation rates and the relative abundance of redeposited benthic foraminifera were still on very high levels (92 cm/kyr, Figs. 2 and 3) indicating ongoing significant resedimentation. The high concentrations during the early Holocene dropped within 2.5 kyr (90–60 cm) to very low late Holocene levels of 10 to 70 ind/g sediment for the last 3 kyr (Fig. 5).

In total, 21 planktic foraminifera species in 11 genera and 4 families were identified in core 17748-2. An examination of the faunal composition showed the dominance of six species, which account on average for approximately 90% of the total planktic foraminiferal assemblage: *N. pachyderma* (dex.), is the dominant species (43%) together with *G. bulloides* (32%), *N. pachyderma* (sin.) (8%), *N. dutertrei* (4.8%), *Globigerinita glutinata* (3.8%) and *Globorotalia inflata* (2.6%) (Fig. 5).

The absolute abundance of the two dominant species, *N. pachyderma* (dex.) and *G. bulloides*, shows a very similar pattern throughout the last 13 kyr mainly reflecting the overall development of productivity along the Chilean margin (Fig. 5b,d). However, their relative contributions to the total fauna are mainly negatively correlated (Fig. 5a,d) implying a different response of the two species to other environmental changes. The relative abundance of *N. pachyderma* (dex.) is almost constant (35–40%) during the deglaciation (13.3 to 11.4 kyr), starting to increase through the Holocene to a maximum of > 60% between 7 and 2 kyr. In contrast, *G. bulloides* has its highest relative abundance during the deglaciation (13.3 to 11.4 kyr) with a maximum (> 35%) between 12.2 and 11.4 kyr. During the Holocene, the relative contribution of *G. bulloides* decreased steadily to minimum values of 10% within the last 3 kyr (Fig. 5a).

Similar to the *G. bulloides* record, *N. pachyderma* (sin.), *Globorotalia inflata* and *Globigerinita glutinata* all show an elevated relative abundance

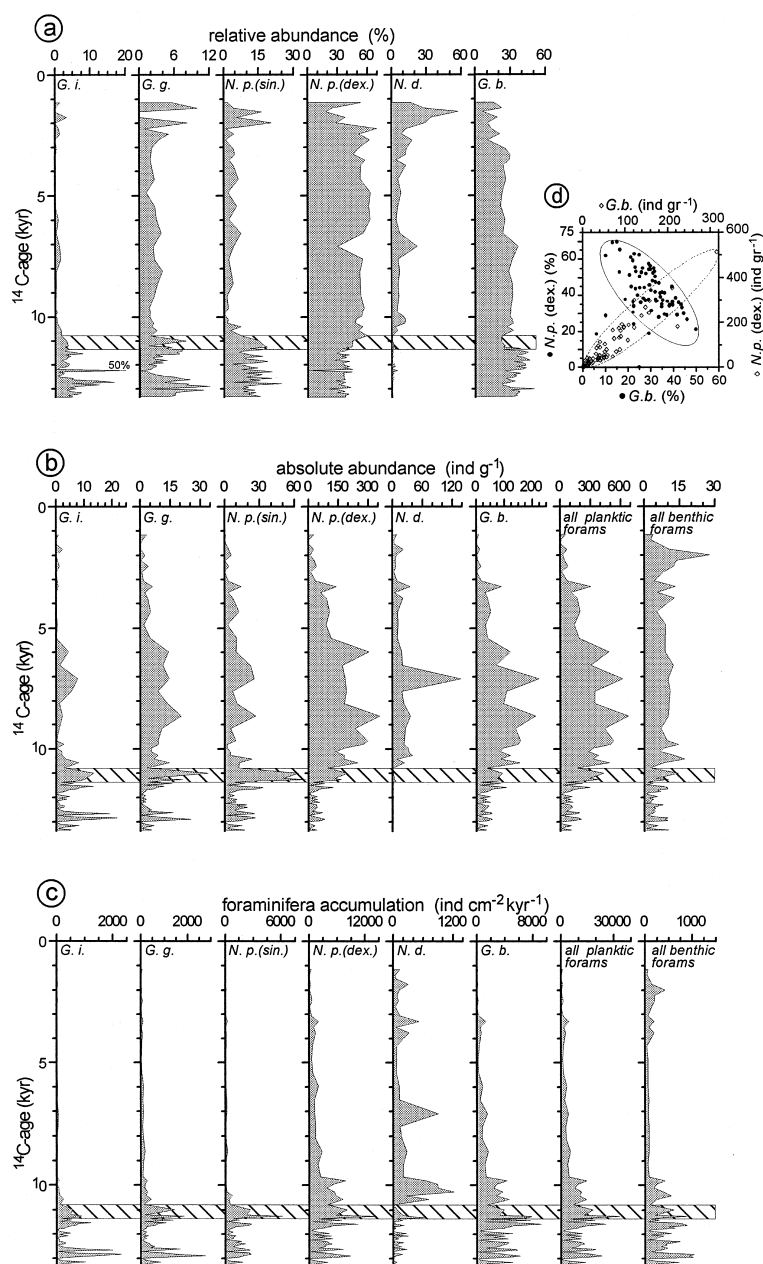


Fig. 5. Time series of (a) relative and (b) absolute abundances of the six most important planktic foraminifera species ($> 150 \mu\text{m}$) and (c) their accumulation rates in core 17748-2: *G.i.* = *Globorotalia inflata*; *G.g.* = *Globigerinita glutinata*; *N.p. (sin.)* = *N. pachyderma* (sin.); *N.p. (dex.)* = *N. pachyderma* (dex.); *N.d.* = *N. dutertrei*; *G.b.* = *G. bulloides*. Absolute abundances and accumulation rates are also given for all planktic and benthic foraminifera. The hatched bars mark the Younger Dryas interval. (d) Comparison of relative (dots) and absolute (open diamonds) abundance of *G. bulloides* and *N. pachyderma* (dex.).

during the deglaciation, although this pattern is more pronounced for the latter species compared to *G.*

bulloides. *N. pachyderma* (sin.) varied continuously between 10% and 20% until 10.9 kyr. During the

same time interval (13.3 to 10.9 kyr), *Globigerinita glutinata* and *Globorotalia inflata* had an increased relative abundance (both 8%) between 13.3 and 12.4 kyr and between 11.8 and 10.9 kyr (with 6% and 3%, respectively). In the early Holocene (10.6 to 3 kyr), the contribution of these three species is only minor with < 5% for *N. pachyderma* (sin.), < 4% for *Globigerinita glutinata* and < 2% for *Globorotalia inflata* (Fig. 5). *Globorotalia inflata* is common close to the continent, because this species requires a weakly stratified surface layer, lowered surface-water temperatures and relative high food-levels (Van Leeuwen, 1989). *Globigerinita glutinata* is a fairly ubiquitous species, occurring from tropical to polar regions without special preferences (Bé and Tolderlund, 1971).

The *N. dutertrei* record is quite different. *N. dutertrei* did not occur in considerable numbers before 10.6 kyr. Then it contributed an average 10% to the planktic foraminifera fauna and had only one relative maximum (60%) in the youngest sediments (1–2 kyr). These sediments are characterised by an unusual species composition with an extremely high relative abundance of *N. dutertrei* and with a high abundances of *N. pachyderma* (sin.), *Globigerinita glutinata*, and *Globorotalia inflata*. Only *N. pachyderma* (dex.) displays a remarkable drop in the relative abundance during this interval (Fig. 5). As the most pronounced variations in species composition during the last ~ 3 kyr occurred among the *Neogloboquadrinas*, which all have a similar susceptibility to carbonate dissolution (Berger, 1970), ecological rather than chemical changes can be assumed to cause this variability.

From these data, several conclusions can be drawn. The total planktic foraminifera assemblage shows a considerable change in the species composition at 10.6 kyr B.P. (Fig. 5) manifested by the distinct relative decrease of the cold water species *N. pachyderma* (sin.) and *Globorotalia inflata* opposed by the increase of the warmer water species *N. pachyderma* (dex.) and *N. dutertrei*. In addition, *Globigerina falconensis* and *Globigerinoides tenellus* only occur between 10.92 and 13.32 kyr (173–383 cm), whereas some warm water species as, e.g., *Globigerinella digitata* and *Globorotalia tumida* appear only within the last 10.6 kyr (3–168 cm). Thus, warm water species become dominant at 10.6 kyr B.P.

This conclusion is supported by the distribution pattern of *N. dutertrei*, which lives in the chlorophyll maximum associated with the thermocline and requires higher water temperatures (preferably > 20°C; Bé, 1977) than *N. pachyderma* (dex.) (Fairbanks et al., 1982). Sediment trap investigations from the PCC indicate that *N. dutertrei* is related to the Subtropical Surface Water of the PCCC, which extends furthest south during El Niño years resulting in considerably enhanced fluxes of *N. dutertrei* in the PCC off Chile (Marchant et al., 1998). Thus, the *N. dutertrei* record (Fig. 5) suggests that more Subtropical Surface Water has been advected to the study area after 10.6 kyr B.P. The increase in the relative abundance of *N. dutertrei* to > 60% after 3 kyr B.P. points to an increasing influence of El Niño conditions. This is in agreement to other paleo-El Niño records, which indicate the onset for El Niños 7 kyr ago, with an intensification to the present-day level within the last 3 kyr (McGlone et al., 1992).

Sediment trap studies from the PCC showed that *N. pachyderma* (dex.) is the dominant species throughout the year with its highest relative abundances during the stratification (March to June) season (Marchant et al., 1998). In contrast, *G. bulloides*, as one of the principal upwelling indicators under coastal upwelling conditions (Thiede, 1975), shows a strong seasonal association with upwelling conditions in the modern PCC (Marchant et al., 1998). *N. pachyderma* (sin.), often described as being related to coastal upwelling regimes (Oberhänsli, 1991; Little et al., 1997), is most abundant today during the upwelling season in the PCC (Marchant et al., 1998). Thus, the relative abundance pattern of these three species in core 17748-2 can be interpreted as a proxy for the upwelling intensity in the PCC during the last 13.3 kyr (Fig. 5).

Another change in the faunal assemblage occurred during the deglaciation, when *Globorotalia inflata* and *Globigerinita glutinata* show two maxima. The first between 13.3 and 12.4 kyr and the second less significant between 11.8 and 10.9 kyr, whereas *G. bulloides* has its relative maximum between 11.8 and 12.2 kyr. The distribution for the two species *Globorotalia inflata* and *G. bulloides* is determined by temperature, as *G. bulloides* tolerates lower surface-water temperatures than *Globorotalia inflata* (Van Leeuwen, 1989). Thus, strongest coastal up-

welling within the last 13.3 kyr is likely to have occurred between 12.2 and 11.4 kyr. Between 13.3 and 12.4 kyr and between 11.8 and 10.9 kyr, upwelling was weaker, but still considerably stronger than during the Holocene.

A similar pattern is indicated by the planktic and benthic foraminifera accumulation rates (Fig. 5), which show remarkable higher accumulation rates between 13.3 and 9.7 kyr B.P. than in the younger Holocene record. However, when comparing these two periods, the differences in resedimentation intensity have to be kept in mind. According to the relative abundance of redeposited benthic foraminifera (Fig. 2), resedimentation intensity was 3 times higher during the deglaciation than during the Holocene. Assuming that planktic foraminifera are affected by resedimentation in a similar way as benthic foraminifera, three-fold higher accumulation rates during the deglaciation can be attributed to redeposition. However, both, the accumulation rates of planktic and of benthic foraminifera, were 5 times higher during the deglaciation (Fig. 5), thus, pointing also to really enhanced productivity during this period. However, as the sedimentary sequence is almost continuously affected by resedimentation, foraminifera fluxes and, thus, surface water productivity cannot be quantitatively reconstructed.

Of special interest is the increased noted on the accumulation rate of benthic foraminifera during the last 3 kyr, an interval during which the species composition of planktic foraminifera is affected by considerable changes. As mentioned above, the relative abundances of *N. dutertrei*, *N. pachyderma* (sin.) and *Globigerinita glutinata* increased, while only the contribution of *N. pachyderma* (dex.) decreased from 70% to 20% (Fig. 5). Even though this shift in species composition points to an increase in surface water productivity, the *N. dutertrei* record indicates very variable paleoceanographic conditions. Nowadays in the study area, *N. dutertrei* is confined to warmer surface waters (as e.g., the *Subtropical Surface Waters* of the PCCC), related to oceanographic fronts, where the warm waters meet nutrient-rich upwelling waters (Marchant et al., 1998). Thus, the parallel increase of *N. dutertrei* and *N. pachyderma* (sin.) points to competing influences of *Subtropical Surface Waters* and upwelling waters. As these two species prefer quite different tempera-

ture ranges ($> 20^{\circ}\text{C}$ to $< 8^{\circ}\text{C}$, see above), which do not overlap, these data imply a strong temperature variability in the PCC through the last 3 kyr. However, that does not necessarily reflect strongly enhanced seasonal temperature differences, but could also indicate large interannual temperature variations associated with El Niño events as has been found in recent years (Marchant et al., 1998). The parallel increase of these two species could therefore result from a parallel increase of upwelling intensity and El Niño intensities and/or frequencies.

Strong variability in surface ocean conditions might favour the development of diatom blooms without leaving enough time for planktic foraminifera to grow to large populations. In such an environment, the diatom flux to the sea floor would provide enough food for an increased benthic foraminifera community resulting in increased benthic foraminifera accumulation rates. At the same time, the accumulation rate of planktic foraminifera would be very low, as it was the case in the PCC during the last 3 kyr (Fig. 5).

4.5. Comparison with the terrestrial record

The paleoclimate record from sedimentological and palynological investigations from Central Chile (34° – 32°S) fits well with the paleoceanographic conclusions drawn in this study. Based on the same core (17748-2), Lamy et al. (1999) provided a detailed reconstruction of the deglacial and Holocene terrestrial paleoclimate of Central Chile. Increasing aridity during the deglaciation, as deduced from grain-size and clay mineral analyses, is due to a southward shift of the westerly wind belt during that time, which also coincided with a rapid warming (Heusser, 1990; Heusser et al., 1996). At about 10 kyr B.P., the subantarctic woods disappeared, the aquatic taxa decreased, and the herbaceous and brushwood semi-arid elements began to dominate (Villagrán, 1993).

The middle Holocene is characterised by relatively stable arid conditions (Veit, 1996; Lamy et al., 1999), while records of the terrestrial paleoclimate during the late Holocene indicate very variable conditions (Veit, 1996; Lamy et al., 1999). Pollen evidence suggest that also modern vegetation patterns were not established before 3 kyr (Villagrán, 1993). Thus, both paleoclimatical and paleoceanographical

evidence indicate that the late Holocene was marked by a strong variability, that might be related to an increase of both the frequency and the intensity of El Niño events (McGlone et al., 1992).

A controversial issue is the existence of a Younger Dryas event in South America. Based on climatic interpretations of terrestrial records, Markgraf (1991) and Villagrán (1993) concluded that there is no signal of a Younger Dryas event in South America. In contrast, Mercer and Palacios (1977) and Thompson et al. (1995) found indications for a Younger Dryas event around 11.5 kyr B.P. in ice cores from Quelccaya and Huascarán, Peru, and Heusser and Streeter (1980) found palynological evidence of cooling in southern Chile at that time. Also our records reveal some indications for a Younger Dryas cooling in the ocean off Chile. The $\delta^{18}\text{O}$ records of *N. pachyderma* (dex.) and of *G. bulloides* both show a pause in the deglacial change from high to low $\delta^{18}\text{O}$ values during the Younger Dryas time interval (11.4 to 10.7 kyr B.P., Fig. 3). In addition, the absolute abundance of the cold water species *N. pachyderma* (sin.) shows a marked maximum during this time (Fig. 5b). Both observations point to a cooling in the PCC during this time and, thus, to a climatic deterioration with the same timing as the Younger Dryas event in the North Atlantic region. However, the data are not clear enough to decide the controversy about the Younger Dryas in South America. To solve this question, additional sediment cores from the region have to be investigated.

5. Summary and conclusions

Based on the analysis of the planktic foraminifera record from a deep-sea sediment core from the Valparaíso Basin on the Chilean continental slope, the evolution of the Peru–Chile Current during the last 13.3 kyr can be divided into three parts.

(1) In the oldest part of the record (up to 10.6 kyr B.P.), the species composition (high proportions of *G. bulloides* and *N. pachyderma* (sin.)) as well as the accumulation rates of planktic and benthic foraminifera point to a relatively high productivity in the surface waters which can be attributed to strong, but variable coastal upwelling. However, due to varying resedimentation intensities, as estimated in

terms of abundances of redeposited (i.e., originally living in shallower waters) benthic foraminifera, paleoproductivities cannot be assessed quantitatively. Indications for slightly cooler conditions between 11.4 and 10.7 kyr B.P. might be related to a Younger Dryas event in this region.

(2) After 10.6 kyr B.P., changes in the species composition of planktic foraminifera point to a considerable warming (increasing relative proportions of *N. dutertrei* and *N. pachyderma* (dex.) and less *N. pachyderma* (sin.), *G. bulloides* and *Globorotalia inflata*). Remarkable is the sudden appearance of *N. dutertrei* at this time. In the present Southeast Pacific, this species reflects the advection of relatively warm *Subtropical Surface Water* and, in addition, it is much more abundant during El Niños than under normal conditions. Thus, it is assumed that the number and/or intensity of El Niño events was greater during the Holocene than during deglaciation. After 9.7 kyr B.P., the foraminiferal accumulation rates drop significantly, indicating low productivity for most of the Holocene, which is also reflected in the species composition.

(3) Another marked change in the faunal assemblage occurred around 3 kyr B.P. During the late Holocene, *N. dutertrei* was the dominant species with elevated proportions of *N. pachyderma* (sin.) and *Globigerinita glutinata* opposed by a significant decrease in the proportion of *N. pachyderma* (dex.). This assemblage indicates very variable conditions with increased upwelling on one hand and increased warm water advection on the other hand. This variability most likely results from an intensification of the El Niño System, which is also evident from terrestrial paleo-records of the last 3 kyr.

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