The late Quaternary paleoenvironment of Chile as seen from marine archives

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1 Introduction

The Chilean margin provides a «natural laboratory» for the analysis of interactions between climate, geology, oceanography, and sedimentation processes due to its extraordinary latitudinal gradients in environmental and geological settings such as topography, climate, tectonics, volcanic activity, oceanography, and onshore geology. North to south changes in topography are obvious from the comparison of latitudinal elevation transects from the coast (or even from the Peru-Chile Trench) towards the high Andes. Highest elevation contrasts are found in the northern part of Chile, where the Andes reach elevations of up to 7000 m asl (Figure 1). In combination with the Peru-Chile Trench caused by the subduction of the Nazca plate underneath the South American one, spectacular topographic differences of up to about 15 km resulted, which gradually decreased southwards. These exceptional topographic differences obviously result in large denudation rates and, as a consequence, high sediment supply to the continental margin off northern Chile is to be expected. Besides this, the environmental setting on the mainland of Chile exhibits spectacular gradients in precipitation from the hyperarid Atacama Desert in the north to the temperate rainforests in the south. Moreover, the Chilean continental margin is characterised by a complex interplay of oceanic currents and hosts the most productive upwelling region on the globe (less than 40 km wide; Berger et al. 1987). The combination of these climatic, geomorphologic, and oceanographic gradients leads to high accumulation of (deep) marine sediments, which act as an archive from which the variables can be read using the proper tools, and thus paleoreconstructions can be made. In this paper a suit of such tools are described with which (paleo-)environmental studies were carried out on the deep-marine sediment archive on the Chilean continental margin including paleoclimatological, micropaleontological, and paleoceanographic studies.

2 Present-day climate

To understand the magnitude of paleoclimate change throughout the late Quaternary first the modern Chilean climate is described, which is controlled by its unique geographic location in between the Andes in the east and the Southeast Pacific in the west (Figure 1). The country stretches over almost 40 degrees of latitude, approximately 4200 km, but is mostly less than 200 km wide. Despite the large latitudinal extent, Chile exhibits a remarkably uniform temperature profile, ranging from about 19°C at sea level in the extreme north to about 5°C in the south (Miller 1976). This relatively small temperature gradient is principally caused by the compensating effect of the Peru-Chile Current (PCC), bringing cool subantarctic water masses up to northern Chile, and by the effective isolation of the country from climatic influences of the South American interior by the Andes.

In contrast to this modest temperature profile, precipitation patterns in Chile show what is probably the most pronounced latitudinal gradients on Earth, ranging from hyper-arid conditions in the northern third of the country (Atacama Desert) to extremely high rainfall in the mountains of southern Chile, which belong to the wettest extratropical regions of the world (see Figure 2; e.g., Miller 1976).

Except for a small highland area in the extreme northeast, which receives tropical summer rain, precipitation in Chile is entirely linked to the rain-bearing Southern Westerlies. The track and intensity of cyclonic storms that make up the Southern Westerlies is controlled by the strength and latitudinal position of the subtropical anticyclone in the Southeast Pacific and the circum-Antarctic low pressure belt (Cerveny 1998). In austral winter (June, July, August) the storm tracks are centred around 40°S and the related rainfall reaches a mean northern limit of about 31°S. Further north, up to about 27°S, only occasional winter rain events occur, these being related to an extreme northward penetration of atmospheric perturbations from the Westerlies (Miller 1976). During austral spring the core of the Westerlies moves 5-10° poleward to reach its southernmost position in austral summer (December, January, February; see Figure 2).

Due to the orographic rise of moist Pacific air-masses, rainfall in the Andes is significantly higher than in low elevation areas of the same latitude, leading to a northward displacement of the Chilean climatic zones in the mountains.

As described by Miller (1976), annual rainfall increases significantly at low elevations south of 31°S, from about 200 mm/year to about 2000 mm/year at 41°S, with even higher values in the Andes (see Figure 2). Central Chile between 31°S and 37°S

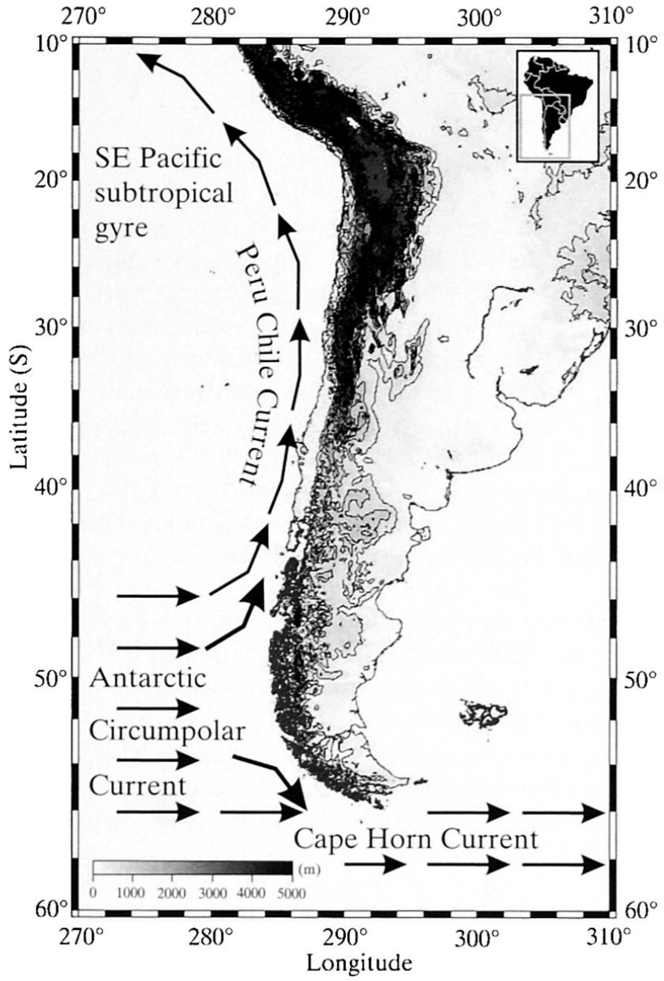

Fig. 1: Simplified sketch of modern geomorphologic features of the South American continent and major current systems in the Southeast Pacific

This map was constructed using Generic Mapping Tool (GMT), based on ETOPO-II data.

Vereinfachte Darstellung der heutigen geomorphologischen Strukturen auf dem südamerikanischen Kontinent und der wichtigsten Strömungssysteme im Südost-Pazifik

Représentation simplifiée des formes géomorphologiques actuelles du continent sud-américain et principaux courants du Pacifique Sud-Est

Sources: Smith & Sandwell 1997; Strub et al. 1998; Wessel & Smith 1991; cartography: C. Winter

is characterized by a typical Mediterranean-type climate with only up to 5% of rainfall during the southern summer.

Between 37°S and 42°S, summer rainfall increases sharply towards the average northern summer limit of the Southern Westerlies. Chile south of 42°S is traversed regularly by cyclones of the Westerlies throughout the year, leading to frequent rain and extraordinary annual precipitation values of up to 7500 mm/year. The amount of rainfall varies strongly locally and depends largely on exposure to the moist Pacific air masses.

Interannual rainfall variability, especially in central Chile, is strongly related to the El Niño Southern Oscillation (ENSO; Karoly 1989; Ruttland & Fuenzalida 1991). During the warm phase of ENSO, a weakening of the Southeast Pacific anticyclone results in a northward shift of the Southern Westerlies leading to wet anomalies in central Chile. Conversely, a strengthening and southward expansion of the anticyclone results in more poleward located westerly storm tracks reducing winter rain in the Mediterranean climate zone of Chile.

An additional important regional climatic phenomenon is the presence of persistent coastal fogs and marine stratus clouds along the coast of Chile, especially north of about 30°S. This coastal cloud cover is caused by subsiding warm air along the eastern periphery of the Southeast Pacific anticyclone above the cold Peru-Chile (or Humboldt) Current system (PCC), resulting in a prominent temperature inversion in the lower atmosphere. Though only supplying negligible amounts of measurable rainfall, the coastal fogs, known as *camanchacas*, greatly reduce insolation and evaporation and allow a comparatively dense vegetation cover (Aravena et al. 1989; Miller 1976).

In summary, it is the latitudinal position of the Southern Westerlies that determines modern rainfall variability in most of Chile, predominantly on a seasonal scale typified by winter rains but also interannually associated with ENSO variability.

3 Present-day oceanography

The surface ocean circulation in the Southeast Pacific Ocean off Chile is dominated by the northward flowing Peru-Chile (or Humboldt) Current (PCC) and the southward flowing Cape Horn Current (CHC), which both originate between 40-45°S where the Antarctic Circumpolar Current (ACC) approaches the South American continent (Boltovskoy 1976) (Figure 1). The northward deflection of the ACC is primarily responsible for the initiation of the PCC, which stretches all along the South American west coast before turning westwards close to the equator to form the South Equatorial Current. Those waters of the ACC that become advected southwards by the CHC are finally transported to the Atlantic Ocean via the Drake Passage (e.g., Strub et al. 1998).

The PCC forms one of the most prominent eastern

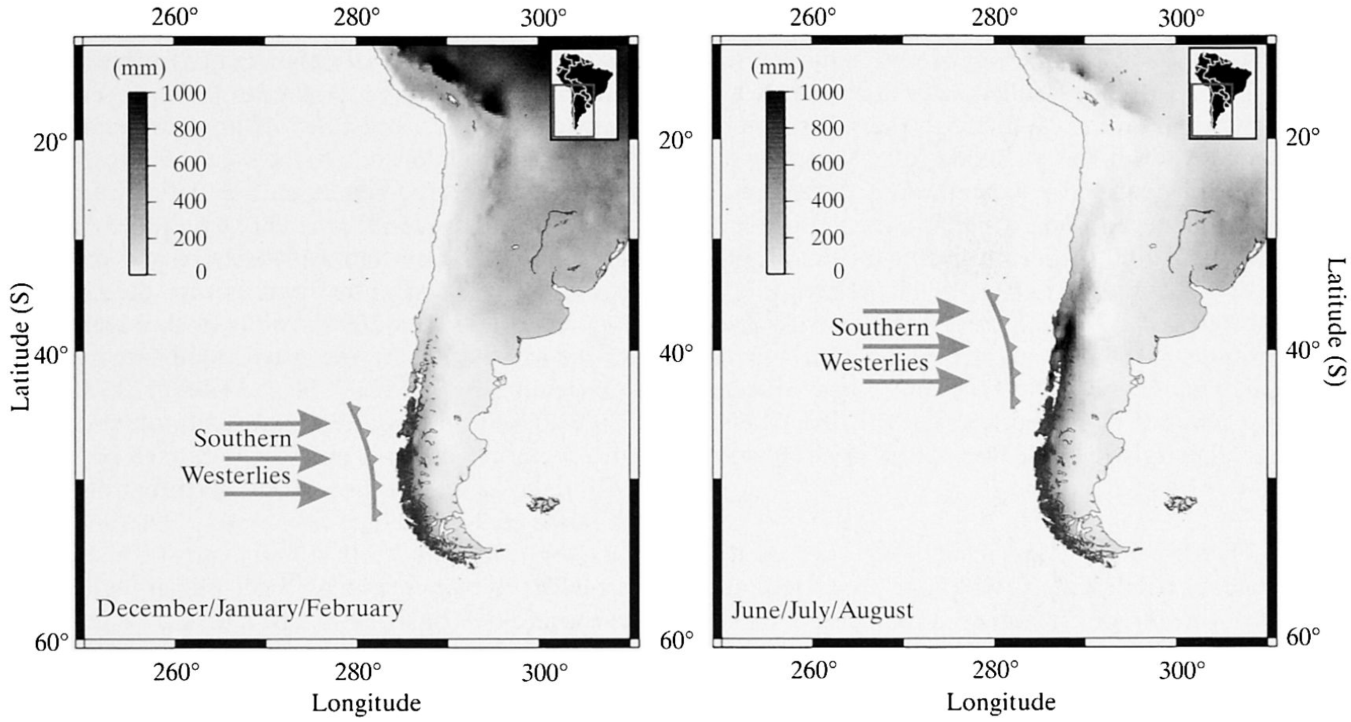

Fig. 2: Simplified sketch of seasonal latitudinal shifts of the Southern Westerlies over the Southeast Pacific, and their consequences for continental rainfall. Average precipitation values on the southern part of the South American continent are shown for austral summer (DJF) and austral winter (JJA), respectively.
This map was constructed using Generic Mapping Tool (GMT), calculated on the basis of present-day rainfall data.
Vereinfachte Darstellung der saisonalen, latitudinalen Verschiebungen der südlichen Westwindzone im Südost-Pazifik und deren Auswirkungen auf das kontinentale Niederschlagsmuster. Durchschnittliche Niederschlagswerte für den südlichen Teil Südamerikas sind sowohl für den Südsommer (DJF) als auch für den Südwinter (JJA) angegeben.
Représentation simplifiée des changements saisonniers latitudinaux des alizés du sud au-dessus du Pacifique Sud-Est et leurs conséquences pour les précipitations continentales. Les moyennes des précipitations de la partie sud du continent sud-américain sont indiquées pour l'été (DFJ) et l'hiver austral (JJA) respectivement.
Sources: NEW et al. 2001; WESSEL & SMITH 1991; cartography: C. WINTER

boundary currents (EBC) in the world oceans. In such EBC regions, dominant equatorward alongshore wind stress induces an offshore surface Ekman transport resulting in the upwelling of relatively cold, nutrient-rich subsurface waters nearshore. Due to this continuous and intense coastal upwelling, the PCC is one of the most important high productivity regions in the world (BERGER et al. 1987) supporting, for example, an intensive pelagic fishery (ALHEIT & BERNAL 1993).

The upwelling process and its main impact on the marine environment is essentially confined to the waters over the shelf and the upper slope region, but the influence of coastal upwelling can be seen at distances as far as 400 km offshore (STRUB et al. 1998; THOMAS 1999). The upwelling-induced nutrient injection stimulates biological productivity and subsequently, phytoplankton pigment concentrations in near-coastal waters can exceed 6 mg m^{-3} (THOMAS et al. 1994) and annual production rates of >200 g C m^{-2} have been recorded (BERGER et al. 1987).

4 Methods

In this paper an overview of paleoenvironmental studies is presented that were carried out on marine sediments deposited on the Chilean continental margin. These can be subdivided into studies of terrigenous (or land-derived) material, and biogenic (or marine-produced) material. The study of the biogenic sediment fraction thereby assumes that the fossil remains of plankton and benthos can be used to reconstruct environmental conditions in the water column and on the seafloor, respectively. Two techniques were used to study the present-day situation of sedimentation patterns offshore Chile: so-called sediment traps, which collect material on its way through the water column to be deposited on the sea floor (e.g., Marchant et al. 2004), and material collected from the sediment surface of the ocean floor, which is assumed to represent modern sedimentation (e.g., Hebbeln et al. 2000; Klump et al. 2000; Lamy et al. 1998b; Mohtadi et al. 2005; Romero et al. 2001). To reconstruct environmental conditions in the past, marine scientists rely on the sediment archives like the sediment cores collected during a number of scientific cruises to the Chilean continental margin (e.g., Hebbeln et al. 1995; Hebbeln et al. 2001; Mix et al. 2003).

X-Ray Fluorescence scanning methods were used to infer paleoenvironmental conditions from sediment cores. It was thereby assumed that certain chemical elements are characteristic for the terrigenous sediment fraction (e.g., Lamy et al. 2004). A further approach was to isolate the terrigenous fraction by removing the organic sediment fraction (organic carbon, biogenic calcium carbonate, and biogenic opal) in several pre-treatment steps with peroxide, acids and bases (see e.g., Lamy et al. 1998a; Lamy et al. 1998b; Stuut & Lamy 2004 for a detailed description of the methods used). The grain-size of the terrigenous fraction was subsequently analysed using a Micromeritics Sedigraph (e.g., Lamy et al. 1998a) and a Beckmann Coulter laser particle sizer (e.g., Stuut & Lamy 2004). Furthermore, the clay-mineralogical composition of the terrigenous fraction was analysed with the X-ray diffraction method (XRD) (see e.g., Lamy et al. 1998a for a more detailed description).

In order to separate the biogenic fraction of interest, the sediments were wet sieved into representative size classes for the respective fossil remains of interest, dried and subsequently studied using a microscope (see e.g., Marchant et al. 1998; Mohtadi et al. 2004; Romero et al. 2001 for more details about the applied methods). Main biogenic sediment constituents, such as organic carbon, carbonate and biogenic opal, were determined following standard procedures as described in Hebbeln et al. (2002). In addition, reconstructions of paleo sea surface temperatures (SSTs) were established based on the alkenone method (Kaiser et al. 2005; Kim et al. 2002). Results of all these various approaches are discussed in the following sections.

5 Present-day sedimentation

5.1 Terrigenous material

Due to the extreme latitudinal rainfall gradient, reaching from hyper-arid conditions in the Atacama Desert through semi-arid Mediterranean type conditions in central Chile to extremely high rainfall values in the southern Andes (Figure 2), the terrigenous sediment input to the ocean, and thus offshore sedimentation rates, increase significantly to the south (Figure 3). This pattern of increasing sedimentation rates, which has been broadly known since the early studies by Scholl et al. (1970), is clearly demonstrated by dated sediment cores recovered during two cruises with the German R/V Sonne (Hebbeln 2004), and is further consistent with data based on the recently drilled Ocean Drilling Program (ODP) Sites 1233, 1234, and 1235 (Mix et al. 2003). Holocene sedimentation rates increase from about 5 cm/kyr off arid northern Chile (Lamy et al. 1998a; Lamy et al. 2000), to about 10 cm/kyr off semi-arid north-central Chile (Lamy et al. 1999; Marchant et al. 1999), 50 cm/kyr off humid central Chile (Hebbeln 2004), 100 cm/kyr at 41°S off year-round humid southern Chile (Lamy et al. 2001; Lamy et al. 2004), and about 200 cm/kyr at around 44°S (Hebbeln 2004), where rainfall reaches extremely high values. Sedimentation rates were even higher during the last Glacial reaching about 10 cm/kyr off northern Chile, 50 cm/kyr off central Chile, and about 200 cm/kyr in the south (at around 41°S).

Generally, the original source rock signal of the different geological terrains of Chile between 25°S and 43°S is best preserved in bulk mineralogical characteristics and the elemental composition of the slope sediments, and can be characterised by generally low quartz contents, the dominance of plagioclase, and high amounts of pyroxenes and amphiboles that emphasise the low maturity of the sediments along the Chilean continental margin (Klump et al. 2000; Lamy et al. 1998b).

Due to the prevailing climate terrigenous sedimentation in the north is dominated by wind-blown sediments, changing into dominant river-derived sediments towards the south. This generalised pattern is reflected in the median grain size of the samples plotted along the north-south transect in Figure 3B. A clear decrease can be observed from about 70 µm at 23°S down to about 10 µm at 34°S. The fact that the median grain size does not decrease further between 34°S and 44°S indicates that similar sedimentation processes may prevail along this relatively large latitudinal range. One exception to this trend, showing a median grain size of about 25 µm at 23°S – indicated by an arrow in Figure 3B – is located directly offshore an ephemeral river mouth. Two other exceptions to the trend, showing a median grain size of >80 µm relatively far south – also indicated by arrows in Figure 3B – are interpreted as the result of mass-flow deposits or turbidity currents (sample at about 32°S), and due to sediment focussing effects of a deep-marine canyon (sample at about 44°S), respectively.

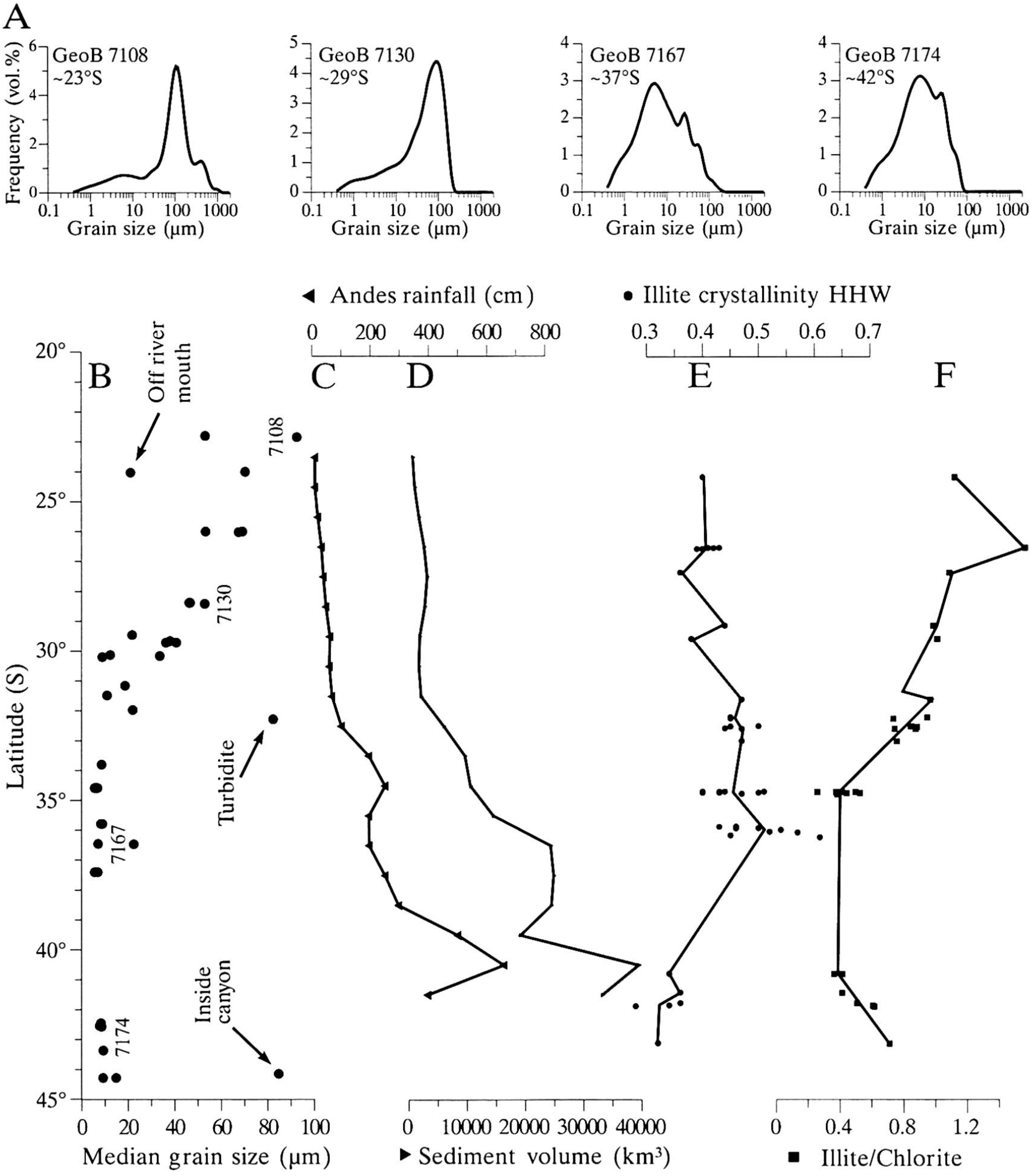

Fig. 3: Physical (grain-size) and mineralogical characteristics of the terrigenous sediment fraction in relation to climate
A) Typical grain-size distributions of the terrigenous sediment fraction illustrating the mixture of land-derived sediments found on the continental slope, ranging from predominantly wind-blown in the arid north to fluvial sediments in the humid south. GeoB 71xx denotes samples, plotted also in B. B) Median grain-size in relation to latitudinal position. C) Yearly precipitation in relation to latitude. D) Cenozoic sediment stack in relation to latitude. E) Illite crystallinity, and F) Illite/chlorite mineral ratios.
Physikalische (Korngrößen) und mineralogische Charakteristika der terrigenen Sedimentfraktion in Abhängigkeit vom Klima
Caractéristiques physiques (granulométrie) et minéralogiques des sédiments terrigènes en relation avec le climat
Sources: LAMY et al. 1998b; SCHOLL et al. 1970; STUUT et al.

Four characteristic grain-size distributions of the surface sediments are shown in Figure 3A, their latitudinal position indicated in Figure 3B. Despite the fact that most distributions are multimodal, it is clear that wind-blown transport processes prevail in the north, leading to a relatively coarse mode (up to 100 µm, for example samples GeoB7108 and GeoB7130) in the grain-size distributions, whereas further south, the mean modal size is much finer grained (about 4-8 µm, for example samples GeoB7167 and GeoB7174). Another characteristic of the wind-blown sediments can be observed in their mineralogical composition: high illite crystallinity indicates low chemical weathering intensities (Figure 3, note that low HHW values correspond to high crystallinity) (Lamy et al. 1998b).

Further to the south, that is at about 33°S, increased precipitation allows rivers originating from the Andes to cut through the Coastal Range and to supply Andean material, mostly basaltic-andesitic source rocks, to the continental slope. This Andean source is clearly reflected in lower illite/chlorite ratios (Figure 3), and also in higher plagioclase and pyroxene, less quartz, K-feldspar and mica contents, as well as higher Fe/Al ratios (Klump et al. 2000; Lamy et al. 1998b). The continental hinterland around 33°S is still characterized by relatively coarse grained source material due to prevailing mechanical weathering under a semiarid climate and high morphologic gradients. But as winter rain increases, sediment is mainly supplied by rivers and eolian sediment input is less important, leading to generally finer grain sizes. The fluvially supplied material is probably mainly deposited by hemipelagic processes, as turbidity currents are canalised off central Chile (33-38°S) and are restricted to submarine canyon and fan systems (Thornburg et al. 1990).

In the southernmost part of the study area (41° to 43°S), the heterogeneity of the bulk mineralogy and grain-size data within the transect increases; while feldspar and quartz contents are comparatively low, amphibole and mica amounts reach their maximum values (Lamy et al. 1998b). The sediments are probably derived from various source rocks including metamorphic rocks of the Coastal Range and volcanic and plutonic lithologies from the Andes. Due to the wide shelf, which includes the sea-covered forearc basin and the dissection and partial submergence of the Coastal Range into an archipelago (Figure 1), the provenance of surface samples cannot be related directly to single drainage basins (Klump et al. 2000).

5.2 Biogenic sediments

In addition to the terrigenous sediment archive offshore Chile, which contains information about environmental conditions on the Chilean mainland, there is a wealth of information stored in the marine archive, from sediment fractions that are produced in the ocean, and which predominantly consist of microfossils from calcareous unicellular organisms like planktic and benthic foraminifera, to siliceous skeletons formed by marine algae. A number of tools are presented here that can be used to describe the varying oceanographic conditions under which the biogenic sediment fraction are deposited offshore Chile.

Planktic foraminifera and coccolithophorids dominate the total carbonate preserved in surface sediments off Chile between 23° and 44°S (Hebbeln et al. 2000a; Mohtadi et al. 2005). Pteropods seem to play a minor role in calcium carbonate vertical fluxes and surface sediment accumulation despite their high species abundance in Chilean waters (39 species, Marchant 2003). The planktic foraminiferal abundances in surface sediments vary from 1 to 1,200 shells per cm³ (see Figure 4). This range is clearly linked to the increasing fluvial input of terrigenous sediments towards the south causing an enhanced southward dilution of the biogenic signal (Scholl et al. 1970). Generally, low amounts of planktic foraminifera (<78 individuals/cm³) occur south of 33°S. The greatest values are found between 30° and 33°S (Figure 4). When considering the composition of planktonic foraminiferal assemblages, the distribution pattern of foraminifera along the Chilean continental margin shows two different spatial characteristics: a typical upwelling composition occurs in the region north of 24°S and between 30°S and 33°S, with high contributions of *Globigerina bulloides*, *Neogloboquadrina pachyderma* sin. and *Globigerinita glutinata*, and south of 39°S, a predominantly high-productivity environment under non-upwelling conditions can be located, with enhanced relative contributions of *N. pachyderma* dex. and *Neogloboquadrina dutertrei* and lower contributions of *G. bulloides*, *G. glutinata* and *N. pachyderma* sin. (Mohtadi et al. 2005).

The occurrence of preserved siliceous phytoplankton in modern (late-Holocene) sediments along the Chilean coast reflects present-day productivity conditions of surface waters in the Southeast Pacific. Diatoms overwhelmingly dominate the siliceous microfossil community preserved in surface sediments between 22° and 43°S off Chile (see Figure 4; Romero & Hebbeln 2003; Romero et al. 2001).

The pattern of diatom concentration closely relates to the amount of opal and coincides with the pattern offered by remote sensing estimations of phytoplankton pigment concentrations in surface waters of the PCC (Thomas 1999). Between 18° and 33°S, where lower pigment concentrations are measured, only secondary peaks of diatom and opal values are observed (Romero & Hebbeln 2003; Romero et al. 2001). In contrast, higher diatom concentration and opal content in

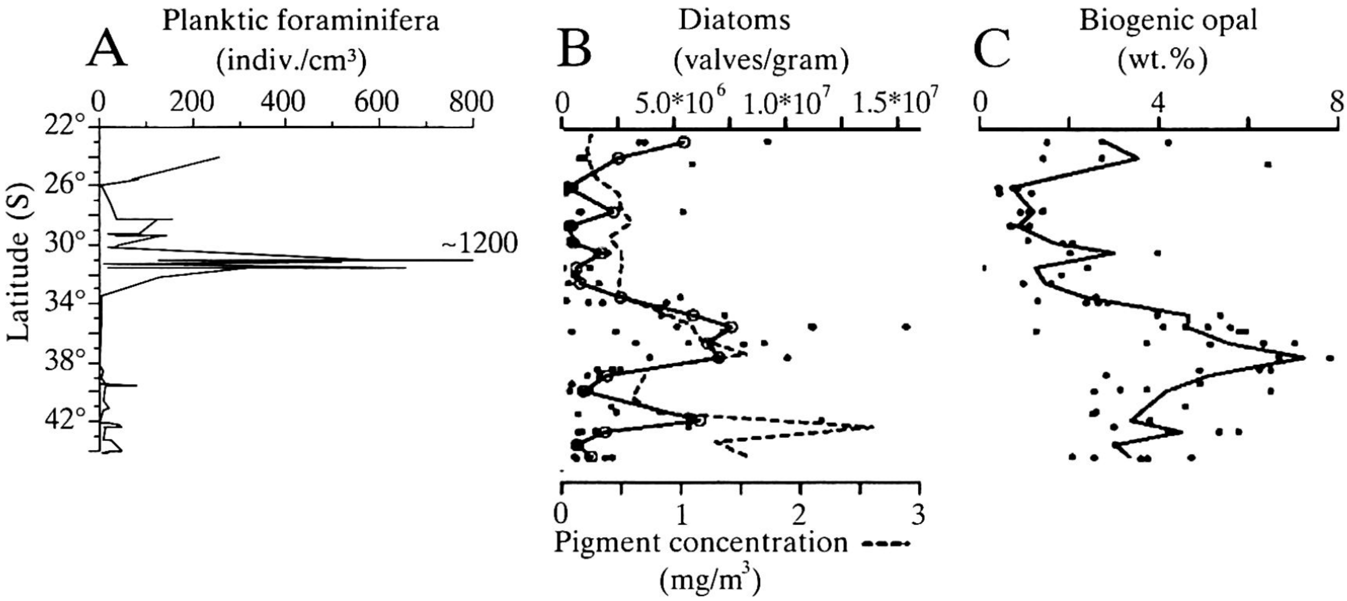

Fig. 4: Abundance of biogenic components in relation to latitude
A) Distribution of planktic foraminifera (>150μm) in surface sediments along the Chilean continental slope between 24° and 44°S. Number of specimens per cm³ sediment. B) Total concentration of diatoms, given as valves per gram of dry sediment and pigment concentration in surface waters (dashed line), which is derived from Coastal Zone Color Scanner measurements. C) Biogenic silica content, as weight %, in surface sediment from the Southeast Pacific, off Chile. The filled lines in B and C represent average values for each degree of latitude between 22° and 44°S.
Häufigkeit biogener Komponenten in Abhängigkeit von der geographischen Breite
Effectifs des composants biogéniques en relation avec la latitude
Sources: MOHTADI et al. 2005; ROMERO & HEBBELN 2003; http:// daac.gsfc.nasa.gov

surface sediments between 34° and 38°S and 41° to 43°S correspond well with estimated higher pigment concentrations (THOMAS 1999). Off northern Chile, the diatom concentration is generally one order of magnitude lower than further north off Peru (SCHUETTE 1981). This divergence also reflects differences in surface water productivity along the PCC – throughout most of the year higher pigment values and a further seaward extension of chlorophyll filaments occur more north of 18°S than south of it (THOMAS 1999).

The diatom assemblages strongly reflect late Quaternary conditions and clearly distinguishes the occurrence of coastal upwelling off northern and central Chile from the influence of southern-originated water masses off southern Chile (ROMERO & HEBBELN 2003; ROMERO et al. 2001). Although surface waters along the entire Chilean coast favour conditions for intense phytoplankton proliferation (STRUB et al. 1998), Coastal Zone Color Scanner-derived pigment concentrations reveal strong north-south variations (THOMAS 1999). Nutrient enrichment of surface waters off the Chilean coast due to upwelling results in intense production of diatoms reflected by the predominance of *Chaetoceros* spores as far south as around 38°S. Though the occurrence of upwelling is limited to a narrow coastal band (less than 40 km wide; MORALES 2001), the upwelling diatom signal is recorded in deep-sea sediments beyond the continental slope, due to offshore streaming chlorophyll filaments (MOHTADI et al. 2004; ROMERO et al. 2001).

6 Past sedimentation patterns and paleoenvironmental implications

6.1 Continental paleoclimates derived from terrigenous sediment input changes

The pronounced north-south rainfall gradients observed at the present-day Chilean continental margin appear to not have been stationary throughout the longer (orbital timescales) as well as the more recent (Holocene, last 12 kyr) past (e.g., LAMY et al. 2001; LAMY et al. 1998a; STUUT & LAMY 2004). On Milankovitch timescales, there is strong evidence for precession-driven paleoenvironmental variations in the Norte Chico (27°S) marked by increased onshore precipitation related to relatively northward positions of the Southern Westerlies during precession maxima (including the last glacial maximum (LGM)) and vice versa (LAMY et al. 2000; STUUT & LAMY

2004). These precessional cycles are evident in different sedimentological parameters that suggest substantial changes of sediment provenance, weathering regimes in the source areas, and modes of sediment input to the ocean. During times of precession minima the grain-size distributions of the terrigenous silt fraction reflect a predominating eolian sediment input (Figure 5; Stuut & Lamy 2004). Low smectite/illite and Fe/Al ratios (Figure 5; Lamy et al. 2000) point to a high contribution of plutonic source rocks from the Coastal Range and, thus, to the absence of perennial rivers delivering material from the Andes. In combination with high illite crystallinities (Figure 5), indicating minimal chemical weathering, these data clearly indicate severely arid conditions during precession minima (Lamy et al. 2000). Conversely, during time-spans correlating to precession maxima, finer grain-sizes (Figure 5) can be interpreted in terms of increased fluvial sediment supply, while higher smectite/illite and Fe/Al ratios (Figure 5) record a stronger Andean volcanic source rock signal.

In addition, lower illite crystallinities point to an increase in the intensity of chemical weathering. Thus, for precession maxima our data suggest a semiarid climate with seasonal precipitation similar to the modern Mediterranean climate further south, where perennial rivers led to increased fluvial sediment input from the Andes. Besides showing dominantly precession-driven rainfall changes over the Andes, the record also reveals millennial-scale changes in weathering intensity over the Chilean Coastal Range, these most likely induced by changes in coastal fog occurrences (Lamy et al. 2000). As the frequency and intensity of coastal fogs along the Chilean coast is today also related to the position of the Southern Westerlies, we can reasonably assume that the past record indicates rapid latitudinal shifts of this wind belt throughout at least the last 120,000 years. These results were confirmed by downcore terrigenous grain-size distributions from a core taken at about 30°S, which show a glacial-interglacial pattern of humidity changes in northern Chile during the last 65 kyr BP (Stuut & Hebbeln). During glacial times, the moisture-bearing Southern Westerlies were displaced towards the equator, thereby increasing precipitation and runoff in northern Chile, and affecting size distributions of the sediments.

Further south, off central Chile at about 33°S, higher sedimentation rates allow a more detailed reconstruction of climatic evolution over the last 30,000 years (Lamy et al. 1999). As with the Norte Chico record, clay mineralogical and element composition data clearly record changes in the relative contribution of Andean versus Coastal Range source rocks. However, as increased precipitation has enabled rivers originating from the Andes to cut through the Coastal Range, sedimentological data instead record the relative dilution of the Andean signal by additional input of Coastal Range material during comparatively humid intervals. Thus, we find a lower contribution of clay mineralogical assemblages and Fe/Al ratios characteristic of Andean provenance during more humid phases. As shown for example by the Fe/Al ratio record (Figure 5), the sedimentological records clearly suggest more humid conditions during the LGM, which is consistent with the other records off Chile. The deglaciation is characterized by a trend towards a more arid climate that reached its maximum during mid-Holocene times (8000-4000 cal yr BP). The late Holocene was marked by more variable paleoclimates with a return to slightly more humid conditions.

Off humid southern Chile (41°S), where extremely high sedimentation rates allow a reconstruction of terrigenous sediment input changes over the last 8,000 years on centennial time-scales, Holocene «long-term» trends are generally consistent with the results off central Chile (Figure 5; Lamy et al. 2001). Element composition data (shown here are only results from the XRF scanner for the element Fe) suggest a higher input of Andean material during the mid-Holocene, indicating less dilution by Coastal Range source rocks and thus less rainfall. However, in this currently year-round humid region, hydroclimatic conditions were probably always humid and never reached semi-arid conditions (Lamy et al. 2001). On millennial to multi-centennial-scales, terrigenous input changes reveal dominating bands of variability centred on about 900 and 1500 years suggesting significant rainfall changes and thus latitudinal shifts of the Southern Westerlies on these time-scales (Lamy et al. 2001).

6.2 Paleoproductivity

A number of recent paleoceanography and paleoproductivity-related publications reflect increasing interest in the role of the PCC throughout the late Quaternary (e.g., Dezileau et al. 2004; Hebbeln et al. 2002; Klump et al. 2001; Marchant et al. 1999; Mohtadi & Hebbeln 2004). These studies suggest that the strength and the position of the Southern Westerly belt and the ACC, which are presently responsible for nutrient supply and upwelling intensity off Chile (Hebbeln et al. 2000b; Marchant et al. 1998; Mohtadi et al. 2005; Romero & Hebbeln 2003; Thomas 1999; Thomas et al. 1994), have also controlled past variations in the oceanographic setting and marine productivity in this region. This is in good agreement with the observations on land-derived sediments (Lamy et al. 2001; Lamy et al. 2004; Stuut & Hebbeln; Stuut & Lamy 2004) from which these latitudinal movements of the Southern Westerlies had been inferred as well.

During the late Holocene, paleoproductivity between 24°S and 41°S increased (Figure 6). Past records of

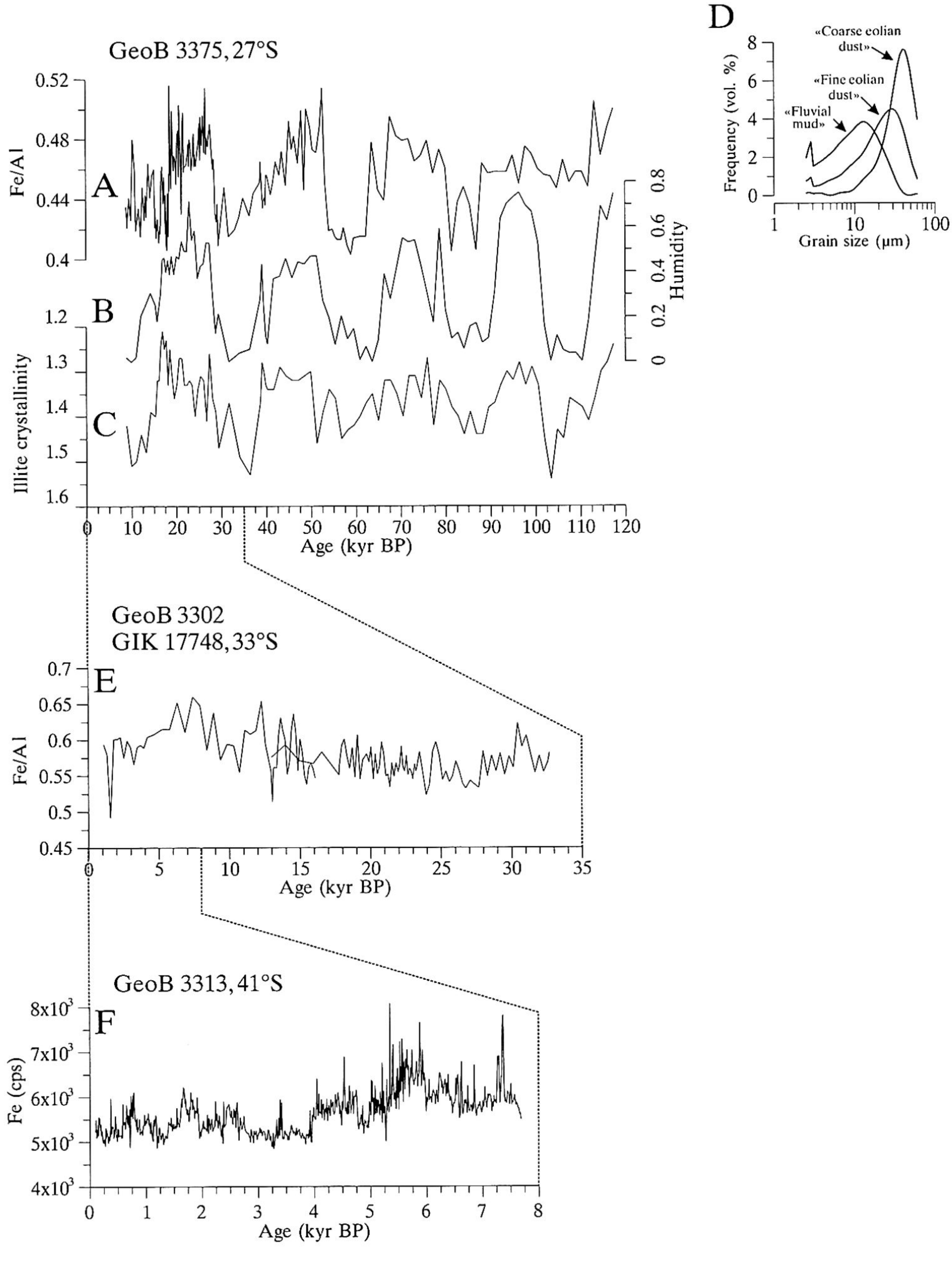

Fig. 5: Sedimentological data of sediment cores along the Chilean continental margin

A) Fe/Al data from core GeoB 3375 at about 27°S. B) Humidity index derived from an end-member analysis of terrigenous silt from the same core. C) Illite crystallinity data from the same core. D) End member size distributions from core GeoB 3375 and their interpretation. E) Combined Fe/Al records of cores GeoB 3302 (around 33-13 kyr BP) and GIK 17748 (around 16-1 kyr BP) at circa 33°S. F) Fe/Al record of core GeoB 3313 at about 41°S.

Sedimentologische Daten in Sedimentkernen des chilenischen Kontinentalhangs

Données sédimentologiques relatives aux noyaux sédimentaires le long de la marge continentale chilienne

Sources: Klump 1999; Lamy et al. 1998b; Lamy et al. 2000; Lamy et al. 2001; Stuut & Lamy 2004

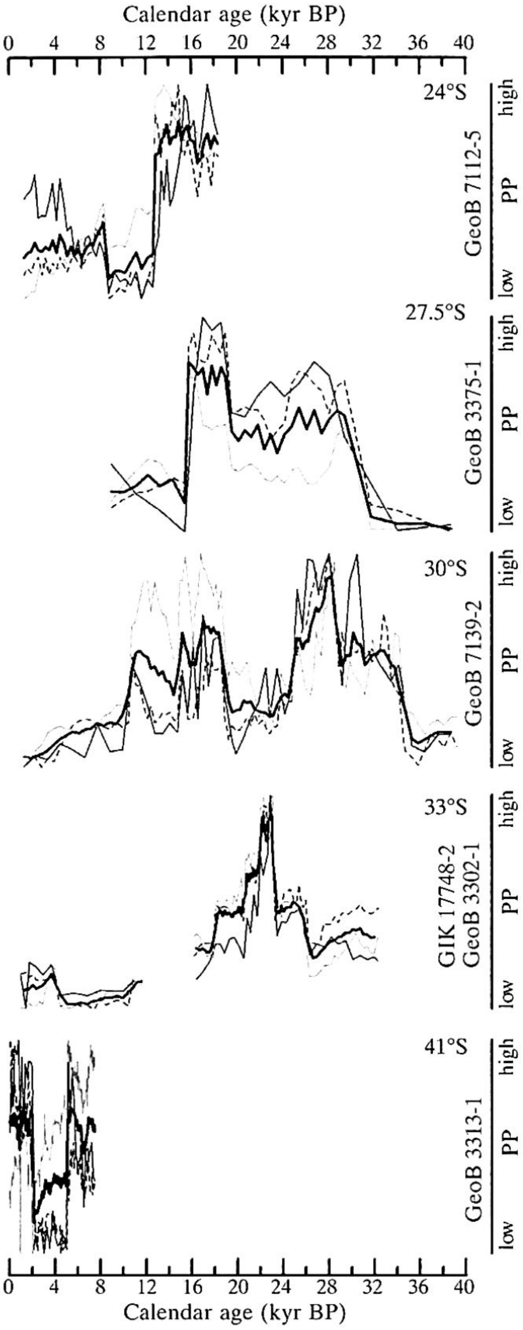

Fig. 6: Comparison of the normalized accumulation rates of biogenic compounds combined with the paleoproductivity index (PP, thick black solid lines)
This is the mean of the normalized accumulation rates of organic carbon (dashed lines), opal (thin black lines), and $CaCO_3$ (gray lines). The data have been normalized to a 0-1 scale (1) by subtracting the minimum value from all values within one data set and (2) by dividing them through the maximum minus minimum value.
Vergleich der normalisierten Akkumulationsraten biogener Komponenten mit dem Paläoproduktivitätsindex (PP, dicke, durchgezogene Linien)
Comparaison des taux d'accumulation normalisés des composants biogéniques combinés avec l'index de paléoproductivité (PP, lignes noires en gras)
Source: MOHTADI & HEBBELN 2004

planktic foraminiferal faunal composition off central and northern Chile reveal distinct periods with relatively decreased upwelling intensity congruent with low productivities before 32,000 cal yr BP, most intense upwelling and highest productivities between 32,000 and 16,000 cal yr BP, and lowest productivities after 16,000 cal yr BP towards the present. Interestingly, the onset and ending of these periods do not show any latitudinal preferences. Relative variations in the paleoproductivity calculated from accumulation rates (MILLER 1976) of biogenic compounds (Figure 6) generally support these findings, although some local differences occurred mainly during the last deglaciation.

The comparatively consistent pattern of planktic foraminiferal fauna over approximately nine degrees of latitude between 24° to 33°S throughout the last 40,000 years implies large-scale changes in the oceanic circulation synchronously affecting the whole area, such as changes in the position and/or advection of the PCC/ACC. During the last Glacial, a more northerly position of the ACC probably led to higher productivities off Chile compared to the Holocene (HEBBELN et al. 2002; MOHTADI & HEBBELN 2004; MOHTADI et al. 2004). According to these authors, a northward shift of the climatic zones brought the ACC and the Southern Westerlies closer to the study area, that is between 24° and 33°S. The ACC as the main macronutrient-source, in particular of phosphate and nitrate (LEVITUS 1994), and the Southern Westerlies as the main onshore precipitation source contributing to micronutrient supply, for example of iron, (LAMY et al. 1998a), contributed heavily to boosting marine productivity during the last Glacial. In addition, a northerly position of these zonal systems would have resulted in a steeper hemispheric temperature gradient, stronger zonal and meridional winds, and intense coastal upwelling. Stronger advection of the PCC/ACC during glacial periods has also been proposed by investigations north of the study area, for example off Peru (FELDBERG & MIX 2002; FELDBERG & MIX 2003), off Galapagos (LE et al. 1995), and in the Eastern Equatorial Pacific (MIX et al. 1999; PISIAS & MIX 1997).

Different paleoproductivity patterns deduced from biogenic compounds can be related to local differences in this region during the last deglaciation. At 33°S and further south, the northward displacement of the Southern Westerly belt led to the highest paleoproductivities around the LGM, when the climate zones were at their northernmost position (e.g., LAMY et al. 1998a; STUUT & LAMY 2004). However, highest paleoproductivities north of 33°S occurred before and after the LGM suggesting additional or different controls on paleoproductivity. Although there is clear evidence for the influence of the Southern Westerlies in marine records of continental climate, onshore records from northern Chile do not show any influence of the Southern Westerlies since the late Pleistocene (e.g., AMMANN et al. 2001; GROSJEAN et al. 2001). These results might explain the different patterns of biogenic components in marine sediments north of 33°S. Within this area, the period of highest productivity during the deglaciation coincides well with the observed late glacial humid phases in northern Chile and Bolivia caused by a more southerly position of the Intertropical Convergence Zone (ITCZ) (CLAPPERTON et al. 1997; CLAYTON & CLAPPERTON 1997; SELTZER 1994). Enhanced onshore precipitations and flooding of the shelves probably launched additional nutrient sources leading to highest productivities in this part of the PCC during deglaciation. The exact effect of the ITCZ on the marine paleoproductivity off northern Chile remains to be determined in future studies. However, it seems that paleoproductivity off northern Chile is not only regulated by the Southern Westerlies, but additionally controlled by variations in the tropical climate.

During the early and middle Holocene, the zonal systems were at their southernmost position (MARKGRAF 1993). This corresponds with lowest marine productivity during the past 40,000 years (see Figure 6; MOHTADI & HEBBELN 2004). During the late Holocene, productivity increased most likely due to a northward shift of these zonal systems. Evidence supporting this shift can be drawn from reports on glacier advances in the Andes (GROSJEAN et al. 1998), evidence of paleosols in northern Chile (VEIT 1996), and from pollen records (HEUSSER 1990; VILLAGRÁN & VARELA 1990), which show a general shift to more humid conditions in northern and central Chile during the late Holocene.

In addition, an intensification of ENSO events occurred in the last 5000 years when rapid fluctuations in the relative contributions of planktic foraminiferal started. The timing of the onset (about 7000 cal yr BP) and the intensification (about 5000 cal yr BP) of ENSO in the marine records off Chile are consistent with records off Peru (KEEFER et al. 1998) and lake sediments from Ecuador (RODBELL et al. 1999). High rainfall in central and northern Chile, Peru and Ecuador seems to have been provoked by intensified El Niño activities (MARKGRAF 1998; MCGLONE et al. 1992) contributing to enhanced marine productivity in this part of the world ocean during the late Holocene.

6.3 Sea surface temperatures

Three late Quaternary sea surface temperature (SST) records have been reconstructed along the Chilean continental margin for the central (about 33°-35°S) and the southern (about 41°S) part of the Chilean continental margin (KIM et al. 2002; LAMY et al. 2004; LAMY et al. 2002; ROMERO et al.). The southern records provide an exceptional high time resolution and clearly resolve millennial to multicentennial-scale variations. The main features of these records are the occurrence of coldest temperatures around 65 kyr BP (marine isotope stage (MIS) 4, only covered by the southernmost core), comparatively warm temperatures in early MIS 3, cold temperatures during the peak glacial period from 45 to 19 kyr B.P without a clearly defined last glacial maximum (LGM), a 6°C SST warming over Termination I, and an early Holocene optimum (Figure 7). Important to note are pronounced millennial-scale variations in the order of 2-3°C that clearly correlate to temperature fluctuations as known from Antarctic ice-cores (e.g., BLUNIER & BROOK 2001), and from marine records elsewhere in the Southern Hemisphere mid-latitudes.

The 6°C warming over Termination I appears to be characteristic for the region and is observed in all three temperature reconstructions (Figure 7), as well as in onshore records (e.g., DENTON et al. 1999). It further corresponds with results from a modelling investigation that matched the modelled ice extent to the empirical evidence of the extension of the Patagonian ice-sheet during the LGM, suggesting that a temperature decrease of about 6°C relative to present day temperatures is probable (HULTON et al. 2002). A further important feature of the Termination I record at Site 1233 is evidence of a cooling event (about 0.8°C) that matches the Antarctic Cold Reversal, and clearly precedes the Northern Hemisphere Younger Dryas (YD) during which a pronounced warming of about 2°C to early Holocene values is observed. Thus the SST record contradicts results from terrestrial records of the Chilean Lake District region and Isla Grande de Chiloé that have been interpreted in terms of a YD cooling (e.g., MORENO et al. 2001). However, it has been suggested recently that the deglacial cold reversal in north-western Patagonia started earlier (at about 14.7 to 13.4 kyr BP), and that the YD interval is characterized more by fire disturbances (e.g., HAJDAS et al. 2003) that may not necessarily imply cooling.

The SSTs reach a maximum in the early Holocene (about 11 to 9 kyr BP) and generally decrease thereafter, reaching modern SSTs in the late Holocene (Figure 7). A warmer, and most likely also drier-than-today, climate during the early Holocene is consistent with regional terrestrial records (e.g., ABARZÚA et al. 2004) and the marine records of terrestrial paleoclimates in northern and central Chile (LAMY et al. 1998a; LAMY et al. 1999; STUUT & HEBBELN; STUUT & LAMY 2004). The main observation that could be made was that SST changes on these time-scales generally correlate to changes in Antarctica. The same applies for continental rainfall changes in the middle Holocene but these changes appear to become out-of-phase with SST changes in the late Holocene, especially off north-

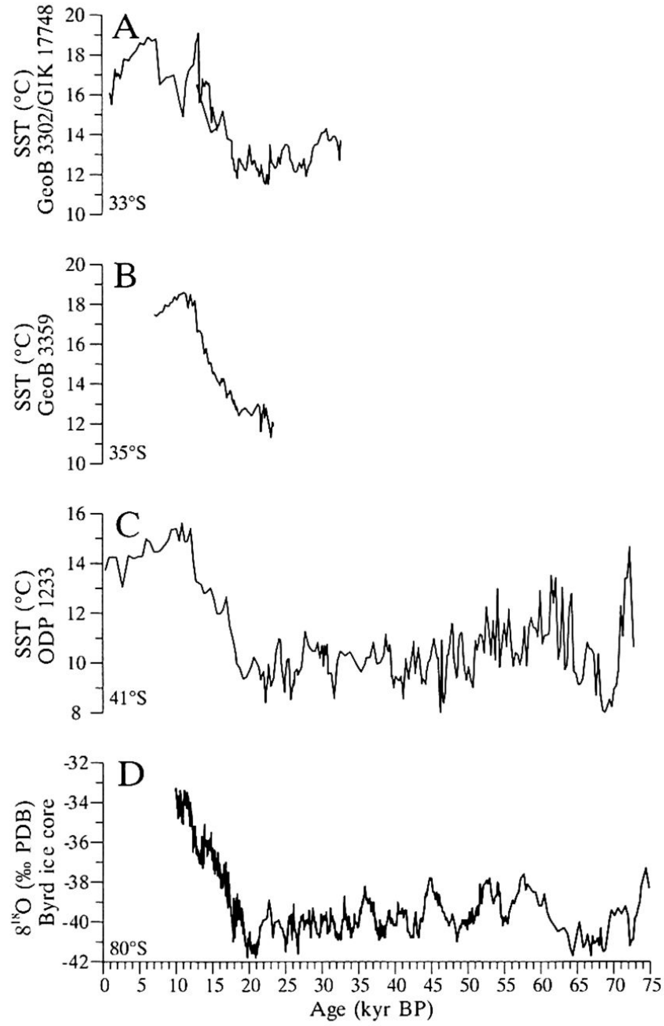

Fig. 7: Comparison of three Southeast Pacific sea surface temperature (SST) records with an Antarctic temperature proxy record
A) The combined records of cores GeoB 3302 (about 33-13 kyr BP) and GIK 17748 (about 16-1 kyr BP) at about 33°S, B) GeoB 3359 at about 35°S , C) ODP Site 1233 at about 41°S, and D) Byrd d180 record from western Antarctica
Vergleich von drei Rekonstruktionen der Meeresoberflächentemperatur (SST) aus dem Südost-Pazifik mit einem Temperaturproxy für die Antarktis
Comparaison des températures de surface du Pacifique Sud-Est avec les variables climatiques de l'Antarctique
Sources: Blunier & Brook 2001; Kim et al. 2002; Lamy et al. 2004; Romero et al.

ern Chile. This could possibly be related to the onset of the present-day state of ENSO (Lamy et al. 2002).

6.4 Driving forces for paleoenvironmental variability
Based on the marine records discussed in the previous sections, it appears that both the terrestrial paleoclimate and the paleoceanography of the PCC system (at least off Chile) are primarily controlled by latitudinal shifts of the dominating atmospheric frontal zones, in this case the Southern Westerlies, as well as oceanographic frontal zones, more specifically, the ACC. The position of the Westerlies and the ACC is controlled by the location of the sub-polar low pressure belt and the strength and position of the Southeast Pacific anticyclone (Cerveny 1998), allowing the potential for both high (southern) latitude and tropical Pacific forcing mechanisms (e.g., Stuut & Lamy 2004).

A tropical impact is most obviously visible on orbital timescales, that is in the precessional band, as precession-driven changes in insolation in the tropics are much more pronounced than at high latitudes. Such changes are thus primarily observed in proxy records off northern Chile (Lamy et al. 1998a; Stuut & Lamy 2004). On shorter timescales tropical forcing mechanisms, possibly involving long-term ENSO changes, have been suggested for paleoproductivity changes in the north (Mohtadi & Hebbeln 2004) and partly for rainfall variabilities in southern Chile (Lamy et al. 2001; Lamy et al. 2002).

In particular the records off southern Chile suggest that the major large-scale control of paleoceanographic changes off Chile are related to latitudinal shifts of the northern margin of the ACC and should be sought around Antarctica and the surrounding Southern Ocean. This clear «Antarctic timing» pattern is consistent with the often discussed seesaw mechanism of interhemispheric climate change (e.g., Broecker 1998) but the very similar temperature pattern around Antarctica in different ocean basins could also imply a larger involvement or even a source of millennial-scale climate variability in the Southern Hemisphere, most likely involving changes in the extent of sea-ice (Stuut et al. 2004).

The latitudinal shifts of the ACC appear to affect not only the midlatitude SSTs but also the large-scale SST pattern along the PCC system further to the north. Kaiser et al. (2005) reconstructed SST gradients covering the complete latitudinal range of the system up to the equator and showed that the subtropical gyre circulation was displaced equatorwards by several degrees of latitude during cold MIS 2 and 4, primarily originating from a northward shift of the ACC which resulted in particularly enhanced SST gradients in the southern PCC (Figure 8). This configuration enhances the equatorward flow of cold water within the PCC. Conversely, during relatively warm periods, such as early MIS 3 and the early Holocene optimum, the oceanic circulation in the PCC system was weakened and the ACC, as well as the associated westerly wind belt, moved southward.

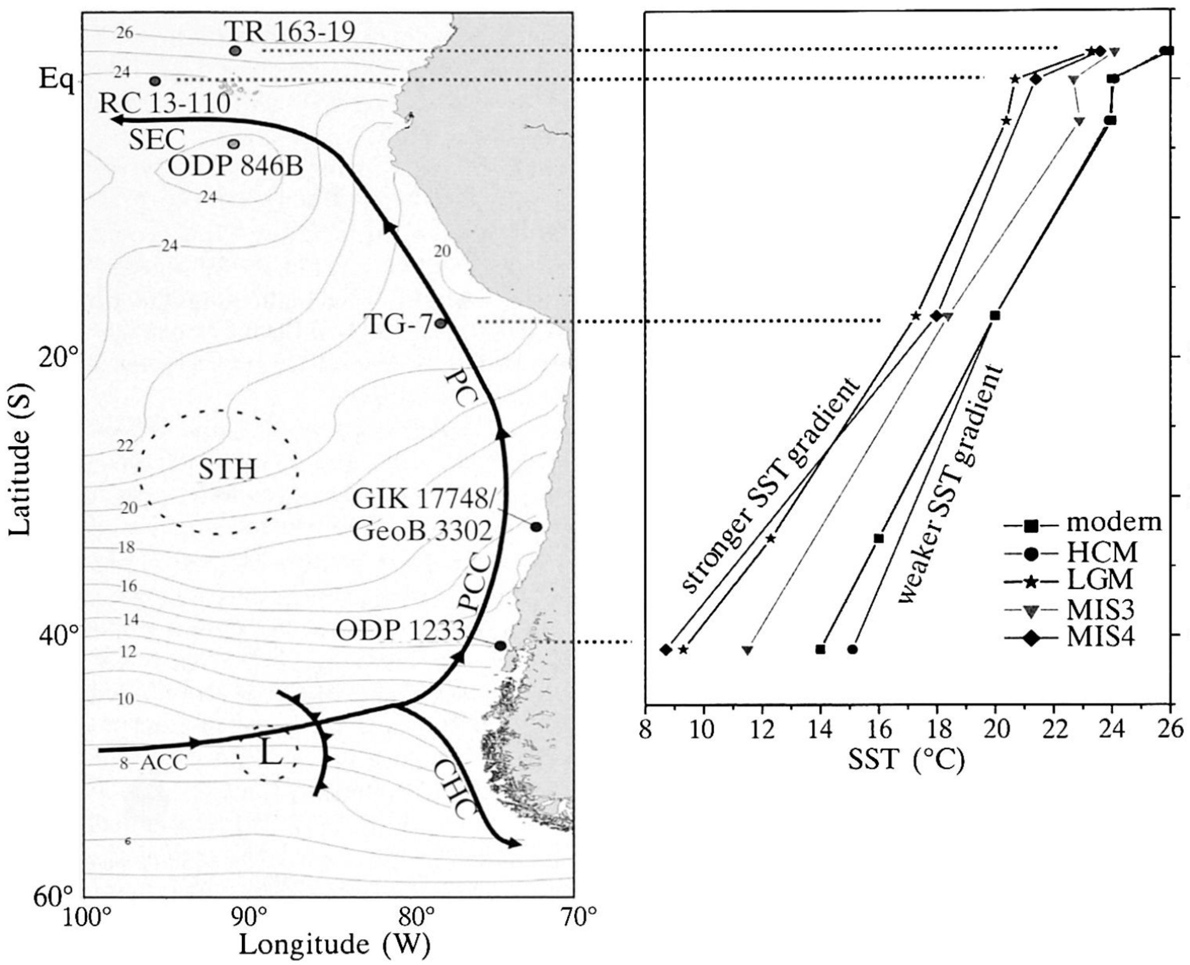

Fig. 8: Reconstruction of the SST gradients in the Pacific Eastern Boundary Current and the adjacent tropical Pacific between 2°N and 41°S during 5 time-intervals

These are defined as follows: Modern = SST values from Levitus and Boyer (1994); HCO = 8-12 kyr (Holocene Climatic Optimum), LGM = 19-22 kyr (last glacial maximum); MIS 3 = 51-60 kyr (early MIS 3); MIS 4 = 63-68 kyr. Map on the left shows location of records used, including: Core TR163-19 (Mg/Ca SST record); Core RC13-110 (SST reconstruction based on planktonic foraminifera assemblages); ODP Site 846 (SST reconstruction based on planktonic foraminifera assemblages); Core TG7 (alkenone based SST reconstruction); Cores GIK 17748-2 and GeoB 3302-1 (alkenone based SST reconstruction); ODP Site 1233 (alkenone based SST reconstruction). Abbreviations used on the map: ACC=Antarctic Circumpolar Current; CHC=Cape Horn Current; PCC/PC=Peru-Chile/Peru-Current; SEC=South Equatorial Current; STH=Subtropical High Pressure; L=Low Pressure Belt associated with the Southern Westerlies.

Rekonstruktion von SST-Gradienten im östlichen Randstrom des Pazifiks und im angrenzenden tropischen Pazifik zwischen 2°S und 41°S für fünf Zeitintervalle. Die Karte links zeigt die Kerne, die benutzt wurden.

Reconstruction des gradients SST dans le courant oriental du Pacifique (Pacific Eastern Boundary Current) et le Pacifique tropical adjacent, entre 2°N et 41°S au cours de 5 intervalles de temps. A gauche, la carte montre les points qui ont été utilisés.

Sources: Calvo et al. 2001; Feldberg & Mix 2003; Kaiser et al. 2005 (modified); Kim et al. 2002; Lea et al. 2000; Levitus & Boyer 1994; Martínez et al. 2003

Following the conceptual model in which high productivity in the southern PCC is sustained by the high nutrient/low chlorophyll (HNLC) waters of the ACC (Hebbeln et al. 2000a), variations in the latitudinal position of the ACC would result in latitudinal movements of the main nutrient source of the Chilean upwelling system. As surface sediment data show that nutrient availability and productivity decrease with increasing distance to the ACC, paleoproductivity changes at a specific core site probably reflect increasing/decreasing distances to this source, resulting from latitudinal movements of the ACC.

Combining the available datasets, it can be deduced that paleoenvironmental variability across both onshore and offshore Chile mainly depends on large scale oceanic/atmospheric circulation patterns in the Southeast Pacific, which in turn are primarily coupled to high southern latitude climate variability in the Southern Ocean and Antarctica. Tropical forcing mechanisms are present primarily in the northern part but are much less important. However, they may well play a more prominent role in short-term, i.e., centennial to decadal-scale climate variability. The investigation of the impact and the behaviour of past long-term changes in modern climate modes such as ENSO, but also in those originating in the high latitudes (e.g., the Southern Annular Mode), is a major issue for future marine research along the Chilean continental margin.

Acknowledgments
Financial support was provided by the German Research Foundation (Deutsche Forschungsgemeinschaft - DFG) as part of the DFG-Research Center Ocean Margins of the University of Bremen, and by the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung - BMBF) for funding RV Sonne cruises SO-102 and SO-156. This is publication no. RCOM0402.

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Abstract: The late Quaternary paleoenvironment of Chile as seen from marine archives

Many variables have been used to reconstruct Chilean paleoenvironmental changes during the late Quaternary. In this paper we present an overview of a number of these variables, so-called proxies, that have been inferred from marine sediments from the Chilean continental margin and summarise the results. In general, a glacial-interglacial pattern of climate changes can be recognised in the proxy records with high-frequency variabilities superposed. The synthesis shows that the records in the Southeast Pacific are clearly dominated by a high-latitude climate forcing mechanism and that there is a noticeable gradual increase of tropical forcing moving from south to north along the South American continental margin.

Zusammenfassung: Die spätquartäre Paläoumwelt Chiles, rekonstruiert anhand von marinen Sedimenten

Veränderungen der Paläoumwelt in Chile im Verlauf des Spätquartärs wurden anhand von vielfältigen Parametern rekonstruiert. Hier wird ein Überblick über einige dieser Parameter, sogenannte Proxies, präsentiert, die an marinen Sedimenten des chilenischen Kontinentalhangs untersucht wurden. Die Daten weisen auf ein klares Glazial-Interglazial-Muster der Klimaveränderungen hin, denen höher frequente Klimaschwankungen überlagert sind. Die Synthese zeigt, dass die Umweltveränderungen im Südost-Pazifik in erster Linie aus den hohen Breiten angetrieben wurden, wobei von Süden nach Norden ein zunehmender tropischer Einfluss entlang des südamerikanischen Kontinentalrandes zu beobachten ist.

Résumé: Le paléoenvironnement du Chili au Quaternaire récent reconstitué à partir de sédiments marins

Plusieurs variables ont été utilisées pour reconstruire les changements subis par le paléoenvironnement du Chili au cours du Quaternaire récent. Cet article présente une vue d'ensemble de certaines de ces variables, aussi appelés proxies, lesquelles sont issues de l'analyse des sédiments marins de la marge continentale chiliennes, et résume les résultats de la recherche. D'une manière générale, il est possible de distinguer un modèle des changements climatiques fondé sur les périodes glaciaires et interglaciaires à partir des données proxy, caractérisé par des variations à haute fréquence. La synthèse montre que les données du Pacifique Sud-Est sont fortement dominées par des mécanismes climatiques associés aux hautes latitudes et que l'influence tropicale s'accroît graduellement du sud au nord tout au long de la marge continentale sud-américaine.

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Manuskripteingang/received/manuscrit entré le 15.2.2006
Annahme zum Druck/accepted for publication/accepté pour l'impression: 21.6.2006