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Final Report for the BMBF-Project

PUCK – SO-156

INTERRELATIONSHIPS BETWEEN PRODUCTIVITY AND ENVIRONMENTAL CONDITIONS ALONG THE CHILEAN CONTINENTAL SLOPE

WECHSELWIRKUNGEN ZWISCHEN PRODUKTIVITÄT UND UMWELTBEDINGUNGEN AM CHILENISCHEN KONTINENTALHANG

01.12.2000 – 30.04.2003

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Content

1) Introduction

The PUCK – SO-156 project has been carried out jointly by three German research institutes in close cooperation with the Universidad de Concepción (Chile). This cooperation focused on investigations regarding the present and past interrelationships between productivity and environmental conditions in the high productive waters of the Humboldt Current System along the Chilean continental slope. Although the foci of the individual groups are concentrating on different disciplines of the marine sciences, in parts these are closely related. The three main fields of investigation were:

Under the leadership of the *Department of Geosciences at the University of Bremen (GeoB)* the imprint of the prevailing environmental conditions on the recent sediments, the paleo-environmental conditions and the paleo-productivity in the Southern Peru-Chile Current have been investigated, with the paleo-reconstructions focusing on the last glacial-interglacial cycle. This project aimed to study the role of this high productivity region in global productivity changes associated with climate change, which are often assumed to cause the observed variations in atmospheric CO_2 concentrations on these time scales.

Under the leadership of *the Max-Planck-Institute for Marine Microbiology in Bremen (MPI)* the influence of the bacteria Thioploca on the nitrogen cycle in an area with extremely high rates of denitrification, exchange processes across the sediment-water interface and the relationships between organic carbon, nitrogen, phosphorus, iron, manganese and sulfur have been investigated.

Under the leadership of the *Alfred-Wegener-Institute for Polar and Marine Research in Bremerhaven (AWI)* the benthic macro and meio faunas in the Southern Peru-Chile Current have been quantitatively and qualitatively studied with special emphasis on the oxygen minimum zone in order to describe the biogeography and biodiversity of these faunas over a rather large latitudinal range. An additional focus was on the impact of El Niño events on the benthic assemblages.

All of these investigations have been carried out in close cooperation with Chilean colleagues, mainly from the *Universidad de Concepción (UdeC)*. This final report provides an overview of the results obtained in the course of the project between Jan. 1, 2001, and March 31, 2003, including a short report about the SO-156 expedition.

2) Aims of the project set out at its beginning

Marked by an extremely long south-to-north extension over ~40° of latitude the coastal upwelling area in the Peru-Chile Current is the largest coastal upwelling region in an Eastern Boundary Current in the world ocean. As the northern part of the Peru-Chile Current off Peru is relatively well studied, still only little is known about the present day settings and the youngest geological history of its southern part off Chile. This project aimed to analyse the interrelationship between the present-day environmental setting and the benthic assemblages and to reconstruct the Late Quaternary paleoenvironmental setting in this important high productivity region.

The reconstruction of the paleoproductivity in the southern Peru-Chile Current was already a focus of the CHIPAL SO-102 project. Results obtained during CHIPAL indicated that the temporal development of productivity in this area was marked by a high spatial variability, with e.g. a decrease in productivity from the Last Glacial Maximum towards the Holocene at 33°S. In contrast, data from 27°S indicated an opposite trend. This regional variability hampered a large scale assessment of glacial productivity, which should be enabled to a much better sample grid obtained during SO-156.

The paleoproductivity in the region is closely coupled to the paleoclimate and the paleoceanography, thus, the PUCK activities contributed and will contribute also to increase the knowledge in these general fields. The stratigraphic focus of the PUCK activities was on the last 50.000 years in order to study paleo-environmental changes on a high-resolution basis possibly related to cyclic paleoclimatic variations in the sub-Milankovitch band known as Dansgaard/Oeschger Cycles, already observed in sediments from the northern part of the Chilean continental slope. Of special interest is also the effect of the contrasting climates of the Last Glacial Maximum and the Holocene on the regional productivity regime. For the time since the onset of the Last Glacial Maximum a number of high-resolution paleoclimatic time-series obtained from terrigenous sequences exist (e.g. lake sediments), which can serve as independent data sets to analyse the relationships between the marine climate, the oceanography and the terrestrial climate of the region.

A key aspect of the microbiological studies were the bacterial mats in the oxygen minimum zone, which can be found over 3000 km along the South American west coast and which have been first described in 1977. Their main component is the bacteria *Thioploca*, whose metabolism was initially studied during the MPI-*Thioploca* cruise. These organisms live at the interface between the nitrate-rich bottom water and the almost anoxic sediment getting their energy by oxidising hydrogensulfur using oxygen taken from nitrate and even the resulting sulfur is oxidised to sulfate. This process is so effective that no more hydrogensulfur can be detected at the sediment surface, although it is steadily produced in large quantities by heterotrophic bacterial sulfate reduction.

The scientific foci of PUCK in the field of microbiology were on the analyses of (1) the influence of *Thioploca* on the nitrogen cycle in an area with extremely high rates of denitrification, (2) the biology of these organisms and their influence on other microbiota, and (3) biogeochemical processes at the sediment-water interface and within the sediment. To investigate the relation between upwelling intensity and the impact of water depth to the benthic communities several transects from the shelf to the slope in areas with different fertility have been studied.

In order to describe the biogeography and biodiversity of these faunas over a rather large latitudinal range the studies in the field of benthic biology focused on the quantitative and qualitative analyses of the benthic macro and meio faunas in the Southern Peru-Chile Current with special emphasis on the oxygen minimum zone. In contrast to the near-coastal, well-oxygenated waters being exploited by artesanal fisheries in Peru and Chile, the macro- and meiobenthic faunas of the deeper parts of the Peru-Chile Current are still only poorly studied. Off Chile the depth region where the oxygen minimum zone hits the sea floor is of special interest, as there the effects on the benthos are extreme.

An additional focus was on the impact of El Niño events on the benthic assemblages. Following the strong 1997/1998 El Niño event the PUCK studies provide a baseline study revealing a typical fauna for the southern Peru-Chile Current to be found under “normal” (i.e. non El Niño) conditions. Thus, based on these results investigations to be carried out during future El Niño events can be compared in order to assess the impact of El Niño events on these populations. In addition, the PUCK results contribute to global biodiversity surveys studying latitudinal and vertical gradients of abundance, biomass, and species richness.

3) Preconditions for the project

All the groups involved had already a long-term experience with the study area, which is, for instance, reflected in the *Thioploca*-cruise in 1994, organised by the MPI, and by the CHIPAL cruise in 1995, organised by GeoB. Based on the experience gained during these earlier activities the cruise plan for the PUCK expedition has been optimised hence resulting in a very successful cruise. The field work as well as the following investigations in the home labs was mainly carried out by the following groups:

GeoB:

a) colleagues paid by the university:

Bickert, T., Dr., scientist	Dehning, K., technician
Donner, B., Dr., scientist	Grimm-Geils, A., secretary.
Fischer, G., Dr., scientist	Scholz, M., technician
Müller, P.J., Dr., scientist	
Pätzold, J., Dr., scientist	
Segl, M., Dr., scientist	
Wefer, G., Prof. Dr., scientist	

b) colleagues paid by NEBROC:

Hebbeln, D., Dr., scientist
Schneider, R., Dr., scientist

c) colleagues paid by other sources:

Lamy, F., Dr., scientist	
Mulitza, S., Dr., scientist	Diekamp, V., technician
Rühlemann, C., Dr., scientist	Meyer-Schack, B., technician

MPI:

a) colleagues paid by the institute:

Brüchert, V., PhD, scientist	Fleischer, S., technician
Böttcher, M., Dr., scientist	Neumann, K., technician
Ferdelmann, T., PhD, scientist	
Forster, S., Dr., wiss. Mitarbeiter	
Jørgensen, B.B., Prof. Dr., scientist	
Könnecke, M., Dipl.-Biol., scientist	
Schubert, C., Dr., scientist	

AWI:

a) colleagues paid by the institute:

Arntz, W., Prof. Dr., scientist	Beyer, U., technician
Gerdes, D., Dr., scientist	Hirse, T., technician
Gutt, J., Dr., scientist	
Starmans, A., Dr., scientist	

Colleagues paid by this project:

GeoB:

Dr. Oscar Romero	Diatoms, Paleoceanography,
(BAT IIa, 01.01.2001-31.12.2002)	Coordination
Dipl.-Geol. Mahyar Mothadi	Foraminifera, Paleoproductivity
(BAT IIa/2, 01.03.2001-30.04.2003)	

MPI:

Dipl.-Geol. Jutta Niggemann	Biogeochemistry
(BAT IIa/2, 01.03.2001-30.04.2003)	
Dipl.-Biol. André Preißler	Microbiology
(BAT IIa/2, 15.07.2001-30.04.2003)	

In addition, significant support for student work (DM 69.840,-) was provided by the project.

In general, the BMBF provided the following financial resources for this project covering the period 01.12.2000 until 30.04.2003:

Personnel:	DM	642.540,-
Charter costs RV SONNE:	DM	3.254.750,-
Orders:	DM	31.500,-
Consumables:	DM	108.400,-
Container transport:	DM	75.811,-
Travel:	DM	143.868,-
Total:	DM	4.256.869,-

4) Planning and development of the project

At the beginning of the project the activities concentrated on the preparation of the SO-156 expedition, which formed an integral part of the project. Besides the coordination and the planning of the cruise, especially the purchase of equipment, needed for the expedition, was an important task. Although the time between project start and the expedition was rather short, everything was prepared in time. In total, six container with equipment were sent to Valparaiso.

On March 30, 2001, R/V SONNE left Valparaiso for the first leg of SO-156 heading northward to the first major working area off Antofagasta (Fig. 4.1). After finishing the first major benthological transect at 23°S this leg ended already at noon on April 6 off Antofagasta. Most of the biologists went by a small boat onshore and were replaced by marine geologists and palynologists. In the afternoon of April 6 the SONNE left Antofagasta for the second leg with the focus on the analysis of sediments obtained by multicorer and by gravity corer along the Chilean continental slope between Antofagasta and Valparaiso.

After 11 days of intense sampling along the Chilean continental slope the station work of leg 2 of SO-156 ended on April 17 with station GeoB 7150. From this station SONNE headed directly towards Valparaiso and in the afternoon of the same day the vessel reached the pier after 19 days at sea. During the stay of the SONNE in Valparaiso another partial exchange of the scientific crew took place and only 7 of 22 scientist stayed for the third leg of the cruise, which began on April 19 at 13:00 h.

During the third leg the dense geological sampling grid was completed towards the southern end of the study area till ~45°S (Fig. 4.2). In addition, two more benthologic transects were done at 36°S and at 42°S, respectively. On these transects a full range of instruments have been used in order to receive as much information about the seafloor as possible. The instrumentation included CTD/Rosette, Photosledge, Multicorer, Agassiztrawl, gravity corer and the huge multi-box corer equipped with online video control.

On Sunday, May 6, the SONNE reached the southernmost point of this expedition at 44°17′S and started to head northward to fill the gaps in the sample distribution left a week before due to bad weather conditions. The sampling programme of SO-156 finished on May 12 at 40°S on the shelf off Valdivia with the 120th station. Around noon the SONNE headed north towards Talcahuano. On Sunday, May 13, at 10:00 h in the morning the SONNE berthed at ASMAR shipyard in Talcahuano and the PUCK expedition ended.

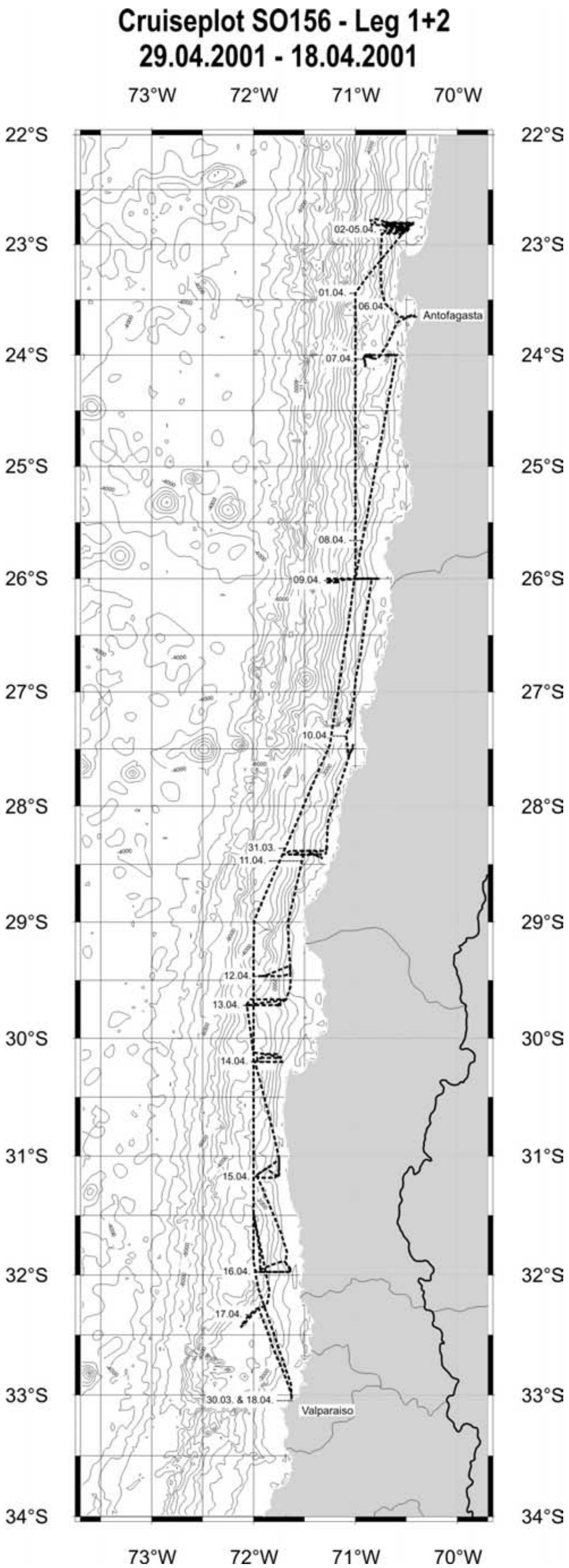

Fig. 4.1: Cruise plot of Leg 1 and Leg 2 of SO-156 PUCK Cruise.

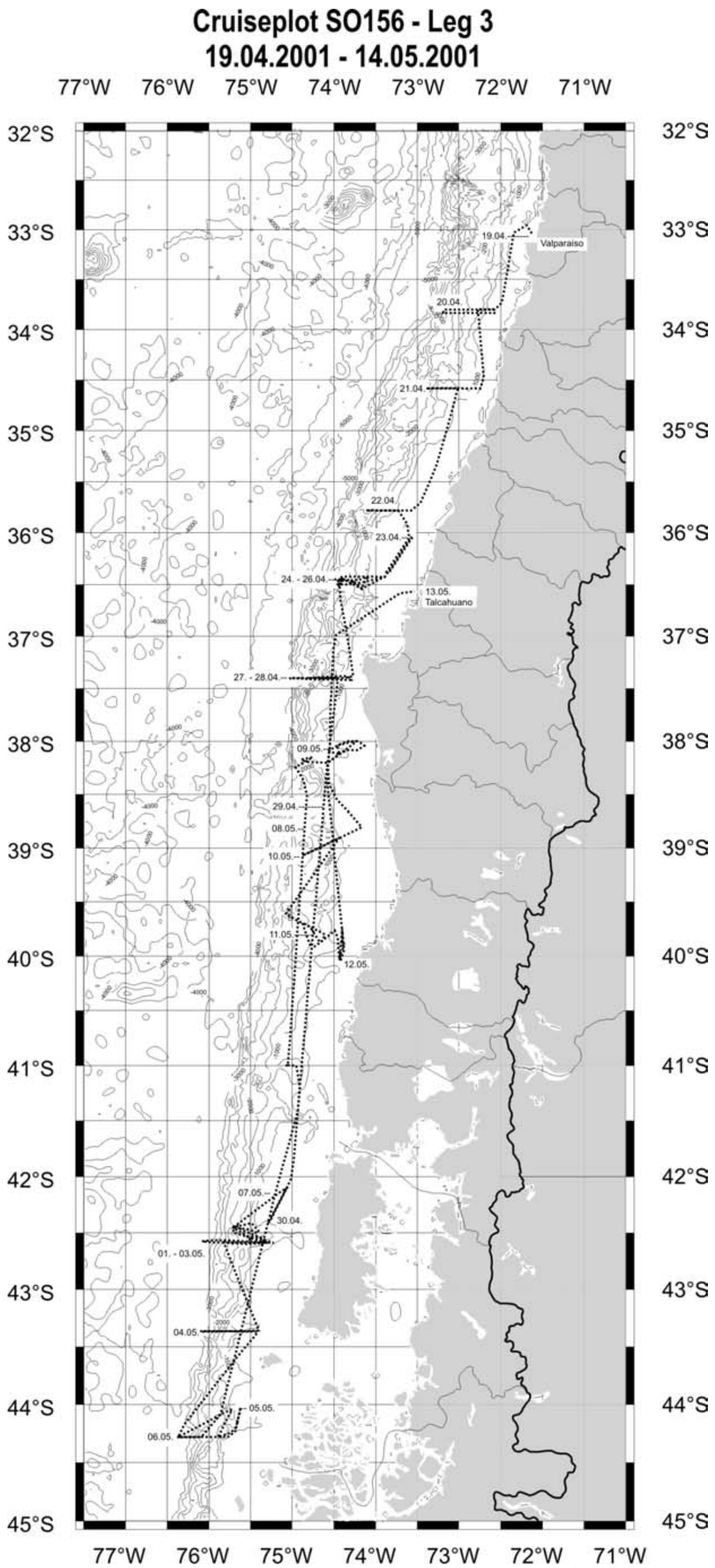

Fig. 4.2: Cruise plot of Leg 3 of SO-156 PUCK Cruise.

Worth to mention are the almost perfect weather conditions during the whole cruise, except for only a few days at the end of April 2001. These good conditions allowed continuous station work and were a major precondition for the success of the cruise, which becomes obvious from the huge amount of samples collected.

Finally, some statistics: 46 scientists of 11 nationalities participated in the PUCK expedition. Most of them came from the main partner institutes of the project (GeoB: 12, MPI: 11, AWI: 5, UdeC: 10), while another five participants were from other Chilean institutions accompanied by three guest scientists from Peru, France and Germany, respectively. During the whole cruise a total of 120 stations have been visited and sampled by 37 CTDs, 11 photosledges, 19 agassiz trawls, 19 multigrabs, 163 multicorers, and 101 gravity corers. Putting all the gravity corers together 387 m of sediment have been retrieved.

After the cruise again six container with equipment and – even more important – with the samples were sent send back to Bremen. After arrival of the container and the careful archiving of the samples, detailed analyses of the samples in the labs in Bremen and partly also at other locations commenced. These analyses were continued until the end of the project period. The results obtained during this time are described below.

5) Scientific state of the art at the onset of the project

- please, refer to the detailed description in the original proposal -

6) Co-operation with national and international partner institutions

Within the frame of the PUCK project there was a close co-operation with the groups from the following institutions:

BGR Hannover (Germany)
Forschungsinstitut Senckenberg (Germany)
Universität Hamburg (Germany)
Universität Oldenburg (Germany)
Inst. Montemar/Viña del Mar (Chile)
SHOA, Valparaiso (Chile)
Univ. Austral, Valdivia (Chile)
Univ. de Chile, Santiago (Chile)
Univ. Concepción (Chile)
Univ. of British Columbia (Canada)
Univ. of Aarhus (Denmark)
NIOZ, Texel (The Netherlands)
Univ. San Marcos, Lima (Peru)
Scripps Inst. of Oceanography (USA)

7) Results

7.1) The imprint of productivity pattern on the surface sediments

Introduction - The coastal upwelling system of the Peru-Chile Current belongs to the most productive regions in the world oceans. In spite of this remarkable fact only very little is known about the sediment distribution in its southern part off the coast of Chile. The PUCK project aims to increase the knowledge about this region by multi-parameter study of the surface sediment distribution along the Chilean continental slope between 23°S and 45°S. Based on >100 surface sediment samples, detailed analyses of sedimentary data (TOC, carbonate, and biogenic opal contents and C:N ratios) reveal a close relation to environmental conditions in the region.

Setting - The strong climatic zonation of Chile, reaching from very humid conditions in the south to the extremely dry Atacama desert in the north, is marked by a pronounced precipitation gradient. The resulting pattern of erosion and seaward transportation of terrigenous material is the main reason behind the parallel gradient in mean sedimentation rate along the Chilean continental slope, which shows a significant increase towards the south (see chapter 7.3). In addition, increasing sedimentation to the south is accompanied by increasing marine productivity as shown by satellite data. Nevertheless, coastal upwelling is restricted to the area north of ~40°S, where the PCC flows northward along the coast. The PCC originates from the ACC, which reaches the South American continent between 40-45°S. In this region prevailing onshore winds of the Southern Westerlies result in predominantly downwelling favourable conditions.

Surface Sediment Data - Organic carbon and biogenic opal contents show a very similar pattern with southward decreasing values in the northern part of the study area, low values between 25°S and 35°S, a maximum between 35°S and 40°S, and again slightly lower values further to the south (Fig. 7.1.1). The carbonate content reveals exactly the opposite pattern. Finally, the C:N ratio varies around 8 pointing to a predominant marine origin of the organic matter. Very shallow (<500 m) and very deep samples (>3500 m) partly do not fit into the dominating pattern and have not been used for the calculation of the latitudinal means (bold lines). While the shallow samples are probably affected by sediment reworking, which becomes obvious by the relatively high sand contents observed in the shelf and upper slope samples, the samples from depths >3500 m may partly be affected by mass wasting, which is more common at the deeper continental slope.

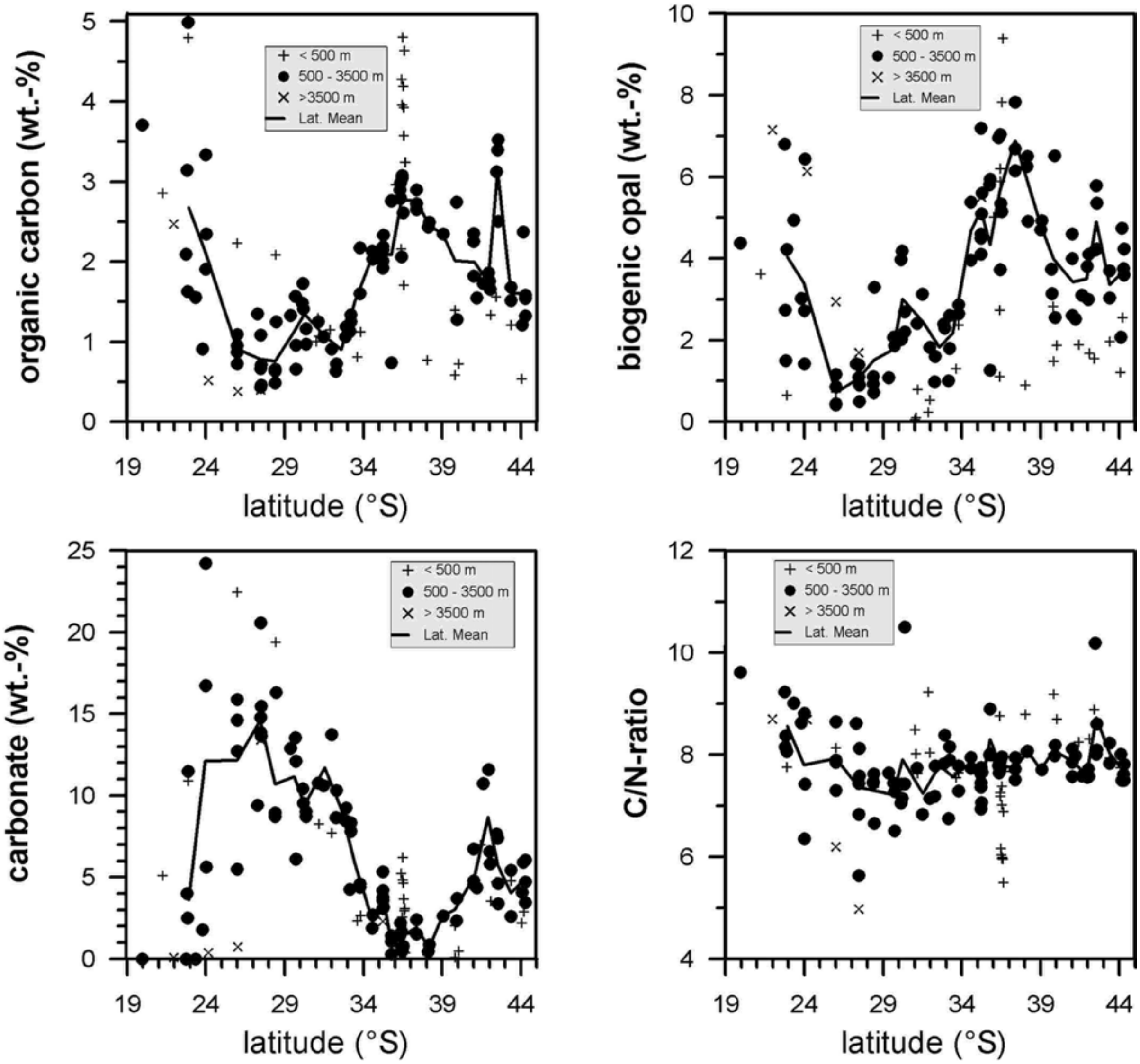

Fig. 7.1.1: Contents of biogenic compounds in surface sediments from the Chilean continental slope between 19°S and 45°S.

<u>Accumulation rates</u> - With respect to the very high proportion of terrigenous material in these sediments, a clear picture of the imprint of surface ocean productivity on sedimentation along the Chilean continental slope can only be obtained by analysing the accumulation rates of the biogenic components. Estimated accumulation rates (AR), based on dated sediment cores (see chapter 7.3), reveal a coherent pattern of increasing accumulation of productivity indicators from north to south (Fig. 7.1.2). It becomes obvious that the carbonate content in the surface sediments, in contrast to that of organic carbon and biogenic opal, is strongly affected by dilution of terrigenous material. This latitudinal pattern clearly reflects the increasing productivity southward along the Chilean margin as it is also indicated by the satellite data. However, both data sets indicate highest productivity south of 40°S, where the physical conditions are in favour for downwelling and not for upwelling.

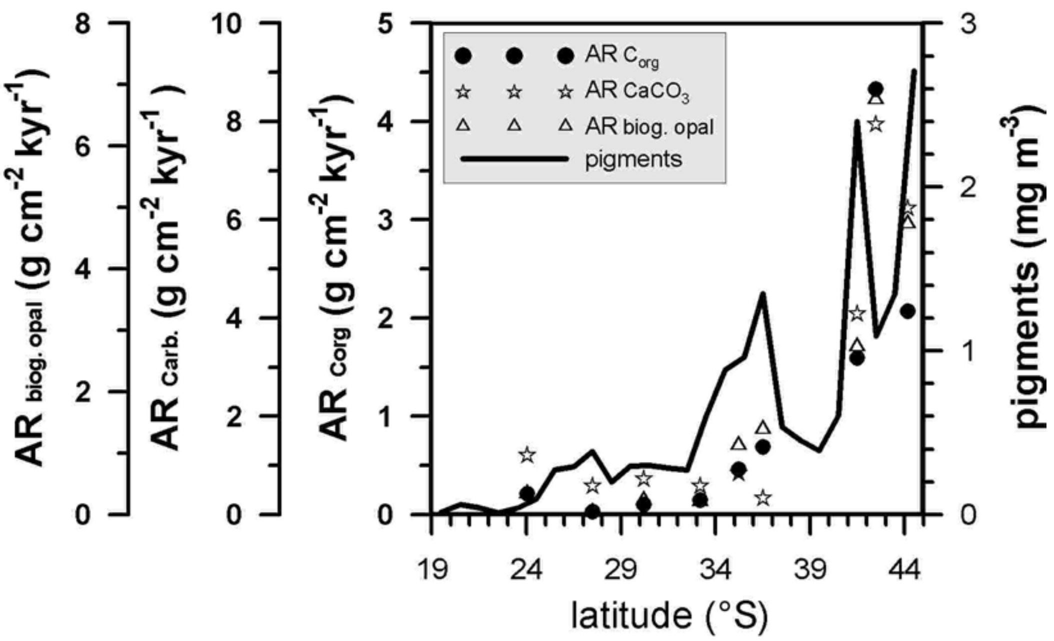

Fig. 7.1.2: Estimated accumulation rates for biogenic compounds in the surface sediments along the Chilean continental slope. The pigment concentration in surface waters (full line) is derived from Coastal Zone Color Scanner measurements (http://.daac.gsfc.nasa.gov).

The nutrients needed to sustain such a high productivity outside the upwelling region most likely come from two different sources: the waters of the ACC and the continental hinterland of Chile. The ACC is a typical high nutrient/low chlorophyll (HNLC) area, where the use of the available nutrients such as nitrate is limited by the low availability of micronutrients, especially of iron. Upon reaching the near coastal areas the availability of iron increases strongly by riverine input and by benthic exchange processes allowing a very high productivity based on the high availability of (micro)nutrients.

Conclusions - Thus, these data support the view that coastal upwelling along the Chilean continental slope sustains a high marine productivity, which is also reflected in the surface sediments. However, a significantly higher marine productivity is indicated by surface sediment and satellite data for the area south of the upwelling region (>40°S) where downwelling is the predominant process. It is assumed that the HNLC-waters of the ACC and the input of micronutrients from the very humid hinterland are the main forcing factors for this extremely high productivity. Probably this nutrient pool also forms the ultimate nutrient source for the marine productivity further to the north, where the upwelling system keeps the nutrients for a rather long time in the system.

7.2) Biogenic silica and diatom thanatocoenosis in surface sediments and their relationship with surface water productivity

Introduction - Based on the fact that the occurrence of preserved diatoms in sediments adequately mirrors productivity conditions of surface waters as well as mechanisms governing the production of diatoms in Eastern Boundary Current systems, we report on latitudinal distribution of biogenic silica (opal) and diatoms in the SE Pacific, off Chile. We show how modern hydrographic conditions are indeed reflected by the diatom abundance and the assemblage composition preserved in core-top sediments collected from approx. each degree of latitude along the Chilean coast between 22° and 44°S (Fig. 7.2.1).

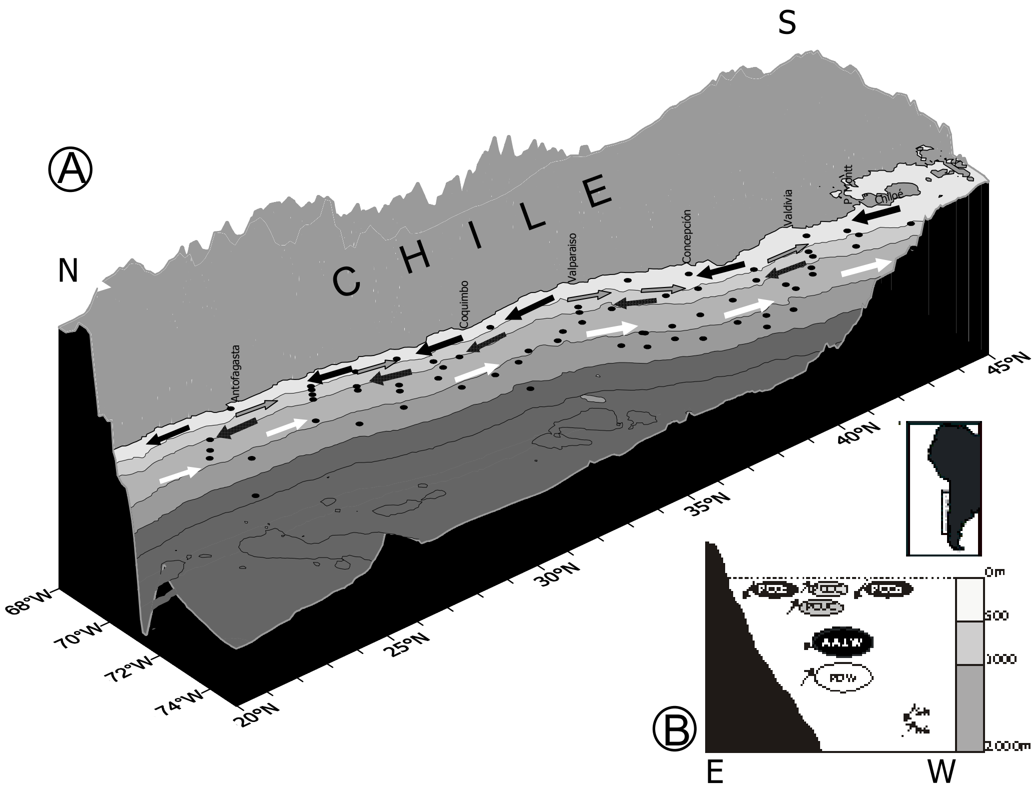

Fig. 7.2.1: (A) 3D-bathymetric map of the Chilean coast in the SE Pacific Ocean indicating locations of 76 surface sediment samples (full dots) and the present-day water circulation pattern. Black arrows, Peru-Chile Current; dark gray arrows, Peru-Chile Undercurrent; light gray arrows, Antarctic Intermediate Water; and white arrows, Pacific Deep Water. (B) Schematic profile of the present-day current system and water masses off Chile: PCCc, Peru-Chile Current, coastal branch; PCCo, Peru-Chile Current, oceanic branch; PCCC, Peru-Chile Countercurrent; PCCC, Peru-Chile Countercurrent; AAIW, Antarctic Intermediate Water; PDW Pacific Deep Water. Arrows show the flowing direction.

Results and Discussion - The siliceous signal in surface sediments underlying the Peru-Chile Current off Chile depicts a clear north-south pattern. Opal content (OC) in surface sediments between 400 and 2550 m water depth ranges between <0.05 and ~7.8 wt.% (dry weight) (Fig. 7.2.2A). The area with the highest opal concentration extends from ~34° to 37°S. North of 34°S, OC is mostly below 2 wt.% till 22°-23°S, where average OC slightly increases again. Two minor peaks are seen at 24°S and at 30°S. A secondary maximum in the mean OC is seen at ~42°S. The diatom concentration (DC) ranges between ~3 * 10^4 and 1.5 * 10^7 valves/g, and follows closely the spatial trend described for biogenic silica (r = 0.68; Fig. 7.2.2B). Highest DC are between ~34° and 38°S: at this latitude the average concentration exceeds 6 * 10^6 valves/g. South of 38°S only one peak in the mean DC is observed at ~41°S. Off northern Chile, only secondary peaks are seen off 27°S and 30°S. As for opal, the mean DC raises again at ~22-23°S.

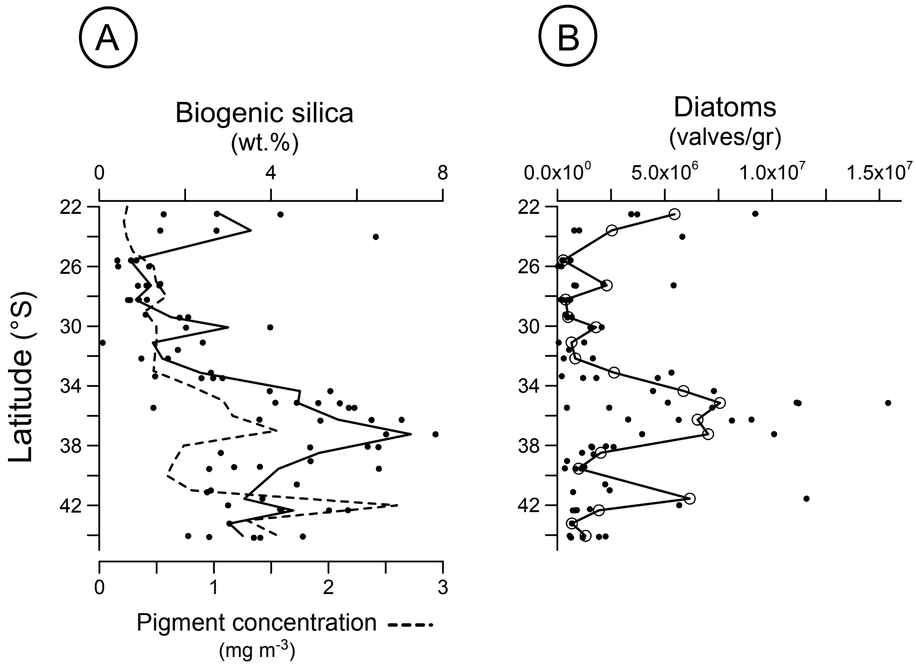

Fig. 7.2.2: (A) Biogenic silica content, as wt.% (dry weight), and (B) diatom concentration, expressed as valves per gram of dry sediment, in 76 surface sediment samples from the SE Pacific Ocean, off Chile. The filled line represents average values for each degree of latitude between 22° and 44°S. The pigment concentration in surface waters (dashed line) is derived from Coastal Zone Color Scanner measurements (http://.daac.gsfc.nasa.gov).

Although the conversion of OC and DC into accumulation rates represents a more reliable measure to assess surface water productivity, their latitudinal pattern in core-top sediments collected in the SE Pacific matches well the N-S differences of the phytoplankton pigment concentration in surface waters as estimated by remote sensing. Between 22° and 33°S, where low pigment values are measured, the OC and DC are correspondingly low. In contrast, higher OC and DC at 34°-38°S and 41°-42°S correspond well with estimated higher pigment concentrations (Fig. 7.2.2). According to satellite observations, both low pigment and primary production values are typical for the coastal area at 23°S off the northern Chilean coast. We propose that enhanced OC and BC at 22°-23°S might reflect localized increase of coastal upwelling intensity, which remains undetected by satellites.

Southward, opal and diatom peaks at 27° and 30°S evidence the recurring high production derived from near-shore upwelling cells and the corresponding downward delivery of siliceous micro-organisms, rather weakly mirrored by annual averages of pigment concentration. A possible explanation for this disparity might be that CZCS pictures are gained from the uppermost centimetres of the water column, while diatoms thrive in a much wider range of depth in the water column. Some discrepancy between the magnitudes of pigment concentration and siliceous signal is seen in the southernmost area. Highest CZCS-derived average pigment concentrations are seen in surface waters south of 40°S. However, highest OC and DC are measured north of 40°S. A possible explanation for this disparity lays on the pattern of increasing sedimentation rates for Holocene time-scales south of 40°S (see chapters 7.1 and 7.3).

The composition of the diatom thanatocoenosis clearly distinguishes the occurrence of coastal upwelling off northern and central Chile from the influence of southern-originated water masses off southern Chile (Fig. 7.2.3). Though favourable conditions for intense phytoplankton proliferation characterize surface waters along the whole Chilean coast, CZCS-derived pigment concentrations reveal strong north-south variations. 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 till ~38°S. Though the occurrence of upwelling is limited to a narrow coastal band (less than 40 km wide), the upwelling diatom signal is recorded in deep-sea sediments beyond the continental slope. We propose that off-shore streaming chlorophyll filaments are determinant in the seaward transport of the coastal upwelling diatom signal possibly supported by the narrowness of the shelf north of 34°S.

The highly diversified diatom community off 34°-38°S represents a transition and points to changing hydrographic conditions. Coastal upwelling-associated diatoms abruptly decrease south of ~38°S, being progressively replaced by non-upwelling representatives, typical of low-temperature, nutrient-rich waters.

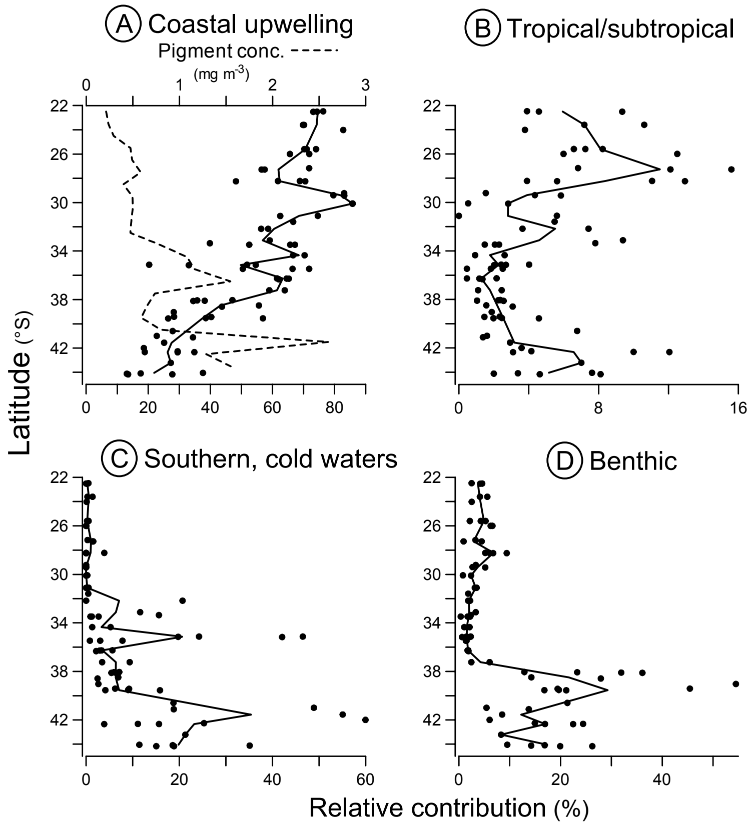

Fig. 7.2.3: Relative abundance of four diatom groups, expressed as percentage of the whole diatom assemblage, in surface sediment samples collected in the SE Pacific, off Chile, between ~22° and 44°S (A: Coastal upwelling; B: Tropical/subtrop.; C: Southern cold waters; D: Benthic). The filled line represents the average abundance for each degree of latitude. The pigment concentration in surface waters (dashed line) is derived from Coastal Zone Color Scanner measurements.

In surface sediments off southern Chile, high DC, dominance of several cold-water, eutrophic *Thalassiosira* species (Fig. 7.2.3C), and enhanced relative contribution of the silicoflagellate *Dictyocha speculum* coincide with higher pigment concentrations and cooler SST than farther north. The higher contribution of nutrient-rich, low-temperature diatoms points to the presumed nutrient supply by two sources: the iron-limited, nutrient-rich Antarctic Intermediate Water, probably in combination with some input of micronutrients from the continent, due to very high precipitation in southern Chile (see chapter 7.1). In addition, benthic, shallow-water diatoms (Fig. 7.2.3D) preserved in sediments from the lower slope and the deep-sea suggest some advection from the continental shelf.

7.3) Sedimentation rates along the Chilean continental slope

Introduction - Prior to the investigations based on SONNE cruises SO-102 and SO-156, average sediment accumulation along the Chilean continental margin could be assessed only from seismic data averaging over very long periods. These analyses indicate a significant increase in the accumulation of sediments from north to south which has been related to the different climatic conditions in the continental hinterland affecting the terrigenous input and hence, the sedimentation rates. With the sediment cores collected during SO-102 and SO-156, high resolution and accurate estimates of sedimentation rates could be carried out on much shorter time scales, allowing e.g. glacial-interglacial comparisons. Besides the quantification of the N-S gradient for the present-day sedimentary conditions, examination of the temporal variability in the sedimentation rates is of special interest.

Five sediment cores, collected between 24° S and 44° S off Chile, were chosen for examination of the temporal and spatial variability of the sedimentation rates (SR) on the Chilean continental margin over the last 30,000 years. The dating of the cores is based on AMS ^{14}C dates in combination with stable oxygen isotope records. In the north (N of 30°S), the sediment cores were relatively short (3.5 - 6 m), but older (up to >30 kyr), while towards the south (S of 30°S), the records became longer (up to 8 m) and younger (down to <3 kyr).

Oxygen isotope records - Different characteristics can be distinguished by the comparison of the $\delta^{18}O$ records from the continental margin off Chile (Fig. 7.3.1): during the last glacial, $\delta^{18}O$ values ranged between 2.5 and 2 ‰ PDB regardless of the latitudinal position of the records. Between 18 and 17 kyr B.P. the $\delta^{18}O$ values started to decrease towards the Holocene when they reached minimum levels. These Holocene values appear to be lighter (~0.5-1‰ PDB) in the north (<33° S) than in the south (~1‰ PDB >33° S) as a result of decreasing water temperatures towards the south. Nonetheless, some lighter values in the south seem to be influenced by lower salinities caused by increased freshwater input from the fjords. At the southernmost part of the investigated area (>40° S), the records do not exceed Holocene ages, whereas towards the north the Holocene is partly absent.

Spatial variability of sedimentation rates - Comparison of the different records reveals a successively southward increase of the sedimentation rates (SR) off Chile (Fig. 7.3.2a). At 24 and 30° S, SR are on average below 17 cm kyr^{-1} (GeoB 7112-5; GeoB 7139-2), while rates up to 280 cm kyr^{-1} have been observed at 44° S (GeoB 7186-3). The southward increase of SR seems plausible by considering the climate of the continental hinterland controlling the continental runoff, and thus, the SR at the investigated sites: North of 30° S the land climate is hyper-arid with precipitation values <50 mm/a. Terrigenous input is mainly of eolian origin. Further south annual precipitation increases slightly, and from 31° S to 37° S the climate can be classified as semi-arid Mediterranean. South-central Chile (south of 37° S) is characterized by humid, cool temperature conditions with heavy precipitation. The fluvial runoff reaches up to 21 km^3 yr^{-1}. The length and age of the sediment records follow the distinct latitudinal sections of the climate zones and the resulting precipitation values, with short, but relatively old cores in the north and long, but younger cores in the south.

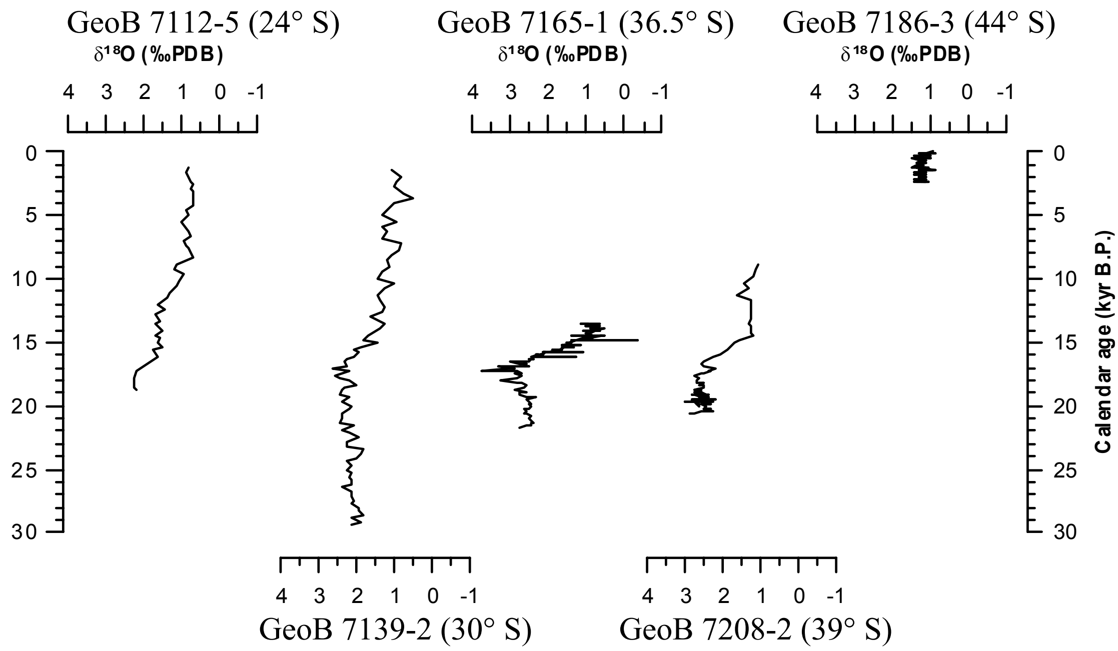

Fig. 7.3.1: Stable oxygen isotope records of the investigated cores, measured on shells of the planktic foraminifera species N. pachyderma sin. and/or N. pachyderma dex., relative to the PDB standard. The age models are based on AMS ^{14}C dates.

<u>Temporal variability of sedimentation rates</u> - Regardless of the latitudinal position of the records higher sedimentation rates are indicated for the last glacial compared to the Holocene (Fig. 7.3.2b). An abrupt shift from high values during the last glacial to much lower levels afterwards is marked in the northern records. The records lying further south are not comparable since either the Holocene or the glacial sediments are missing. The drop in the accumulation rates occurs at slightly different times: About 12-13 kyr B.P. at 24° S, between 13 and 14 kyr B.P. at 30° S, and close to 14 kyr B.P. at 33° S (data from GeoB 3302-1, SO-102). This discrepancy might be partly due to stratigraphic uncertainties of the cores. The lack of the Holocene in records off middle and north Chile could have been caused by bottom currents (winnowing) during this period.

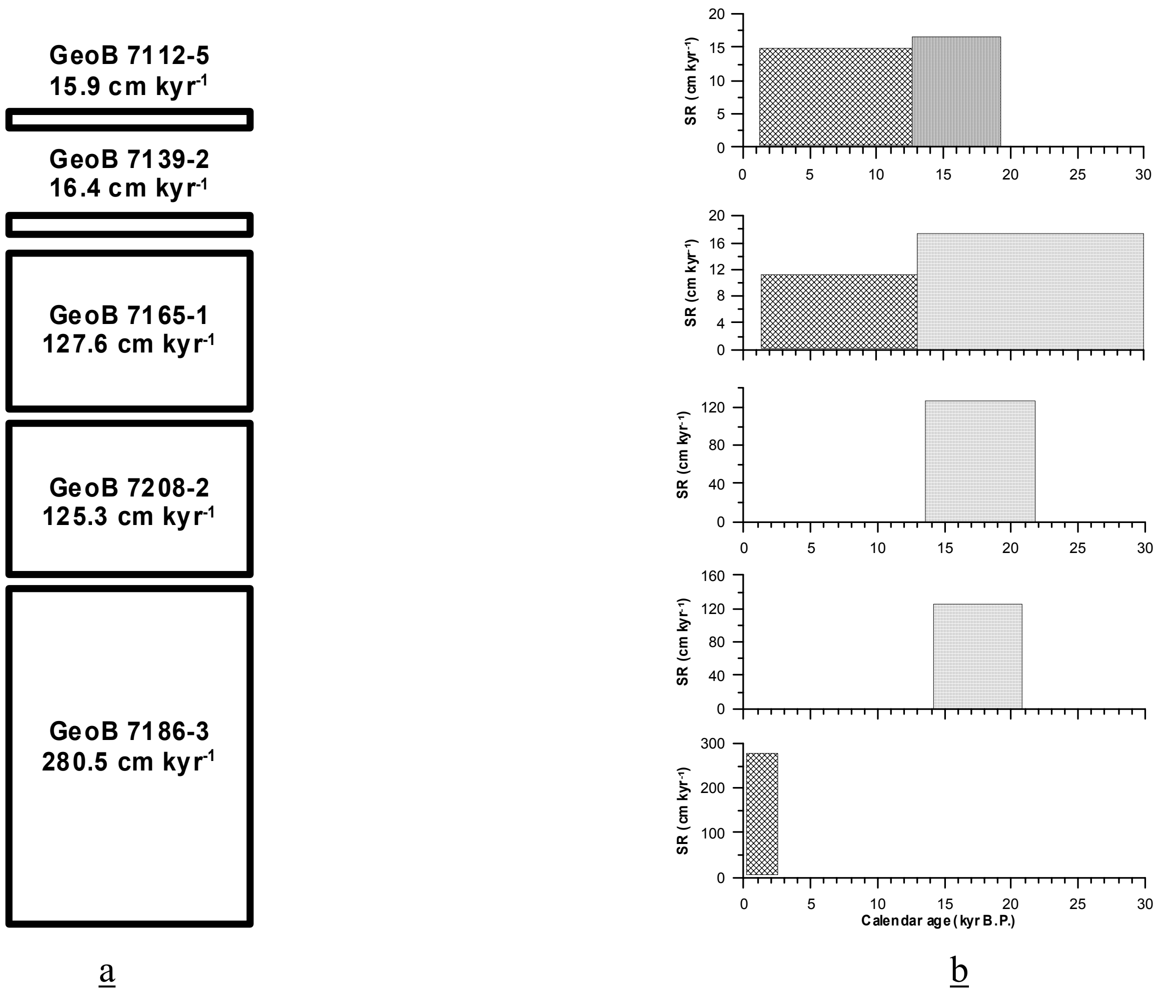

Fig. 7.3.2: a) Average sedimentation rates at the core sites (boxes), in cm per thousand years (cm kyr^{-1}), from N (above) to S (below). b) Average sedimentation rates divided into before (dotted) and after (dashed) the abrupt decrease in the sedimentation rates that occurred during the last deglaciation.

<u>Conclusions</u> **-** Sedimentation rates were considerably higher during the last glacial compared to the Holocene between 24° S and 39° S off Chile, which is most likely due to a northward shift of the climatic zonation resulting in enhanced onshore precipitation in central and northern Chile. The timing of the onset of a considerable drop in the sediment accumulation appears to be slightly asynchronous, occurring between 12 and 14 kyr B.P., with younger dates farther to the north. The sedimentation rates increase significantly from north to south (up to 30 times higher), which can be referred to higher precipitation in the continental hinterland and increased fluvial runoff.

7.4) Planktic foraminifera assemblages as paleoproductivity indicators

Introduction - The variability of ocean productivity can be traced by studying the qualitative and quantitative variations of primary and secondary producers, such as e.g. planktic foraminifera. Thus, one way to assess variations in paleoproductivity in the Peru-Chile Current is the downcore analyses of planktic foraminifera (>150 µm) which has been conducted on selected gravity cores: GeoB 7112-5 (24° 01.99' S, 70° 49.41' W, water depth 2507 m), GeoB 7139-2 (30° 12.00' S, 71° 59.01' W, water depth 3267 m), and GeoB 7186-3 (44° 08.96' S, 75° 09.49' W, water depth 1171 m). These cores cover a broad range of recent productivity with the extremes being on one hand core GeoB 7112-5, recovered from the northern Chile-upwelling area with a small terrigenous input, mainly of eolian origin, and relatively low productivity. In contrast, GeoB 7186-3 is retrieved from the southern non-upwelling area (see chapter 7.2), where a high terrigenous input mainly of fluvial origin dominates, in addition with the inflow of the nutrient-rich ACC waters allows nowadays a very high marine productivity in this area.

Relative species contribution - Six species account on average for 80-95% of the total planktic foraminiferal fauna in the investigated cores: *Neogloboquadrina pachyderma* sin, *N. pachyderma* dex., *N. dutertrei*, *Globorotalia inflata*, *Globigerina bulloides* and *Globigerinita glutinata* (Fig. 7.4.1). Examination of the species composition shows a high productive environment during the last glacial (>17 kyr B.P.), with high relative contributions of colder water species *N. pachyderma* sin. and *G. inflata* indicating a sub-polar planktic foraminifera assemblage. A distinct shift at 17-16 kyr B.P. to a less productive regime is evident. During the warming period between 17-16 kyr B.P. and 12 kyr B.P., the relative contributions of warmer water species such as *N. pachyderma* dex. and *N. dutertrei* increased rapidly, parallel to decreasing contributions of colder water species, although with different paces in each record. During the Early and Middle Holocene, the planktic foraminifera formed a "transitional" assemblage, with dominating warmer water species pointing to least productive conditions within the last 30,000 years. During the Late Holocene (<4 kyr B.P.), however, a drop in the relative contribution of *N. pachyderma* dex., accompanied with higher relative contributions of *G. bulloides* in the two northern cores suggest colder conditions, while periodically increasing contribution of *N. dutertrei* points to a stronger advection of warm, subtropical surface waters from the north, probably implying stronger El Niño activities within this period. Nonetheless, numerous fluctuations on a smaller scale (decadal to multi-decadal) during this period point to short term variability of the hydrographic conditions.

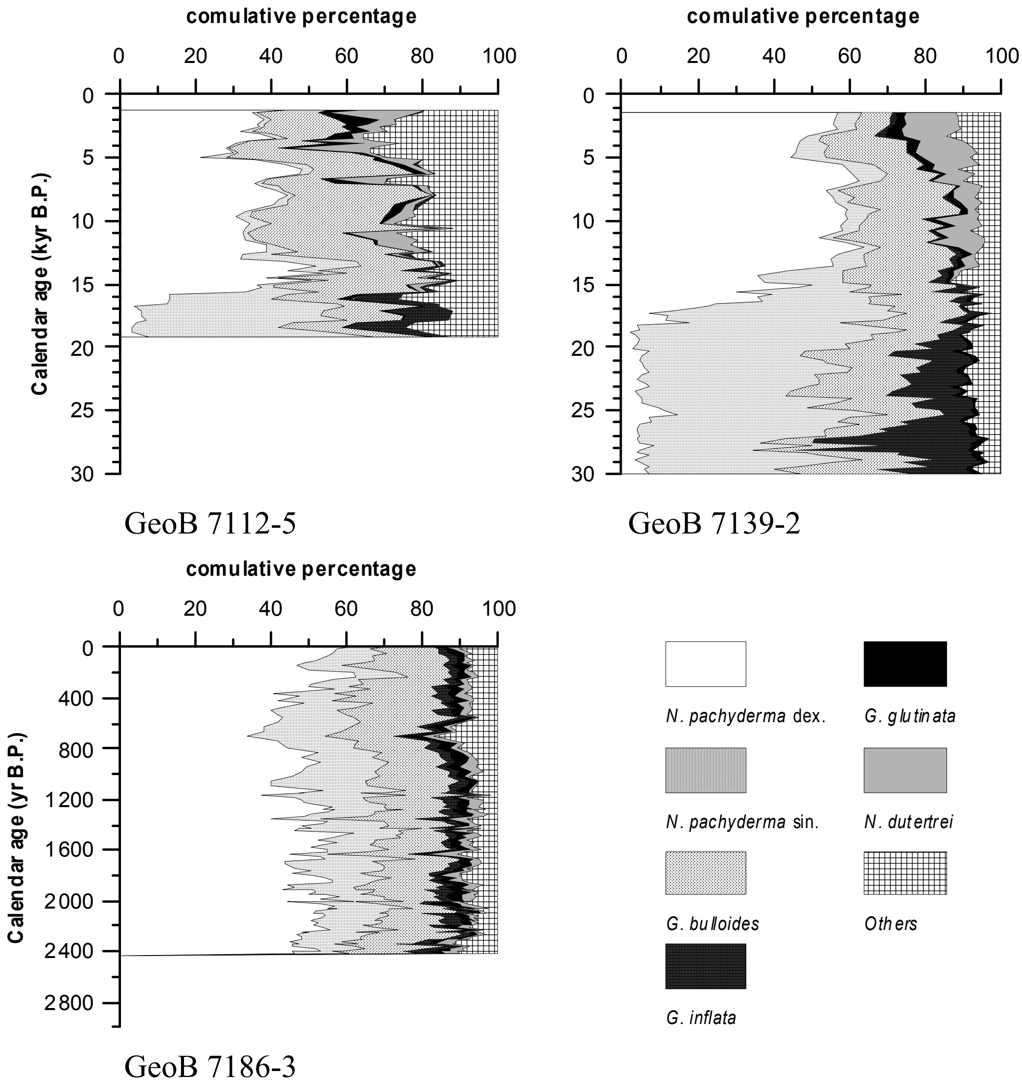

Fig. 7.4.1: Relative abundance of planktic foraminifera species at the investigated cores, given in percent (%). Note the different age scale for GeoB 7186-3.

<u>Planktic foraminifera accumulation rates</u> - A southward increase of the accumulation rates (AR) of planktic foraminifera is evident (Fig 7.4.2). This coincides with the present-day N-S gradient in productivity off Chile. Highest AR of planktic foraminifera are recorded during the LGM, between ~23 and ~16 kyr B.P. These high levels, mainly contributed to by *N. pachyderma* sin. and *G. bulloides*, indicate highest productivity within the last 30,000 years. A prominent boundary in the AR is recorded at ~16 kyr B.P., when the AR dropped to much lower values compared the LGM levels. Between 16 and 11 kyr B.P., *N. pachyderma* dex. shows its highest AR pointing to a considerable warming, which is associated with a lower productivity during this period indicated by the decrease in AR and by the species composition of the planktic foraminifera. Another distinct boundary is found at ~12 kyr B.P., when the AR dropped even further to very low Holocene values. During the Holocene, the AR decrease continuously towards present, while *N. pachyderma* dex. remains the species

with highest AR. For this period, we assume lower productivity and upwelling intensity compared to the LGM and the deglaciation. Interestingly, the very high-resolution core GeoB 7186-3 reveals a significant drop in the AR approximately 1000 years ago.

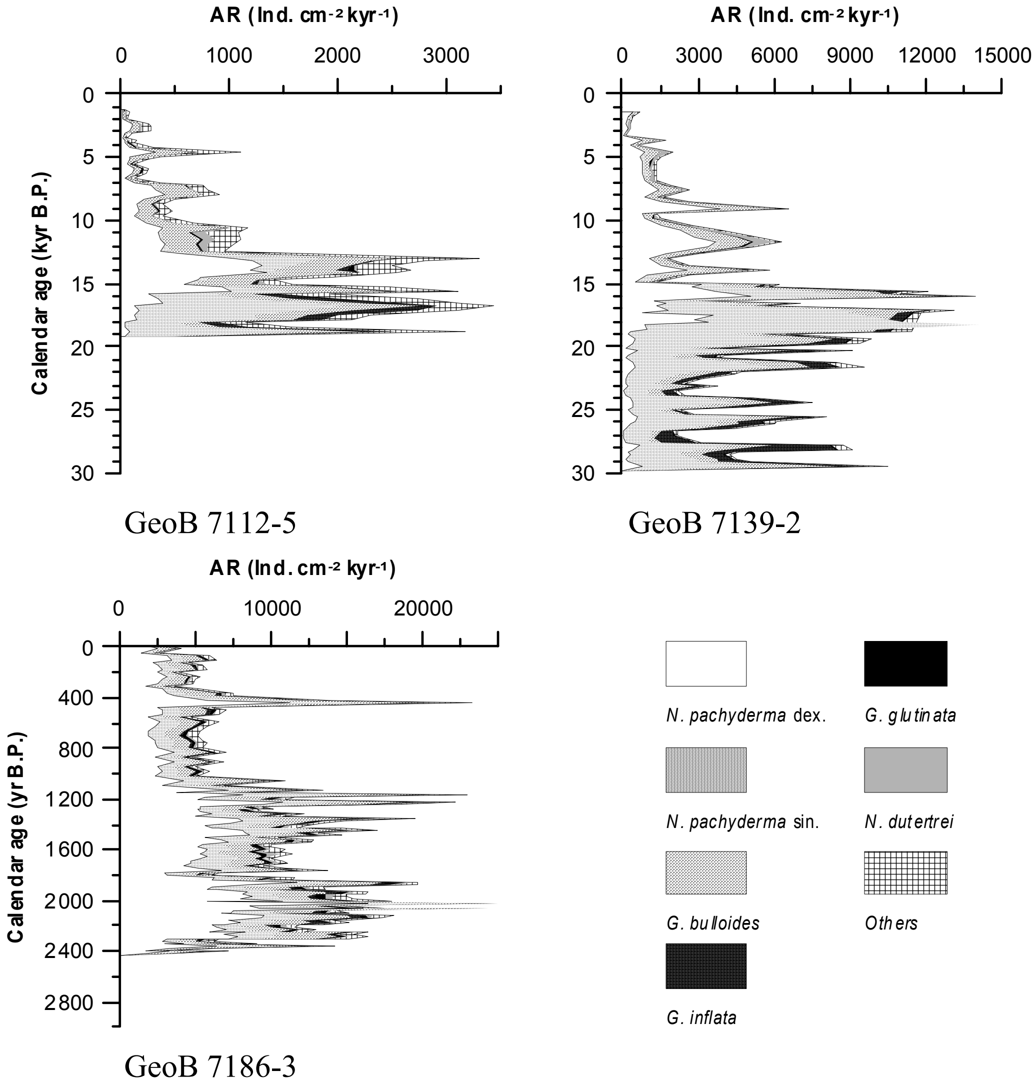

Fig. 7.4.2: Accumulation rates (AR) of planktic foraminifera species in the investigated sediment cores, given in individuals per square centimeter and thousand years (ind. cm-2 kyr-1). Note the different age scale for GeoB 7186-3.

<u>Timing vs. latitude</u> - Assuming that the ratio *N. pachyderma* sin./*N. pachyderma* dex. represents in a general sense the cold/warm ratio and also serves as a proxy for productivity, we can easily use this ratio to compare the development of the system through the last ~30 kyrs (Fig. 7.4.3). It appears that there is a dramatic shift towards warmer and less productive conditions between 16 and 17 kyr B.P., which occurred simultaneously at 24°S and 30°S.

Most likely this has to be attributed to a major global change related to the last deglaciation instead of only regional temperature/productivity changes.

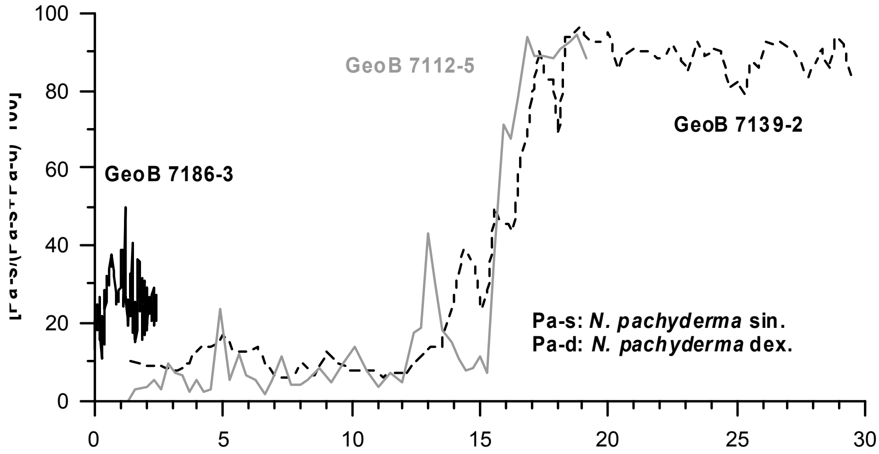

Fig. 7.4.3: Relation between N. pachyderma *sin. and* N. pachyderma *dex., given as normalized values between 0 and 100, in the investigated sediment cores for the last 30 kyrs. Solid black line represents GeoB 7186-3, solid gray line GeoB 7112-5, and dashed line GeoB 7139-2.*

<u>Conclusions</u> - Variations in the paleoproductivity through the last 30,000 years recorded in the Chilean continental slope sediments can be divided into four periods: (1) A highly productive period during the last glacial (>16 kyr B.P.), with high total accumulation rates of a “sub-polar” planktic foraminifera assemblage. (2) A period of lower productivity and weaker upwelling intensity during the deglaciation (17-12 kyr B.P.), with a “sub-polar” to “transitional” planktic foraminifera assemblage. (3) Lowest productivity during the Early and Middle Holocene (12-4 kyr B.P.), with lowest accumulation rates of a “transitional” planktic foraminifera assemblage. (4) Slightly enhanced productivity and upwelling intensity during the Late Holocene (<4 kyr B.P.).

7.5) Changes in productivity patterns and upwelling variability off northern Chile for the last 19,000 years: The downcore siliceous signal

Introduction - Like calcium carbonate and organic carbon, biogenic silica (opal) can be used to reconstruct past surface water processes. The global overall preservation efficiency of opal is close to 3%, more than one order of magnitude higher than the preservation efficiency for organic carbon. This is especially true in coastal upwelling regions, where sediments are high in opal content mainly due to the abundance of diatoms. The role of diatoms in the biological pump, the reasonably good overall preservation efficiency of opal as well as the global significance of the opal sedimentary record contribute to the idea that biogenic silica is a reliable paleoproductivity proxy in Eastern Boundary Currents (EBC), such as the Peru-Chile Current (PCC).

A high-resolution analysis on the downcore siliceous signal was performed in the gravity core GeoB7112-5 collected in the pelagic realm off northern Chile (24°02S, 70°49W, Fig. 7.5.1). We focus on the qualitative variations of the diatom community, and show how the variability of the hydrographic conditions and productivity pattern is indeed reflected by the biogenic silica and siliceous plankton accumulation rates, and the qualitative and quantitative composition of the downcore diatom assemblage.

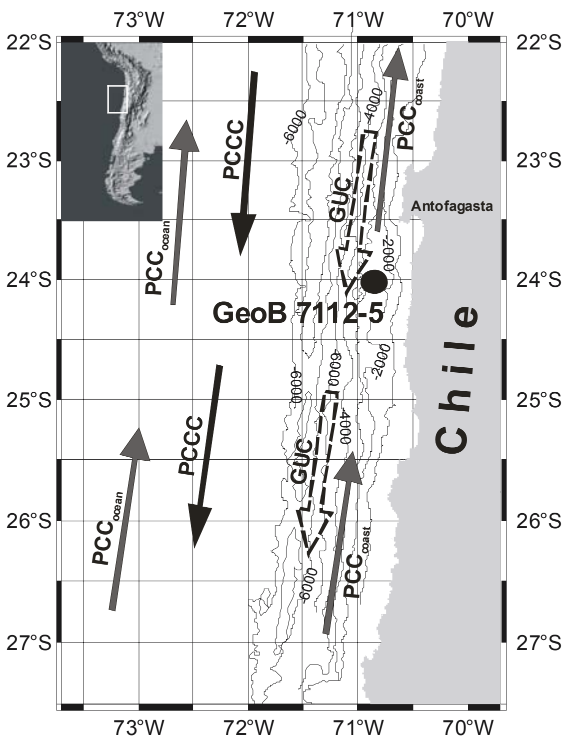

Fig. 7.5.1: Location of the GeoB 7112-5 (full dot) off northern Chile and the present-day water circulation pattern. Black and grey arrows: surface currents; dotted arrows: subsurface current. PCCcoast, Peru-Chile Current, coastal branch; PCCocean, Peru-Chile Current, oceanic branch; PCCC, Peru-Chile Countercurrent; PCCC, Peru-Chile Countercurrent; GC, Gunther Current.

Results and discussion - The biogenic sedimentation is dominated by calcium carbonate ($CaCO_3$), followed by biogenic silica (B_{si}) and organic carbon. The relative content of $CaCO_3$ fluctuated between ~5.4 and 27.3 %, opal varied between ~2.5 and 7.5%, while organic carbon content ranged between 1.8 and ~2.6 %. The accumulation rate of B_{si} ($B_{si}AR$) decreases stepwise from 19 kyr towards the begin of the Holocene: two very sharp decreases are observed, the first between ~15.5 and 14.8 kyr, and the second one around ~13 kyr (Fig. 7.5.2A). After reaching the lowest values between ~12.5 and 11.5 kyr, the $B_{si}AR$ increased moderately throughout mid Holocene, but became more abrupt around 5.6 kyr. After 4.3 kyr, the $B_{si}AR$ reached similar pre-Holocene values.

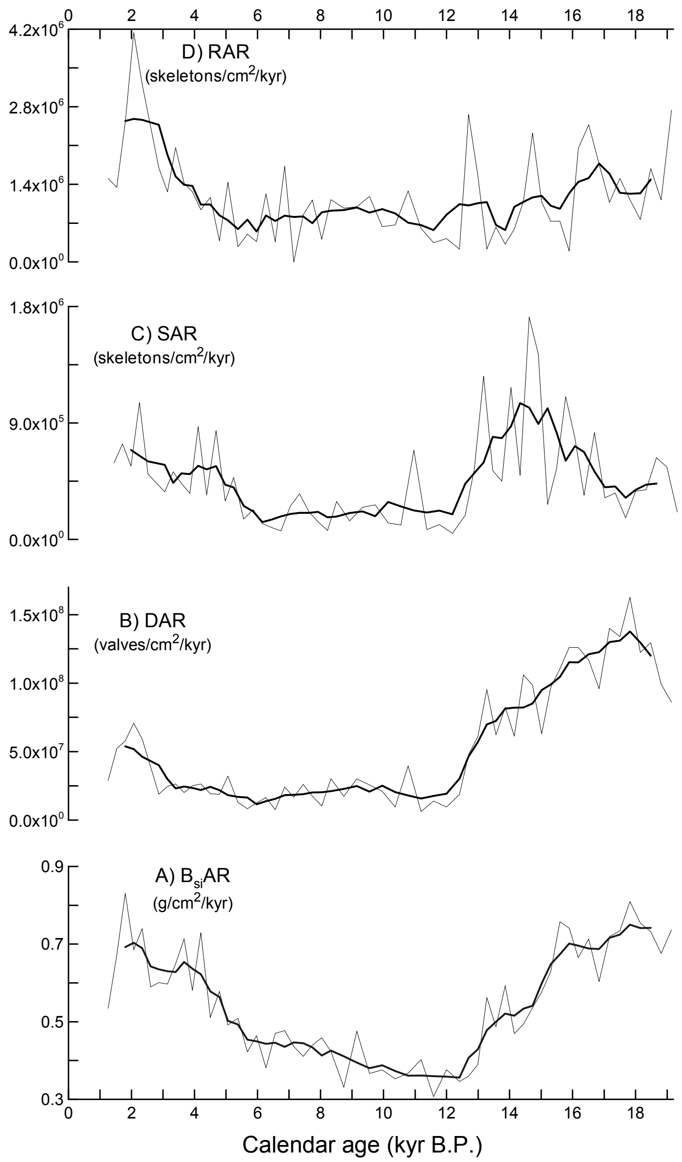

Fig. 7.5.2: Accumulation rate of (A) biogenic silica [$B_{si}AR$], (B) diatoms [DAR], (C) silicoflagellates [SAR], and (D) radiolarians [RAR] in GeoB7112-5 off northern Chile, SE Pacific Ocean. The bold line represents the 5-point running average.

The siliceous thanatocoenosis is dominated by primary producers (diatoms and silicoflagellates), whereas secondary producers appear as accompanying components. The accumulation rate of diatoms (DAR) ranges between 1.6 * 10^8 and 6.2 * 10^6 valves cm^{-2} kyr^{-1} (mean = 5.6 * 10^7 valves cm^{-2} kyr^{-1}, Fig. 7.5.2B). Silicoflagellate accumulation rate (SAR) is two orders of magnitude lower than DAR (range = 1.7 * 10^6-4.7 * 10^4 skeletons cm^{-2} kyr^{-1}, mean= 4.6 * 10^5 valves cm^{-2} kyr^{-1}, Fig. 7.5.3). The accumulation rate of radiolarians (RAR) ranges 4.1 * 10^6 and 2.0 * 10^5 skeletons cm^{-2} kyr^{-1} (mean = 1.2 * 10^6 valves cm^{-2} kyr^{-1}).

The highly diversified diatom assemblage, composed by 167 marine species, is dominated by the **coastal upwelling assemblage** (several resting spores of *Chaetoceros*, mean relative contribution ~83%, range 98.8-66.4%, Fig. 7.5.3A). Highest percentages are seen from ~19 till 13 kyr. At this time a significant reduction in the relative contribution of upwelling-associated *Chaetoceros* spores parallels well the decrease in DAR. From ~13 kyr toward the early Holocene, the contribution of upwelling diatoms increased again without reaching values recorded before ~13 kyr.

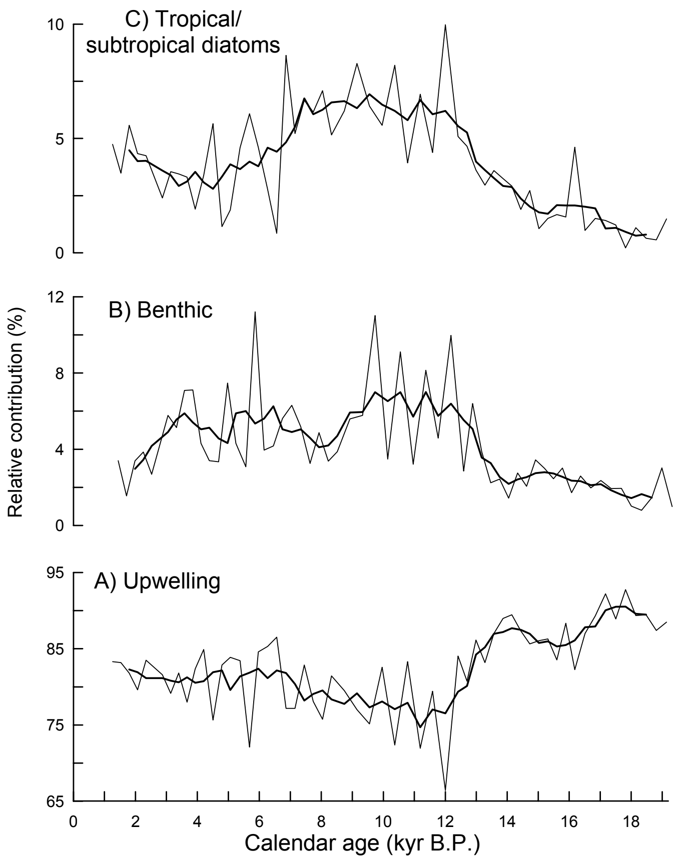

Figure 7.5.3. Downcore relative contribution (as percentage) of (A) coastal upwelling, (B) benthic and (C) tropical/subtropical diatom groups occurring at GeoB 7112-5 off northern Chile, SE Pacific Ocean. The bold line represents the 5-point running average.

Accompanying members of the diatom thanatocoenosis are **benthic** and **tropical/subtropical** species. Their average contribution remained below 4% till ~13 kyr, to abruptly increase afterward (Fig. 7.5.3B-C). Benthic diatoms show two maxima after 13 kyr: a first one between ~13 and 8.3, and a second, with slightly lower mean values, between ~7.7 and 1.8 kyr. Both periods are characterized by very strong variations in the percentages of benthic species. Two species of *Actinoptychus*, *A. senarius* and *A. vulgaris*, contribute the most to the benthic community, with *Grammatophora marina* and *Paralia sulcata* as secondary components. Warm water diatoms show the highest contribution between ~13 and 6 kyr. A slight increase is observed towards the Early Holocene. The highly diversified community of tropical/subtropical diatoms is dominated by *Fragilariopsis doliolus*, and *Azpetia tabularis*, accompanied by *A. barronii*, *Thalassiosira ferelineata*, and *Roperia tesselata*.

Large downcore variations in biogenic silica and siliceous plankton, in addition to the species dynamics of the diatom association, indicate considerable fluctuations in the hydrographical conditions off northern Chile at 24°S. Derived from different characteristics, we discuss the record divided in four time periods.

19-16 cal. kyr B.P.

Fully glacial conditions dominated at 24°S off northern Chile. During this late glacial period, considerably high $B_{si}AR$ and the highest upwelling diatom contribution indicate a very productive environment. The shallowing of the cold, nutrient-rich Antarctic Intermediate Waters (AAIW), flowing northward between 400 and 1700 m water depth, might have been determinant in causing permanent, strong upwelling. The AAIW presently approaches the surface during periods of intense upwelling. Stronger upwelling might have also been induced by a stronger temperature gradient between pole and equator, hence generating stronger winds and a northward shift of the climate zones. This, in turn, brought the ACC, as the main nutrient source, closer to the core location.

16-13 cal. kyr B.P.

The period of deglaciation was characterized by the onset of a considerable, rapid change to warmer, less productive conditions: DAR and SAR record a significant drop through this period towards very low Early Holocene values. Though the qualitative variations in the foraminifera assemblage probably reflect changes in the quality and quantity of subsurface waters (see Chapter 7.4), while the uppermost surface waters and the qualitative composition of siliceous plankton remain unaffected due to the strong upwelling. The global nature of this warming event off northern Chile agrees well with the timing of the ice core records from Taylor Dome and Siple Dome in west Antarctica, and from the Huascarán glacier in Peru.

13-5 cal. kyr B.P.

The increased contribution of tropical/subtropical diatoms, coupled with decreased contribution of upwelling diatoms (Fig. 7.5.3A), reflect weakest upwelling intensity during

Early and Middle Holocene at 24°S. Patterns of decreased productivity have been observed farther south along the Chilean coast, in good agreement with increased aridity in the coastal areas during Early and Middle Holocene. Decreasing productivity during this period point to a southward shift in the position of the climate zones, *i.e.* the Southern Westerlies and the circum-Antarctic circulation.

5-1 cal. kyr B.P.

The minor increase in the accumulation rate of opal and all siliceous organisms, and the relative abundance of upwelling diatoms points to an increased upwelling intensity and productivity as a consequence of changes in the hydrographical setting during the late Holocene. Land record variations evidence the transition from an arid, less productive Middle to a less arid, more productive Late Holocene. The foraminiferal assemblage in the youngest part of the GeoB7112-5 record suggests increased advection of warmer waters into this core area from the north, probably reflecting stronger El Niño events (see Chapter 7.4).

7.6) Reconstruction of paleotemperatures and paleosalinity

Introduction - Among various paleoceanographic parameters paleotemperature and paleosalinity stand out as the probably most important ones, as these parameters give direct information about the physical setting in former times and, thus, can directly be used to feed climate models. While there is a number of proxies providing information about paleotemperatures (assemblages of planktic foraminifera, $\delta^{18}O$, alkenones, etc.), proxies for paleosalinity are still rare. The most widely used approach so far is to use an independent temperature reconstruction, to put the result in the respective $\delta^{18}O$-paleotemperature equation and to solve this equation towards the $\delta^{18}O$ composition of the seawater which in turn is closely related to salinity.

Results and discussion - Here, paleo-sea surface temperatures (SST) have been reconstructed for the southern Peru-Chile Current (PCC) by means of the alkenone method. Such analyses have been carried out on the combined record 17748-4/GeoB 3302-1 (33°S), GeoB 3359-1 (35°S) and GeoB 3313-1 (41°S). While the first two records comprise Last Glacial Maximum (LGM) and Holocene sediments, the latter covers only the youngest part of the Holocene, i.e. the last 7800 years.

The two records reaching as far back as the LGM show a consistent picture. The range between the lowest LGM temperatures of ~11°C and the highest reconstructed temperatures for the Early Holocene of ~19°C is 8°C. Subrecent, Late Holocene temperatures recorded in core 17748-2 are in the order of 16°C, i.e. 3°C below the Holocene maximum (Fig. 7.6.1). Comparing these results with the $\delta^{18}O$ data reveals some differences. The glacial-interglacial difference in the $\delta^{18}O$ values is 1.9‰, which is 0.7‰ higher than the global ice effect of 1.2‰. Transferred into a rough paleotemperature estimate this indicates ~3°C colder SSTs compared to a difference of 8°C deduced from the alkenone method. This difference is most likely due to the fact that in this region the planktic foraminifera, on which the $\delta^{18}O$ data have been measured, live significantly deeper in the water column than the coccolithophores, which generate the alkenone signal. Consequently, the planktic foraminifera record much less temperature variability than the coccolithophores.

While both alkenone records from 33°S and from 35°S off Chile show an almost perfect fit for the LGM and for the deglaciation period, in terms of range and timing, a major discrepancy is observed between 13 kyr B.P. and 7.5 kyr B.P., when suddenly the record from 33°S dropped back to colder temperatures while the 35°S record stayed at a maximum level (Fig. 7.6.1). It may be speculated that the drop in temperature at 33°C is due to the extension of the Valparaiso upwelling cell as far out as the core site during this time, which would explain the significantly lower temperatures. However, the extension of the upwelling cell to the core site would also imply a significantly enhanced productivity, although all proxies indicate an extremely low paleoproductivity at this site for this period. Thus, up to now, there is no explanation for the rather cold paleotemperatures at 33°S in the Early Holocene.

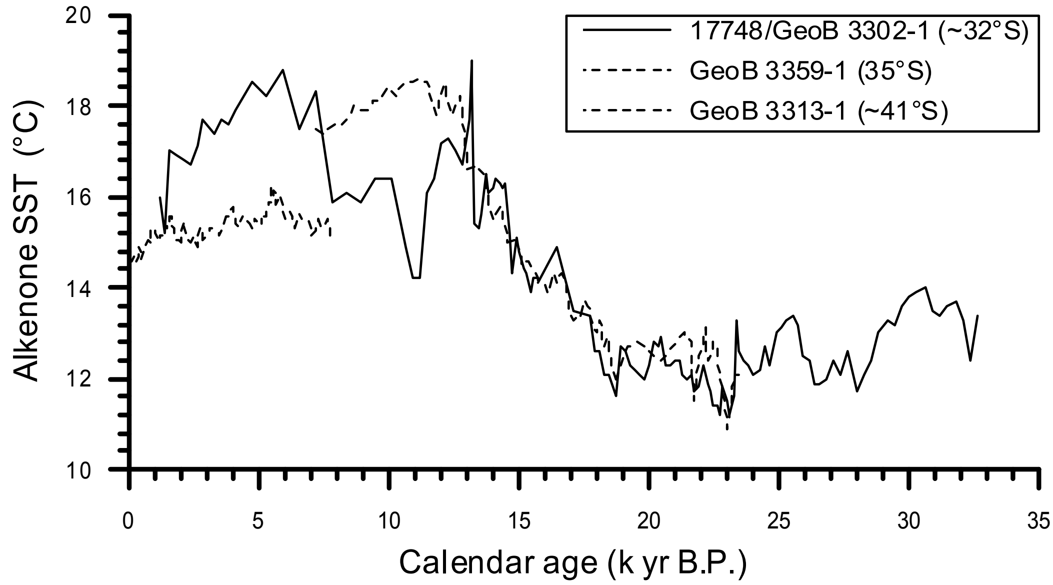

Fig. 7.6.1: Alkenone-based paleotemperature reconstructions for three cores from the Chilean continental margin.

Due to extremely high southern sedimentation rates at 41°S the available paleotemperature records only span part of the Holocene. They range from 14.2 to 16.2°C and increase from the beginning of the record at ca. 7800 calendar years B.P. (7800 B.P) towards maximum values around 5500 B.P. reaching 2°C above modern SSTs (Fig.7.6.1). Thereafter, temperatures show a general cooling trend especially during the last ca. 1500 years. Additionally, multi-century scale paleotemperature variations appear throughout the record, the most prominent occur shortly after 4000 B.P. and at ca. 1550 B.P.

For this southernmost site also paleo-sea surface salinity (SSS) reconstructions have been carried out. These estimates show variations between ca. 33 and ca. 36 psu with a significant scatter (Fig. 7.6.2). The observed scatter of the paleosalinity data is obviously induced by the oxygen isotope data which vary between ca. 0.6 and –0.15 ‰ PDB without any pronounced long-term trend (Fig. 7.6.2). As this scatter might be related to the environmental range of *N. pachyderma* (dex) resulting in varying depth habitats and seasonal preferences of individual foraminifera specimen, in the following only the smoothed record of reconstructed SSS (Fig. 7.6.2) is used and regarded as a qualitative estimate. The smoothed paleosalinity reconstruction indicates an increase from minimum values near 7000 B.P. towards a middle Holocene maximum near 5500 B.P. when paleosalinities were ca. 1.5 psu above modern values. Thereafter, paleosalinities generally declined towards the late Holocene including several short-term fluctuations which generally parallel short-term variations in paleotemperatures (Fig. 7.6.2).

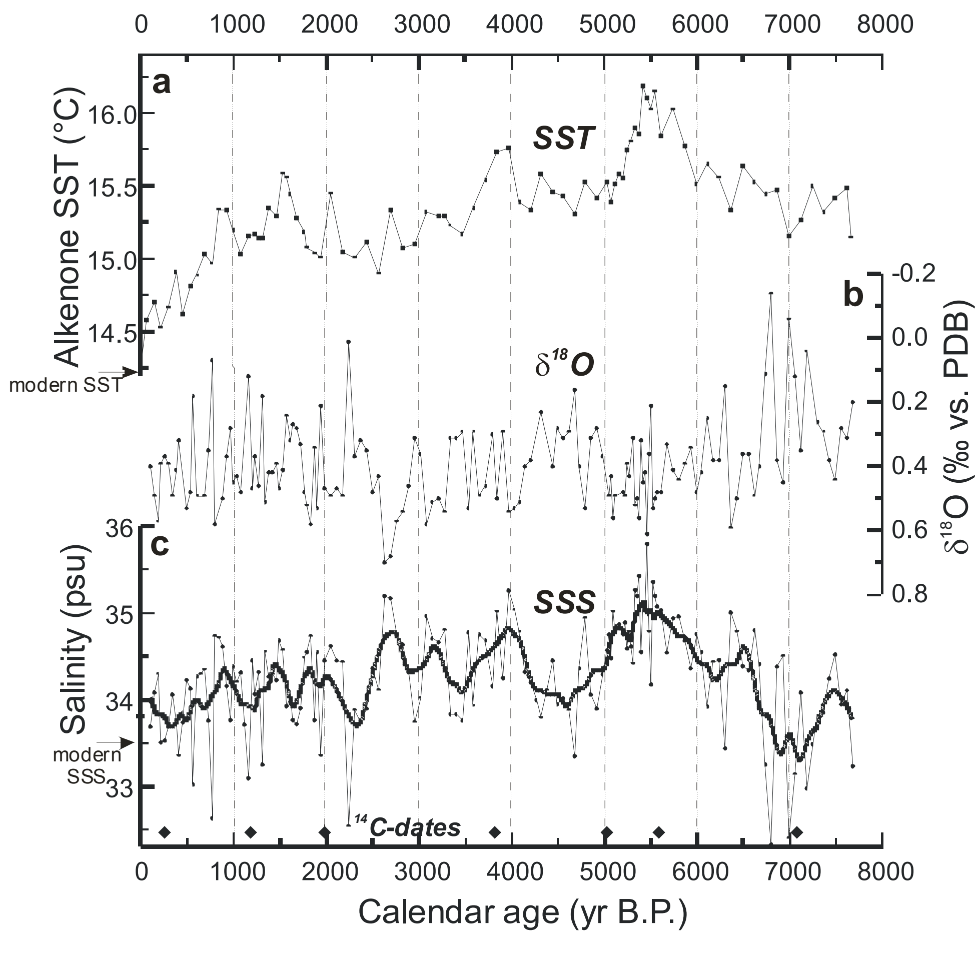

Fig. 7.6.2: Sea surface temperature (SST) and sea surface salinity (SSS) reconstructions in relation to $\delta^{18}O$ data obtained on N. pachyderma (dex) from core GeoB 3313-1 (41°S).

Paleotemperature and -salinity estimates for the southern PCC show a significant long-term trend which corresponds to continental rainfall changes. The observed long-term evolution is primarily attributed to (1) latitudinal displacements of the Antarctic Circumpolar Current (ACC) and the southern westerly wind belts possibly caused by insolation-induced long-term changes in large scale Southern Hemisphere atmospheric circulation patterns (e.g., Hadley cell intensity) and (2) global SST variations due to planetary albedo changes combined with long-term variations in the strength of the Atlantic thermohaline circulation leading to temperature changes especially around Antarctica.

Higher paleotemperatures and salinities during the middle Holocene (8000-4000 B.P.) most likely indicate a decreased advection of cold subpolar water masses through the ACC combined with diminished advection of low-salinity Chile Fjord Water and/or reduced supply of freshwater to the Chilean fjord region through decreased continental rainfall. Together with other continental paleoclimate records from both central Chile (33°S) and southern Chile (43°S), this record indicates reduced rainfall during the middle Holocene, most likely caused by a poleward shift of the Southern Westerlies. As the modern location of this wind-belt is strongly related to the steepest SST gradients within the ACC, less advection of ACC-derived water masses most likely implies a further southward location of this current system.

7.7) The characterization of sedimentary organic matter underlying low oxygen water masses

Introduction - Sediments from coastal upwelling regions are known for their high organic carbon content. This is in part due to the high productivity of the surface waters. Oxygen deficiency in the water column and at the sediment-water-interface supports the preservation of organic detritus. The aim of this study was to characterize the composition of the sedimentary organic matter with respect to sources and state of degradation.

Material - For this study we concentrated on the uppermost sediment layer, retrieved by multicorer sampling. We chose a total of eight sampling sites located on two transects across the shelf-slope-area, one off Antofagasta (23°) and the other off Concepción (36°S). Both areas comprise active upwelling cells.

Table 1: List of stations chosen for organic-geochemical investigations.

station	latitude	longitude	water depth [m]	core length [cm]	bottom water O_2 [ml/l]
transect at 23°S					
GeoB 7103	22°51,99 S	70°32,54 W	891	26	1.00
GeoB 7104	22°52,00 S	70°29,42 W	307	26	0.15
GeoB 7106	22°48,00 S	70°36,70 W	1350	22	1.18
GeoB 7108	22°50,50 S	70°34,79 W	1007	13	n. d.
transect at 36°S					
GeoB 7160	36°02,33 S	73°04,39 W	367	30	0.16
GeoB 7161	36°25,51 S	73°23,32 W	126	26	0.01
GeoB 7162	36°32,52 S	73°40,02 W	798	22	2.36
GeoB 7163	36°25,55 S	73°35,71 W	536	18	2.30

Bulk composition - The total organic carbon (TOC) concentration in the investigated sediments ranged from 1.5% to 12.4%. On both transects highest TOC concentrations were found in sediments from the oxygen minimum zone (GeoB 7104, GeoB 7161, and GeoB 7160). In most sediment cores we observed a slight overall decrease of the organic carbon content with sediment depth reflecting the ongoing degradation of organic matter (Fig. 7.7.1). This is especially true for the sediments sampled on the more southern transect off Concepción (Fig. 7.7.1a) indicating a constant sedimentation history in this region for the time period recorded in the core length sampled (estimated to ~300 years). On the more northern transect off Antofagasta, where sedimentation rates are at least one order of magnitude lower than at 36°S, the TOC-profiles at sites GeoB7103 and GeoB7108 also show an undisturbed depth trend (Fig. 7.7.1b). Taking into account the estimated time span recorded in these cores (2000-3000 years) this is a remarkable finding. At site GeoB 7104 the present surface TOC concentration is more than twice lower than TOC values in deeper parts of the sediment (5.1% versus 12.4% of sediment dry weight, Fig. 7.7.1b). The depth trend indicates that at this location the depositional conditions changed significantly over time. These long-term changes might be attributed to changing currents, moving position of upwelling cells, increasing water depth, and the location of the OMZ and thus might reflect changes coupled to longer-term climatic variations.

Total inorganic carbon (TIC) concentrations are lower than 0.1% of sediment dry weight for most samples retrieved off Concepción. Off Antofagasta TIC contents are higher (up to 2.2%), probably due to less dilution of the pelagic carbonate flux by terrigenous material from the hinterland desert and a lack of fluvial input in this region.

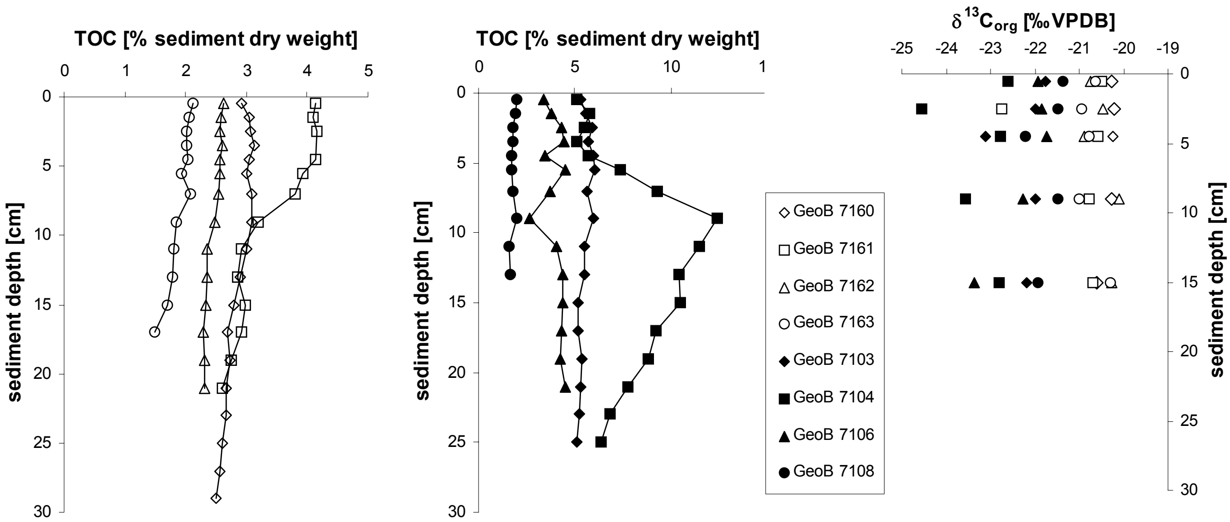

Fig. 7.7.1: Depth profiles of total organic carbon (TOC) concentration in sediment cores off Concepción (a) and off Antofagasta (b) and isotopic composition of the organic carbon (c).

<u>Organic matter sources</u> - The C/N-ratio and the isotopic composition of the organic carbon provide information on the source of the organic material in the sediments. Terrestrial organic matter typically has C/N-ratios higher than 20 while low C/N-ratios of 5-7 are characteristic for fresh marine material. Preferential degradation of N-containing compounds during early diagenesis causes an increase of the C/N-ratio to values of up to 10. Measured C/N-values for samples from the sediment surface range from 8.6 to 10.3 off Antofagasta and from 9.3 to 10.0 off Concepción indicating a predominating marine source of the organic matter at all sampling locations.

The carbon isotopic composition of the organic material provides further information on its origin. Whereas relatively heavy carbon isotope values (-22‰ to -19‰) are characteristic for marine organic matter, terrestrial organic matter shows values of –28‰ to –25‰. The $\delta^{13}C_{org}$-values measured were lower in sediments off Antofagasta (Fig. 7.7.1c). As several factors affect the isotopic composition of marine plankton, the observed distribution might in part reflect differences in water temperature, dissolved CO_2-concentrations, phytoplankton growth rates, and species composition. The net input of terrestrial organic matter at 23°S should be significantly lower than at 36°S and thus the more negative isotopic composition of the total organic carbon probably is the result of overall low sedimentation rates off Antofagasta. The more effective degradation of marine organic matter in the sediments leads to an enrichment of terrestrial relative to marine organic carbon. Since sedimentation rates are about 10 times lower in the North, the sediments are older and more of the originally deposited marine organic material is remineralised prior to burial.

As the bulk composition did not reveal a significant terrestrial contribution we looked for more specific indicators. Long-chain n-alkanes (C_{25}-C_{35}), n-alcohols ($>C_{24}$), and fatty acids ($>C_{22}$) are tracers for terrestrial organic material. Concentrations of n-alkanes and n-alcohols were low in all investigated samples. We identified a series of C_{14}-C_{20} n-alkanes with a maximum at C_{17}, while the only n-alcohols detected in all samples are C_{16} and C_{18}. Fatty acids were found in higher concentrations in the range C_{11}-C_{32} with C_{16} being the dominant fatty acid in all samples. There are indications that algae can produce small amounts of C_{20}-C_{30} fatty acids and thus the long-chain fatty acids in the investigated sediments might be of marine origin.

<u>Algal biomarkers</u> - Further information on the origin of the sedimentary organic matter can be drawn from sterol compounds specific for special phytoplankton groups. Brassicasterol (24-methylcholesta-5,22-dien-3?-ol) has been frequently used as a biomarker for diatoms as it represents over 90% of the sterols in most species of this algal class. 24-methylenecholesterol is another specific compound of diatoms, while dinosterol has been used as an indicator of dinoflagellate contribution to marine sediments. In all investigated samples from the sediment surface brassicasterol was higher concentrated than dinosterol (ratio up to 2.3) indicating the predominance of diatom biomass. Fig. 7.7.2a shows the good correlation of the diatom biomarkers brassicasterol and 24-methylenecholesterol. The strong correlation of the diatom derived sterols and the phytoplankton pigment derived phytol (Fig. 7.7.2b) indicates that the phytoplankton community is dominated by diatoms whereas the distribution of dinosterol does not reflect a significant contribution of dinoflagellates to the phytoplankton biomass.

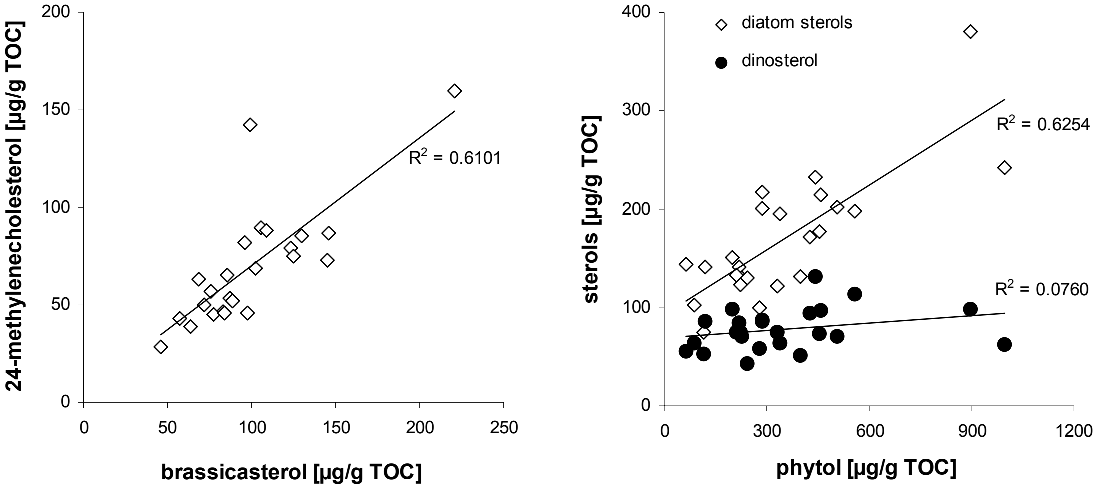

Fig. 7.7.2: Correlation of the diatom derived sterols 24-methylenecholesterol and brassicasterol (a) and the sum of both diatom sterol concentrations versus phytol concentrations (b). Dinosterol distribution is shown for comparison. The data plotted comprise samples from 0-1 cm, 2-3 cm, and 4-5 cm sediment depth.

<u>Bacterial biomass</u> - The fatty acid fractions in sediment surface samples comprise 15 to 30 % of the bacteria specific iso- and anteiso-fatty acids and bishomohopanoic acid. These biomarkers derive from *in-situ* produced as well as from imported bacterial biomass from the overlying water column. The samples from the oxygen minimum zone exhibit higher proportions of 10-methyl-16:0 fatty acid compared to the sediments underlying more oxygenated bottom waters (Fig. 7.7.3a). So far 10-methyl-16:0 has only been reported for sulfate- and iron-reducing bacteria of Desulfobacter- and Geobacter-species. For GeoB 7161 the depth profiles of measured sulfate reduction rates and the concentration of the bacterial specific iso- and anteiso-fatty acids show a good correlation. It is not clear whether the enhanced concentrations of bacterial biomarkers are a measure for input from the water column or if they reflect *in-situ* produced bacterial biomass. For GeoB 7161 the depth profiles of measured sulfate reduction rates and the concentration of 10-methyl-16:0 show a similar shape indicating that this fatty acid reflects the abundant sulfate reducing bacteria (Fig. 7.7.3b).

<u>Organic matter freshness</u> - Chlorin concentrations provide information on the amount of phytoplankton detritus reaching the sediment. Average chlorin-concentrations range from 10 µg/g sediment dry weight in 1350 m water depth (GeoB 7106) to 23 µg/g sediment dry weight in 126 m water depth (GeoB 7161). The measured concentrations are comparable to chlorin-contents determined for sediments from the upwelling regions off Peru (SO 147) and off Namibia. The Chlorin-Index provides a measure to assess the freshness of the

phytodetritus. Values range from 0.67 to 0.69 for sediments from water depths deeper than 500 m and reach values of 0.58 (GeoB 7161) and 0.59 (GeoB 7104) in samples from the OMZ. Higher values indicate a higher proportion of more degraded pigments, whereas fresher material is characterized by smaller ratios.

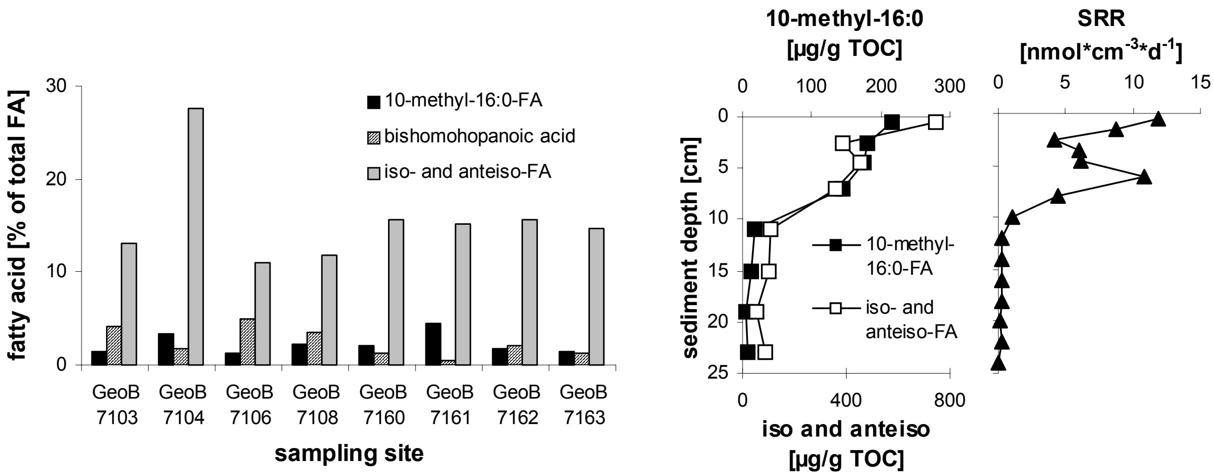

Fig. 7.73: Concentrations of bacterial specific fatty acids in samples from the sediment surface (a) and depth profiles of iso- and anteiso-fatty acids, 10-methyl-16:0-fatty acid, and sulfate reduction rates (SRR) in GeoB 7161 (b).

Summary - The surface sediments retrieved from different water depths off Antofagasta and off Concepción did not reveal any contribution of terrestrial organic material. The abundance of diatom biomarkers in the sediments reflects that diatoms are the main source of the marine input of organic matter. Chlorin-concentrations are in the typical range for sediments from coastal upwelling regions. In sediments deposited under oxygen-deficient conditions the phytodetritus appears to be less degraded than in sediments underlying more oxygenated bottom waters. Specific biomarkers of selected bacteria are enhanced in sediments deposited within the OMZ either reflecting a better preservation of deposited organic material or tracing *in-situ* produced biomass.

7.8) The microbiology and biogeochemistry of the deep methane-sulfate transition

Introduction - Anaerobic oxidation of methane (AOM) is a microbial process of the methane-sulfate transition zone, which is mediated by a consortium of methane-oxidizing archaea and sulfate-reducing bacteria. During AOM methane is oxidized with sulfate via the following overall equation:

$CH4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$ (Eq. 1)

Under alkaline conditions, authigenic carbonates may form by the following reaction:

$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3$ (Eq. 2)

In contrast to methane seeps, where high upward directed fluid flow and methane ebullitions lead to a fast depletion of sulfate and a simultaneous removal of methane within the surface sediment (0-10 cm), the sediments of the Chilean continental margin are dominated by diffusion and show a deep methane-sulfate transition. It was the aim of the present study to investigate the microbiology and fate of methane in a diffusive system.

Materials and Methods - Sediment samples from different water depths (796, 1169, 2745 and 4640 m) were taken by gravity cores along the Chilean continental margin and deep sea basin (Tab. 1). Prior to the main sampling, the intact cores were investigated for methane (gas chromatography), hydrogen sulfide (electrode), temperature (thermometer), pH (electrode) and porosity (electrode). This was made possible by cutting small windows into the liner (20 cm intervals), which were closed gas-tight after the sampling. Subsequently the core was cut into subunits according to the methane concentration, i.e. the methane-sulfate transition was kept in one unit whereas the units above and below that zone were cut into 1 m (or smaller) units. Samples for AOM and sulfate reduction (SR) were taken in short intervals (2 or 10 cm) within the transition and in larger intervals (20 or 40 cm) above and below the transition. Samples for sulfate and carbon were taken in 20 cm intervals. AOM and SR were determined with ^{14}C-methane and ^{35}S-sulfate radiotracer measurements. Pore water sulfate concentrations were determined by non-suppressed ion chromatography. Total carbon (TC) was determined by combustion/gas chromatography. Total inorganic carbon (TIC) was measured on a CO_2 Coulometer after acidification with H_3PO_4. Total organic carbon (TOC) was calculated as the difference of TC and TIC. Additional samples were taken for the identification of the AOM consortium with molecular methods.

Results and Discussion - Depth profiles of AOM, SR, methane, sulfate, sulfide, pH, TC, TIC, and TOC are shown in Fig. 7.8.1. All cores revealed a distinct methane-sulfate transition wherein methane was strongly depleted towards the surface and sulfate decreased with depth. The location of the methane-sulfate transition, defined as the zone between rapid increase of methane concentration (upper boundary) and depletion of sulfate (lower boundary), as well as methane and sulfate turnover via AOM and SR differed between the cores:

Core GeoB 7165-2, water depth 796 m - The methane-sulfate transition was located between 260 and 365 cm. Single peaks of AOM (51 nmol cm^{-3} d^{-1}, 365 cm) and SR (1.1 nmol cm^{-3} d^{-1}, 355 cm) were found within the steepest change of methane concentration. The peaks of AOM and SR were located in two different but successive sections. AOM, at its maximum, exceeded SR extremely. This does not agree with the stoichiometry of the two processes (see Eq. 1), but the partly high deviations of rates, even within AOM replicates (0.3 compared to 52 nmol cm^{-3} d^{-1} in two replicates at 365 cm), presume a high patchiness in this core. The methane-sulfate transition was accompanied by an increase of sulfide (due to SR), reaching a maximum concentration of 1.8 mM at 380 cm. Within and below the methane-transition three peaks of inorganic carbon were detected (295, 375 and 455 cm). They appear to represent authigenic carbonates formed as a result of AOM (see Eq. 2). The carbon isotopic composition of the total inorganic carbon (TIC) and the dissolved inorganic carbon (DIC) in the pore-water provides evidence for an authigenic origin of the carbonate enrichments. Minimum $\delta^{13}C$ values of -14.6‰ for the TIC were found in 375 cm and in 455 cm sediment depth. The carbonate peak at 455 cm could represent a former location of the AOM zone. Sedimentation processes presumably forced the methane-sulfate transition to slowly migrate upwards leaving carbonate signals at their prior location behind. The actual zone of AOM is reflected in the isotopic composition of the DIC, reaching –24.6‰ in 335 cm and in 375 cm sediment depth.

Core GeoB 7186-2, water depth 1169 m - The methane-sulfate transition was located between 110 and 290 cm. In contrast to core GeoB 7165-2, AOM and SR were not restricted to a distinct section within the methane-sulfate transition but occurred over its whole extension and increased with depth (AOM between 0.68 (115 cm) and 1.8 nmol cm^{-3} d^{-1} (270 cm), SR between 0.12 (115 cm) and 0.87 nmol cm^{-3} d^{-1} (270 cm)). The peak rates and discrepancies between AOM and SR were much lower compared to the shallower core GeoB 7165-2. Possibly the centering of AOM on a small depth zone at core GeoB 7165-2 results in elevated rates with a higher patchiness compared to core GeoB 7186-2. The methane-sulfate transition was also accompanied by elevated sulfide concentrations reaching a peak of 27 µM at 150 cm.

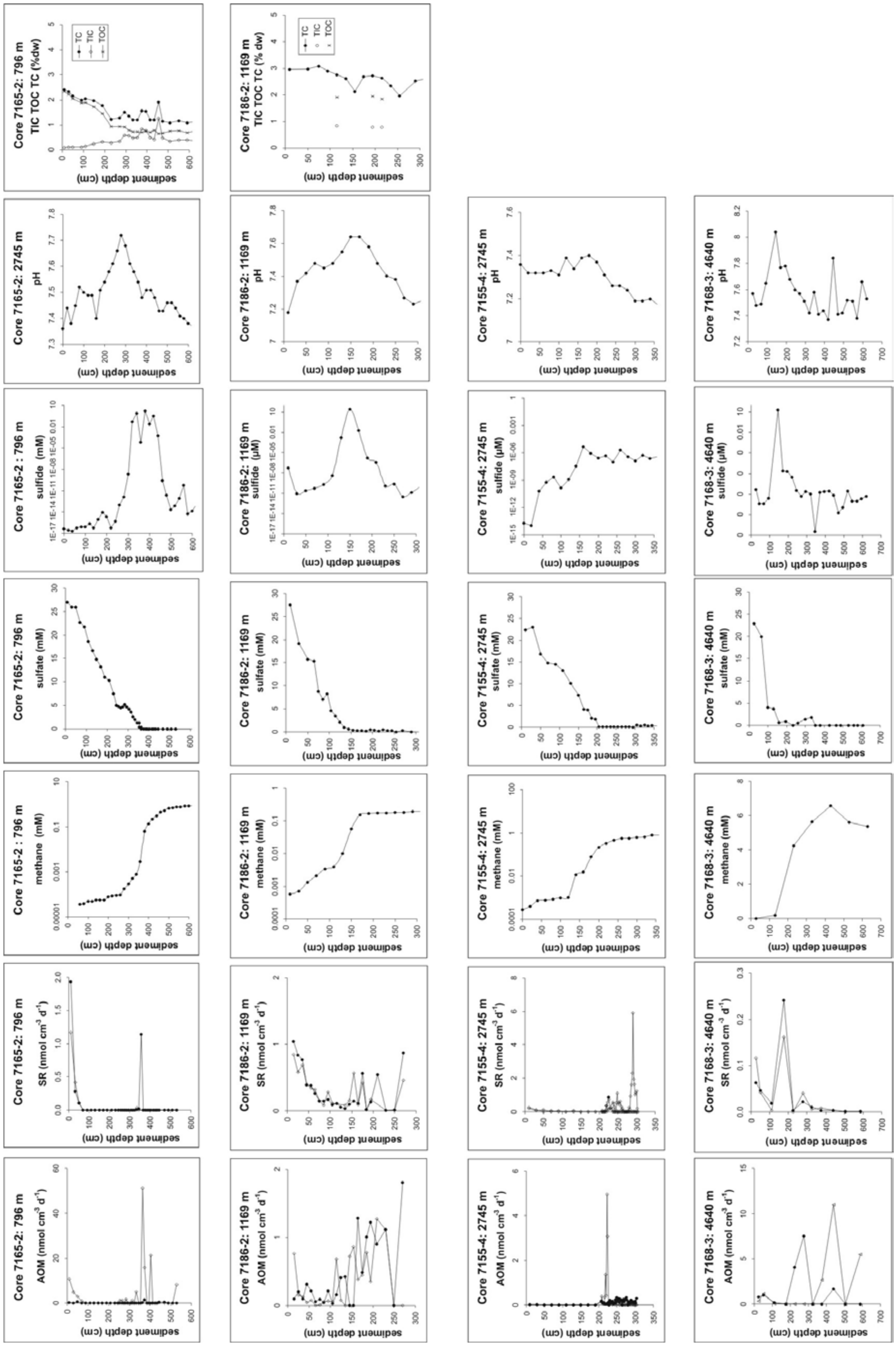

Fig. 7.8.1: Data profiles of the investigated gravity cores.

Core GeoB 7155-4, water depth 2745 m - The methane-sulfate transition was located between 120 and 350 cm. AOM and SR activity was found in the zone below the steepest increase of methane (206-304 cm) were sulfate revealed very low concentrations (around 0.2 mM). The peaks of AOM and SR mismatched (AOM 5 nmol cm^{-3} d^{-1} at 222 cm, SR 6 nmol cm^{-3} d^{-1} at 290 cm) but the averaged consumption of methane and sulfate between 206 and 304 cm agreed well (around 0.2 nmol cm^{-3} d^{-1} (± 0.6) for AOM and 0.3 nmol cm^{-3} d^{-1} (± 0.7) for SR). Sulfide increased with depth and reached its maximum at 160 cm ($5 * 10^{-6}$ µM) where it stayed relatively constant. The amount of sulfide was much lower compared to the cores GeoB 7165-2 and GeoB 7186-2.

Core GeoB 7168-3, water depth 4640 m - Considering the deep-sea location of this core the methane-sulfate transition was situated relatively close to the surface (between 130 and 355 m). AOM was also higher than expected as it exceeded the peak rates of the shallower cores 7186-2 and 7155-4. AOM occurred between 225 and 588 cm with rates ranging between 1.7 and 11 nmol cm^{-3} d^{-1}. It may proceed deeper but due to the short core length we were not able to measure AOM in deeper parts of the sediment. SR in the zone of AOM was between two and three orders of magnitude lower compared to AOM (between 0.003 and 0.04 nmol cm^{-3} d^{-1}). This finding can not simply be explained by patchiness. It is unusual that AOM exceeds SR in these dimensions. AOM, to our knowledge, only coexists with an equal turnover of sulfate. It can not be stated at this moment whether the reasons for the observed discrepancy are methodical or microbial. Usually, the measurements of AOM and SR with radiotracers show a good reproducibility when sediments are homogenous. The sulfide profile showed a maximum at 145 cm (19 µM) in the zone of the steepest methane increase. A minimum of $4 * 10^{-17}$ µM was located at 320 cm. At this depth the sediment showed a very dark colour pointing to the formation of metal sulfides.

Summary **-** Compared to fluid impacted methane seeps, the methane-sulfate transition of the Chilean continental margin is located much deeper in the sediment, starting at depths between 110 and 260 cm, and reaches larger dimensions in most cases. Only at core GeoB 7165-2, AOM was restricted to a small sediment section of about 20 cm. The rate of AOM is between one and three orders of magnitude lower compared to methane seeps. In all cores, methane was reduced to very low concentrations or even zero before it reaches the sediment surface. Therefore AOM represents an effective filter, removing methane above its production zone.

7.9) Microbiological analyses of deep-sea sediments

Introduction - Both cultural and molecular approaches were used to describe the prokaryotic diversity of sediment samples as a function of depth below the sea floor. During this work, we focused on samples obtained from a gravity core taken from 4650m of water depth (GeoB 7168-3; Pos: 37°24.00'S 74°30.83'W, core length: 634cm)

Sampling - To minimize the risk of contamination, the intact gravity core was aseptically sub-sampled, immediately after coring on board, with sterile 5 ml plastic syringes at seven depths (30, 120, 225, 325, 425, 525 and 625 cm). Syringes were immediately transferred into an anaerobic (argon gas) glove box (glove bag I2R, Bioblock). Sub-samples were two fold diluted into anaerobic synthetic sea water adjusted to pH 7 and reduced with Na2S. In addition, sub-samples were removed from the center of the core with sterile glass syringes of 50ml for direct DNA extractions. Both crude and diluted sediment samples were stored at 4°C.

Enrichment cultures - All enrichments were performed in 50ml penicillin vials sealed with butyl rubber septa and aluminium crimp tops. Enrichment cultures were performed using five modified anaerobic liquid media designed for:

-sulfate-reducer (Medium SRB),

-methanogen (medium MOM),

-heterotroph sulfur-reducer (medium YPS).

Prior to inoculation, autoclaved media were dispatched into vials and initial vial preparation involved sequential evacuation and gassing with N2 (100%) 100kPa (YPS medium) or H2 (80%)/CO2 (20%) 200kPa (SRB and MOM media) in the vial headspace. Sediment suspensions were inoculated (1% v/v) in each medium and incubated at 20°C and 50°C. All sediment samples from site GeoB 7168-3 were tested for growth. Enrichments obtained after 3 to 70 days of incubation are listed in Table 7.9.1.

DNA extraction from crude samples - DNA extractions were performed by using commercial DNA extraction kit as recommended in the manufacture's instructions on 5g and 10g of crude sediment to avoid humic acid contamination (UltraClean soil DNA, kit mega prep., MoBio, Solana Beach CA, USA). Relatively high quantities of DNA were obtained which presumably reflects the high biomass in these samples (Fig. 7.9.1).

Table 7.9.1: Enrichment cultures from GeoB 7168-3.

Depth (cmbsf)*	media	Incubation Temp. (°C)	Incubation time (days)	***Dominant cell type***
30	YPS	20	3	Long and large rods
120	YPS	20	4	Long rods and cocci
225	YPS	20	20	Long thin rods and large short rods with inclusions
	YPS	50	10	Long thin rods
325	YPS	20	20	Long thin rods and large short rods with inclusions
	YPS	50	10	Long rods
	MOM	50	70	Lemon shaped cells
425	YPS	20	40	Long thin rods and large sporulating rods
625	YPS	20	40	Long thin rods
	SRB	50	70	Short and long thin rods

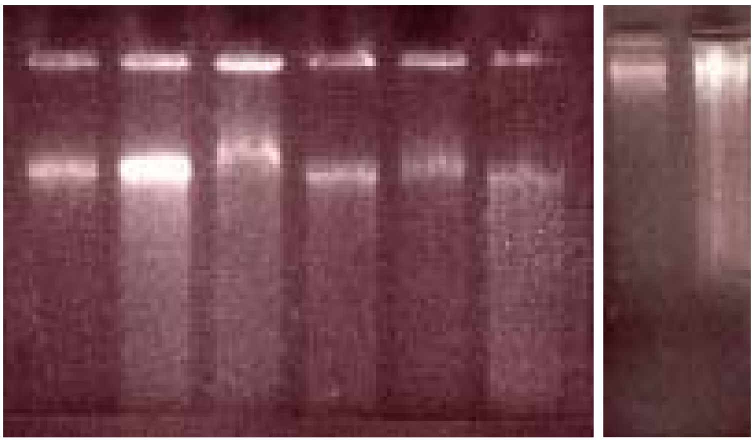

Fig. 7.9.1: Gel electrophoresis of DNA extracted from 5g and 10g of GeoB 7168-3 sediments.

PCR amplification of 16S rRNA genes, cloning and sequencing - DNA obtained from samples at 120 cm and 625 cm were used as template DNA for PCR in order to compare shallow and deep sediments. Amplification using the primers pair 27F-1492R, 63F-1492R (Bacteria) and 4F-1407R (Archaea) resulted in PCR products of about 1.4kb; nearly a full length sequence of the 16S rRNA gene. Three clone libraries were constructed (ARCH625, BACT120 and BACT625). 20 clones from each library were selected and partially sequenced (Table 7.9.2).

Microbial diversity in the Chilean continental margin - Sequences determined during this work were affiliated to organisms involved in three major metabolisms in marine sediments:

methanogenesis, sulfate-reduction and fermentation. All sequences were closely related to environmental clones recovered from deep sea sediments. Phylogenetic analysis of libraries BACTI and ARCHI placed the sequences in a cluster whose closest relatives were associated with consortium in marine sediments where anaerobic methane oxidation occurs. Within the BACTI library, two sequences were closely related to Desulfosarcina genus with only 46 to 48% of similarity. In addition, 15 sequences which belonged to ARCHI library were affiliated to genus Methanosarcinales and Methanobacterium with high % of similarity; 70-90 and 77-93 respectively. Consistent with others studies, our phylogenetic analyses demonstrated that microbial consortium in marine sediments could be involved in anaerobic oxidation of methane.

Table 7.9.2: Phylogenetic affiliations of clones from two sediment layers; 600bp determined.

samples	Phylogenetic groups	Closest match in RDP	% of similarity	Number of clones
BACT I (120cm)	Gram +	Moorella spp.	84-99	10
		Syntrophomonas wolfei	79	1
	Proteobacteria Delta	Desulfobacterium anilini	73	1
		Desulfosarcina variabilis	46-48	2
		Nitrospina gracilis	40-60	3
	Proteobacteria Epsilon	Wolinella sucinogenes	75	1
	Proteobacteria gamma	Escarpia spicata	65	1
BACT II (625 cm)	Gram +	Moorella spp.	86-97	13
		Dehalococcoides ethenogenes	40-64	3
	Proteobacteria Delta	Pelobacter acidigallici	43-51	3
		Nitrospina gracilis	74	1
ARCH I (625 cm)	Methanosarcinales	M. siciliae	70-90	2
	Methanobacterium	M. arboriphilicus	77-93	13
	Methanococcales	M. jannaschii	25	2
	Archaeoglobales	A. fulgidus	60-78	2

<u>DGGE analysis revealed a complex bacterial community</u> - Bacterial 16S rRNA primers 341 forward (with GC clamp), 518 and 907 reverse were used to amplify V3 region by PCR to check for bacteria diversity. DGGE was performed at the University of Cardiff, Wales, on DNA extracted from crude samples. Comparative DGGE analysis of the bacterial diversity in deep-sea sediment samples revealed a high complexity in the community structure of the sediment (Fig. 7.9.2). Archaeal signatures on DGGE profiles were also observed (data not shown, G. Webster).

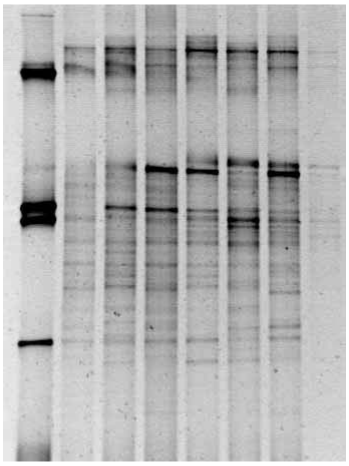

Fig. 7.9.2: Comparative DGGE profile analysis of bacterial 16S rDNA V3 fragments from 7 vertical depth intervals of crude sediment samples. M; Marker, 1; 30cm, 2; 120cm, 3; 225cm, 4; 325cm, 5; 425cm, 6; 525cm, 7; 625cm.

Conclusion - The results of enrichment cultures performed in various cultural conditions (culture media and incubation conditions) show a clear difference in the composition of the microbial communities associated with superficial samples versus deep sediments. These observations are in good agreement with the data obtained from the partial sequencing and the DGGE analysis of PCR-amplified 16S rDNA from crude samples.

Nevertheless, the diversity observed in deep sediment samples is as high as in superficial ones. Most of the Bacterial and Archaeal sequences obtained from deep samples show significant similarities with sequences in the data bases corresponding to clones previously described in deep-sea sediments and to clones associated with the anaerobic oxidation of methane.

7.10) Inorganic geochemistry of upwelling sediments taken off Chile (36°S)

Introduction - The sediments of gravity core GeoB 7165-1 (taken off Concepción, 800m water depth; below the OMZ) were analyzed for major and trace elements (using XRF and ICPMS) as well as total organic carbon (TOC), total inorganic carbon (TIC) and total sulfur (TS). The aim of this work was (a) to provide a first inorganic-geochemical data base on Chilean upwelling sediments and (b) to trace environmental conditions and find indications for former climatic variability in the sediments by using e.g. productivity/redox-sensitive trace metals.

Results and Discussion - The major element composition in core GeoB 7165-1 is similar to average shale with minor contents of biogenic carbonates and OM (organic matter). The terrestrial detritus is delivered mainly by the rivers Bio-Bio and Itata (Fig. 7.10.1) since major element chemistries are comparable (Table 7.10.1). TOC seems to be uniquely derived from marine sources, which is confirmed by C/N-ratios between 6 and 9.

Table 7.10.1: Element contents of river Bio-Bio and core GeoB 7165-1

	Al_2O_3 [%]	Fe_2O_3 [%]	Ba [ppm]
Bio-Bio	16.4	7.7	301
GeoB 7165-1 (average values)	16.1	6.8	363

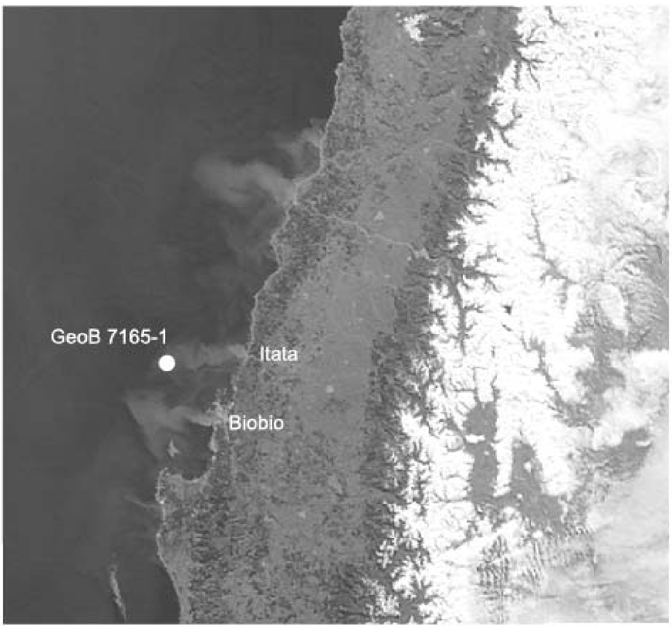

Fig. 7.10.1: Satellite picture showing sediment plumes of rivers Bio-Bio and Itata. The position of core GeoB 7165-1 is also indicated.

The degree of pyritisation can be used to characterize sedimentary redox-conditions and was estimated based on bulk sediment analyses from a ternary $Fe_{reactive}$-TOC-S diagram. The content of reactive iron (Fe_x) was estimated by the empirical relation $Fe_x = Fe_{sample} - 0.25 \bullet Al_{sample}$ which is based on the assumption that a specific fraction of silicate-bound iron is not available for pyrite formation.

From Fig. 7.10.2 it is apparent that pyrite formation is strongly restricted due to the lack of OM and S. Low TOC values are either due to a low productivty and/or consumption of OM during settling through the water column. The above findings indicate oxic-suboxic sedimentary conditions and contrast findings for sediments from the Gulf of California and the Peru Margin where all reactive iron is already fixed as pyrite and sedimentary conditions are (sub)anoxic.

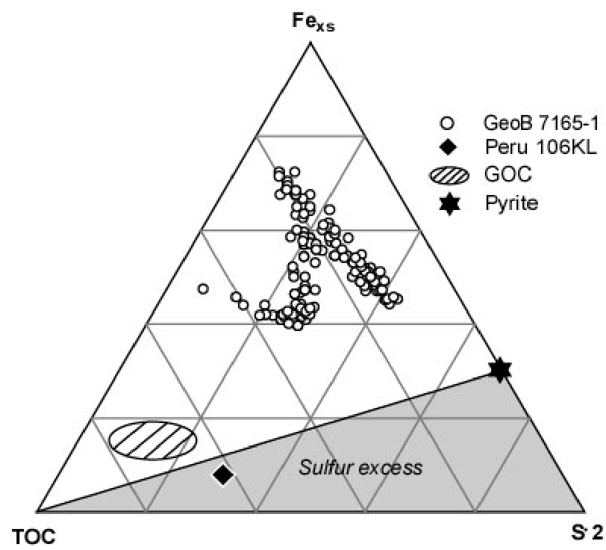

Fig. 7.10.2: Major components of Chilean upwelling sediments in the system Fe_x–TOC–S•2 (relative weight ratios). Shaded area = Fe-limitation. GOC = Gulf of California, Peru 106KL.

Trace elements Cd, Ni and Ba are involved in bio-cycling and clearly coupled with TOC (Fig. 7.10.3) reflecting the association with plankton. Redox-sensitive Cr is also well correlated with TOC indicating the early diagenetic association of Cr with OM (Fig. 7.10.3).

A significant change from oxic to suboxic sedimentary conditions can be observed at about 300 cm core depth which is ~10,500 years b.p. (Fig. 7.10.4a). This is indicated by the gradual decrease of the TOC content and the coupling of several trace elements such as e.g., productivity-related Cd and redox-sensitive Mo (Fig. 7.10.4b). The Chemical Index of Alteration (CIA) representing the grade of terrestrial detritus weathering, leads to the assumption that more humid conditions prevailed during the last glacial and less precipitation during interglacial times (Fig. 7.10.4a).

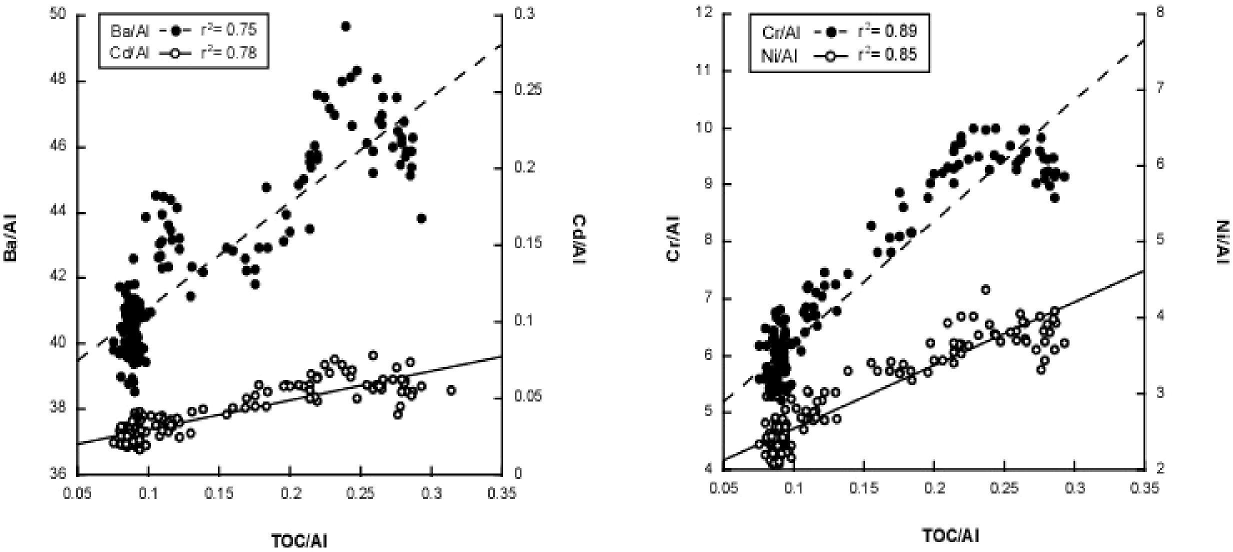

Fig. 7.10.3: Scatterplot of TOC vs. Cd, Ba, Cr and Ni (Al-normalized). E/Al (•10-4) except TOC/Al.

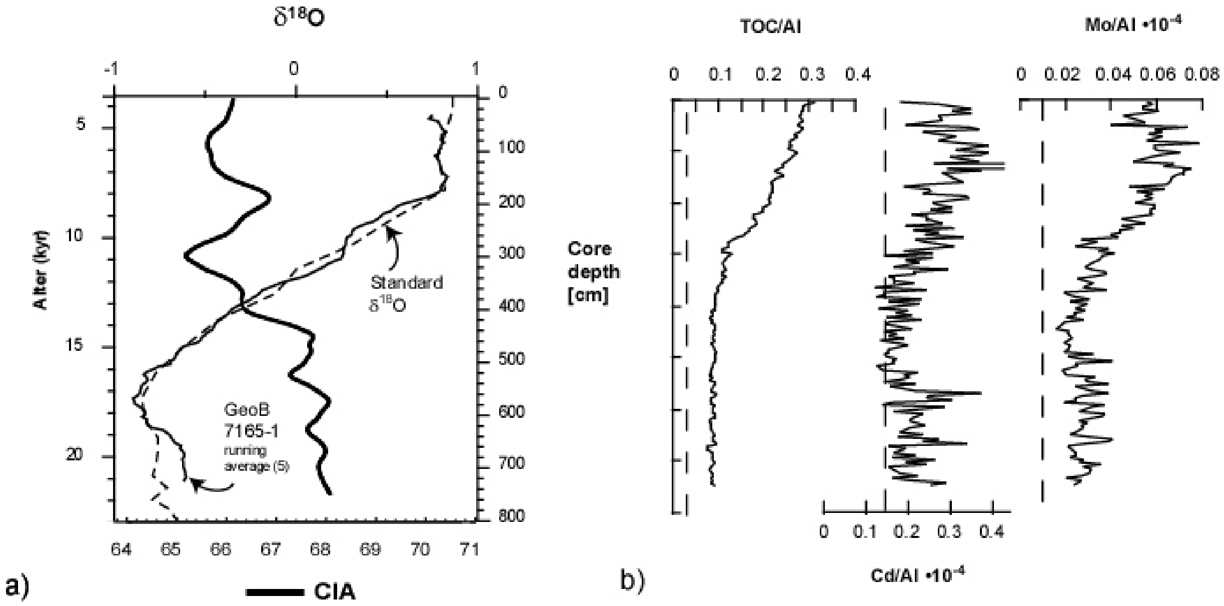

Fig. 7.10.4: a) Chemical index of alteration (CIA) of GeoB 7165-1 sediments and preliminary age adapted to standard $\delta^{18}O$ by Martinson et al. (1987). b) Downcore profiles of TOC, Cd, Mo (Al-normalized).Vertical dashed line: average shale.

The sediments from GeoB 7165-1 are less enriched in OM and productivity/redox-sensitive elements than sediments from other upwelling systems (Fig. 7.10.5). This is most likely reflected by the core position below the OMZ outside of the active upwelling cell.

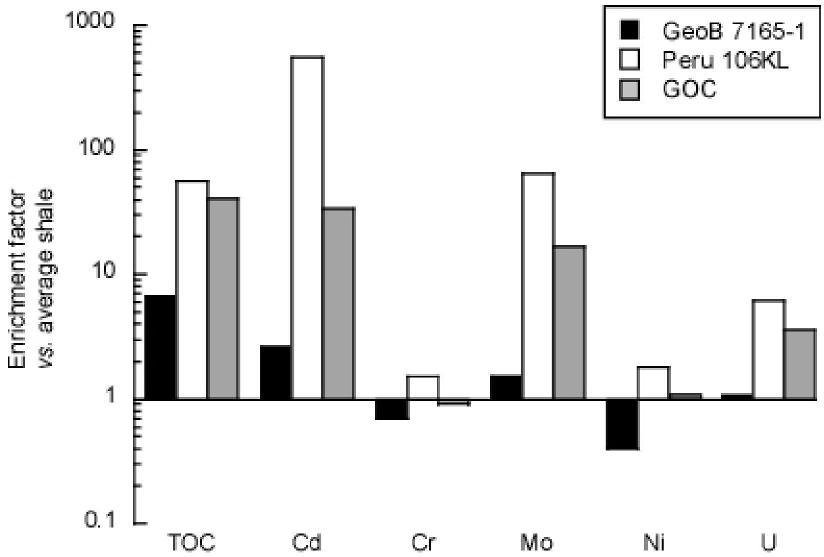

Fig. 7.10.5: Enrichment factors vs. average shale of TOC and trace elements compared with other upwelling areas [Peru; Gulf of California (GOC)].

7.10) Distribution patterns of macro- and meiofauna around the oxygen minimum zone along the Chilean coast

Objectives of work - Whereas intense macrobenthic studies have been performed along the Peruvian coast-line, comparable data from the Chilean coast further south are scarce. The overall objective of the biological part of the PUCK – Expedition was to determine principal factors that control the structure of bathyal benthic communities (mega-, macro-, and meiofauna) in relation to the oxygen minimum zone (OMZ) in specific areas along the Chilean coastline, which differ ion their local production.

Specific objectives we worked on were:

- to assess potential adaptations of characteristic benthic species living in OMZs,
- to determine the spatial distribution patterns of environmental conditions in and beneath OMZs in the areas under study,
- to determine latitudinal and downslope changes in distribution patterns (composition, densities, biomasses) of benthic communities.

These data provide the base to describe benthic community patterns in relation to latitudinal (in comparison to older and recent AWI Antarctic/Patagonian programs further south) and depth gradients, to environmental conditions in the water column as well as in the sediments.

Another field touched are El Niño studies. After the last El Niño event in 1997/98 our data describe an almost ´normal non-El Niño situation´, i.e. these data could provide a base for evaluations of future changes of the system due to El Niño.

Status quo of the work - The PUCK Expedition was an interdisciplinary approach of geology and biology to investigate the relationships between the present-day environmental conditions and the biology, and to reconstruct the Late-Quaternary paleo-environmental conditions of this high-production area. The amount of data obtained from these different disciplines will allow interdisciplinary approaches for joined papers. Contributions from geology, oceanography and different fields of biology will increase our knowledge of this special study area that oscillates between La Nina/El Nino periods, which is influenced by different water masses and the topography of which changes within few miles from shallow to abyssal. For the joined analysis of the numerous data we look forward to interesting contributions to be presented on a workshop planned for November 2004 to be held in Concepción.

With the exception of the meiofauna samples, which still are under work, all biological macro- and megafauna samples from Agassiz Trawl, multibox corer, and UW photography are worked up. Up to date several manuscripts are under preparation, submitted or already accepted. These manuscripts cover a wide range of scientific fields. In the following chapters we present extended abstracts of some manuscripts with important tables and figures in order to demonstrate in which way the numerous data obtained from the expedition will be published.

The first paper deals with adaptations of macrobenthic organisms to hypoxic conditions prevailing off northern and central Chile during ´normal´ non-El Nino periods. In the second contribution distribution patterns of macrobenthos organisms sampled with the multibox corer along depth gradients off Antofagasta, Concepcion, and Chiloe in and beneath the oxygen minimum zone are described. Another two papers combined here describe new records of crustacean species from AGT samples collected during the ´SONNE Expedition´.

These manuscripts represent a considerable part of the obtained data, however, much more has to be published in the future, especially taxonomical paper, but also interdisciplinary aspects paper. The second manuscript makes evident that the biology in the study area is influenced by the OMZ, but there is also evidence that other environmental parameters like e.g. sediment properties are important for patterns in the benthic realm.

7.12) Biomass size-spectra of macrobenthic communities in the oxygen minimum zone off Chile

Introduction - In the Humboldt Current System (HCS) a pronounced OMZ is associated with the Equatorial Subsurface Water mass (ESSW), which flows poleward over the shelf and upper slope. This water mass produces a large O_2-depleted region extending at least from 50 to 400 m depth in northern Chile with concentrations <0.5 ml L^{-1}. In central Chile the OMZ continues to be a significant feature extending in winter from 100 to 300 m. Early studies on benthic communities on the shelf and upper slope in northern Chile suggested that low oxygen concentrations within the water column had important effects on the benthic biomass. Furthermore, it is known that the OMZ of the HCS represents an important barrier to aerobic metabolic processes, leading to diverse questions about responses of the fauna to hypoxic conditions.

Many authors have stressed the importance of body size in benthic marine fauna, but very little is known about the processes that determine size distribution in marine invertebrates. Studies have focused on bathymetric patterns in relation to the availability of food, physiological and ecological factors, or phylogenetic constraints. More recently, it has been proposed that maximum body size in benthic marine invertebrates is a function of the availability of dissolved oxygen in the surrounding water. This hypothesis is related directly to physiological effects of oxygen concentration on invertebrates, although other factors, such as life history, may be involved. Small organisms are better able to satisfy their metabolic demands because they have a higher surface area to body volume ratio. However, studies dealing with the effect of environmental factors on body size distribution of marine benthic communities are scarce. Thus, this work aims (1) to analyze the density, biomass and biomass size-spectra (BSS) of the benthic macrofauna living on the continental margin off Chile and (2) to determine the influence of the OMZ on the BSS of the benthic macrofauna.

Material and methods - The study area is the continental margin off Chile (Table 7.12.1). Five cruises were conducted in this area between 1999-2001. The surveys were carried out off Iquique (21° Lat.S), off Antofagasta (22° Lat.S), off Concepción (36° Lat.S) and off Chiloé (42° Lat.S), covering a depth range from 100 to 2000 m. A mini-multiple corer with six tubes (inner diameter = 95 mm) was used to collect the samples.

Biomass size spectra were normalized (NBSS) as this is required since the width of the size classes varies through the size-spectra. The procedure consists of dividing the variable of interest *m(s)* in the size class characterized by the weight or volume *(s)* by the width of the size class, Δ*s*. Thus the normalized version of the variable m is equal to:

$$M(s) = m(s) / \Delta s$$

The parameters of the NBSS were determined by regressing the $\log_2$ (normalized biomass) against $\log_2$ (individual weight). The spectra were constructed with a maximum of 11 size classes.

Tab. 7.12.1: Expeditions and summarized station data.

Location	Expedition	Vessel	Date	Station	Water depth (m)	DO (ml L^{-1})	Latitude (°S)	Longitude (°W)	No. cores examined
Iquique	MinOx	R/V Vidal Gormaz	30.03.2000	St 1	111	0.24	20°14'07	70°12'04	6
			31.03.2000	St 2	204	0.24	20°16'36	70°13'98	4
			01.04.2000	St 3	300	0.24	20°16'84	70°14'88	5
			02.04.2000	St 4	517	0.97	20°15'50	70°17'24	4
			03.04.2000	St 5	840	1.39	20°16'73	70°28'21	4
			04.04.2000	St 6	1278	1.98	20°13'40	70°38'15	4
Antofagasta	PUCK	R/V Sonne	01.04.2001	7102	142	0.05	22°49´59	70°28´29	3
			02.04.2001	7104	295	0.06	22°51´96	70°29´39	6
			04.04.2001	7107	518	0.90	22°50´50	70°30´93	6
			02.04.2001	7103	890	1.28	22°51´99	70°32´58	8
			04.04.2001	7106	1350	1.70	22°47´98	70°32´58	8
Concepción	ETC	R/V Vidal Gormaz	29.03.1999	St 1	120	0.10	36°26'06	73°23'24	12
			30.03.1999	St 2	206	0.13	35°44'60	73°04'41	8
			04.04.1999	St 3	364	0.52	36°02'31	73°04'22	11
			05.04.1999	St 4	810	2.89	36°32'70	74°04'90	8
Concepción	PUCK	R/V Sonne	23.04.2001	7161	124	0.45	36°25´52	73°23´36	7
			23.04.2001	7160	365	0.79	36°02´35	73°04´40	7
			24.04.2001	7163	535	2.92	36°25´49	73°35´72	7
			24.04.2001	7162	798	2.30	36°32´54	73°40´05	9
			25.04.2001	7166	1294	1.48	36°27´99	73°46´47	9
			26.04.2001	7167	2060	1.82	36°27´17	73°54´18	6
Chiloé	PUCK	R/V Sonne	39.04.2001	7173	160	1.28	42°05´36	74°33´55	5
			39.04.2001	7172	297	1.52	42°24´61	74°47´26	5
			03.05.2001	7177	902	2.31	42°34´96	74°50´22	7
			01.05.2001	7174	1224	1.87	42°32´66	75°01´10	7
			01.05.2001	7175	1961	1.93	42°27´13	75°12´61	8

Results and discussion - Normalized spectra were constructed for groups of stations pooled by depth range (Table 7.12.2). Most NBSS were statistically significant ($P<0.05$) presenting slopes ranging from –0.481 to –0.908 (Table 7.12.2). No significant differences ($P<0.05$) were found among the slopes of the NBSS when comparing different depth ranges as well as among locations. When the spectra are pooled together by location disregarding depth all NBSS can be represented by the linear model ($P<0.05$). No significant differences were found among the slopes of the NBSS. However, and as expected from the different levels of benthic biomass found between Concepción and the rest of the locations the intercept of the NBSS of

Tab. 7.12.2: Regression parameters of the normalized biomass size-spectra for stations on the continental margin off Chile (Model: log2 Y= log2 a + b log2 X). Size range: 0.01 – 512 mg wet weight; depth range: 111 – 2060 m).

Location	Depth range (m)	Slope	Log_2 a	r^2	N	Std. Err Slope	Std. Err Log_2 a	p value
Iquique (MinOx)	100 - 300	-0.952	1.855	0.33	6	0.956	1.482	p>0.05
	300 - 1000	-0.687	2.354	0.62	8	0.221	0.693	p<0.05
	1000 - 2000	-0.291	0.938	0.41	5	0.199	0.551	p>0.05
	Combined depth	-0.475	2.001	0.48	8	0.203	0.637	p<0.05
Antofagasta (PUCK)	100 - 300	-0.956	3.088	0.56	6	0.419	1.144	p>0.05
	300 - 1000	-0.481	1.547	0.76	9	0.103	0.426	p<0.01
	1000 - 2000	-0.706	1.246	0.91	6	0.113	0.296	p<0.001
	Combined depth	-0.685	2.593	0.81	9	0.124	0.512	p<0.001
Concepción (ETC)	100 - 300	-0.908	4.785	0.74	9	0.201	0.741	p<0.01
	300 - 1000	-0.299	2.087	0.20	10	0.213	0.905	p>0.05
	Combined depth	-0.569	4.268	0.77	10	0.110	0.467	p<0.001
Concepción (PUCK)	100 - 300	-0.848	5.038	0.69	10	0.202	0.926	p<0.01
	300 - 1000	-0.351	2.385	0.35	11	0.158	0.758	p>0.05
	1000 - 2000	-0.777	3.293	0.81	9	0.145	0.536	p<0.01
	Combined depth	-0.611	4.097	0.87	11	0.079	0.378	p<0.001
Chiloé (PUCK)	100 - 300	-0.742	2.284	0.77	9	0.151	0.588	p<0.01
	300 - 1000	-0.502	2.037	0.49	9	0.194	0.716	p<0.01
	1000 - 2000	-0.537	2.290	0.74	10	0.112	0.475	p<0.01
	Combined depth	-0.565	2.427	0.85	10	0.084	0.356	p<0.01

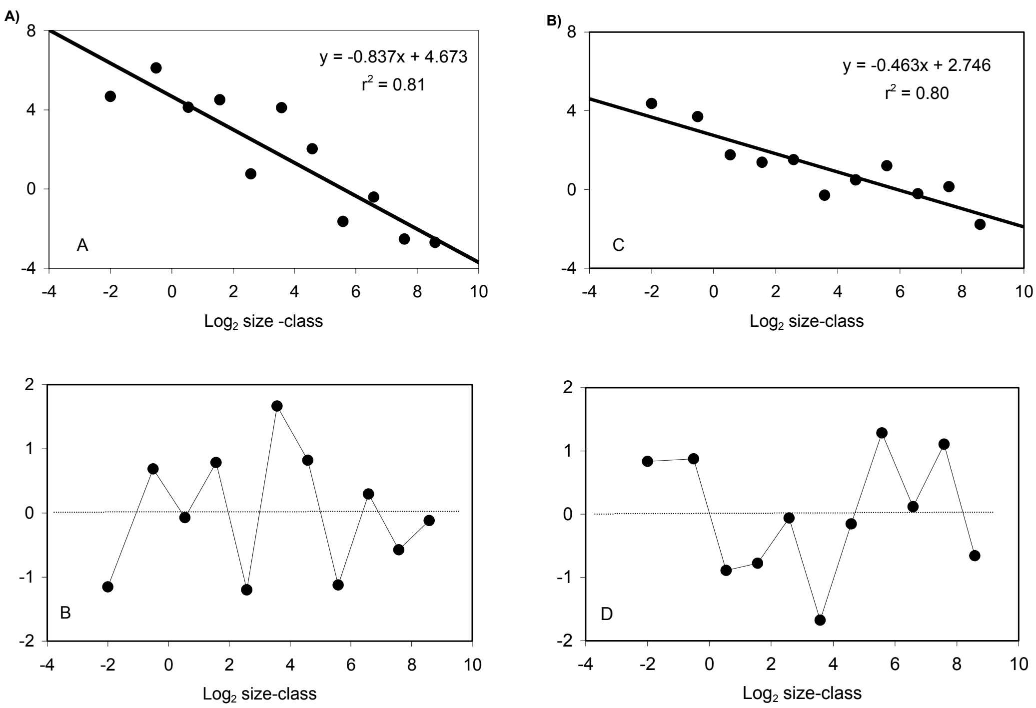

Fig. 7.12.1: Normalized biomass size-spectra and residuals distribution of the macrofauna in the OMZ (A) and beneath the OMZ (B).

this location was significantly different from the other locations ($P<0.05$). It is known that intercepts of NBSS are an indicator of total biomass of the system.

For comparative purposes NBSS were constructed pooling the data from all stations located in the OMZ and outside the OMZ. Both regression models were highly significant ($p<0.001$) and residuals variations were small. The slope of the NBSS of organisms living in the OMZ (–0.837) was significantly different ($P<0.05$) from that of organisms living beneath OMZ (–0.463). This indicates that benthic communities inhabiting the OMZ consist of smaller macrofauna organisms being more abundant than larger ones in comparison to the size-structures observed in stations located beneath OMZ.

7.13) Macrozoobenthos communities within and beneath the oxygen minimum zone off Chile (23° to 42°S) and their relationships to environmental conditions.

Introduction - A quantitative study of the macrozoobenthos was carried out on three transects on the shelf and continental slope off Chile (23° to 42° S; from 100 to 2000 m water depth) within and beneath the oxygen minimum zone (OMZ). Macrobenthos densities ranged from 13,808 to 483 ind. m^{-2} with highest values found off Concepción, where highest chloroplastic pigment equivalents (CPE) were also observed. Polychaetes were the numerically dominant group on all transects and depths, followed by peracarid crustaceans. Increasing bottom-water oxygen concentrations and decreasing sediment bounded pigments correlated with observed changes in the species richness and diversity. Our results show that the shelf macrobenthic communities were affected by low oxygen saturations. In addition, contrasting distinct differences became evident in the composition of the communities in different depths, probably related to different water masses, the boundaries of which coincide with the station depth ranges.

This work aims (1) to determine the influence of the OMZ on the macrozoobenthos density, biomass and on community parameters (i.e. composition, species richness, diversity) along the shelf and continental slope off Chile and (2) to assess the relationships between the macrobenthic fauna (i.e. density, biomass and community parameters) and physical sediment properties in the study area. We hypothesize that (i) macrozoobenthos communities on the continental margin off Chile are affected by the presence of the OMZ and (ii) the community parameters correlate with bottom near oxygen concentrations and sediment-bounded pigment concentrations. In addition, we provide original data for the region, especially from the up to now hardly studied deeper slope, thus contributing to studies of biodiversity and community structure in the Southern Hemisphere.

Extension of the OMZ - The lowest bottom-water dissolved oxygen concentrations were recorded on the shelf at 98 to 295 m water depth off Antofagasta (0.02, 0.05 and 0.06 ml L^{-1}, respectively), hereafter defined as the OMZ. Oxygen levels increased with depth, reaching 0.9 ml L^{-1} on the upper slope (518 m depth) and the highest values at the lower slope sites at 900 and 1350 m water depth with 1.3 and 1.7 ml L^{-1}, respectively.

Off Concepción the OMZ did not exist as distinct as compared to Antofagasta, and OMZ like saturation levels occurred exclusively in 124 m water depth (0.45 ml L^{-1}), whereas in 365 m water depth the critical 0.5 ml L^{-1} value, which normally characterizes OMZ areas, was already exceeded. At 535 m a maximum of 2.92 ml L^{-1} occurred and with increasing depth the saturation decreased slightly to 1.5 and 1.8 ml L^{-1} in 1300 and 2000 m depth, respectively. Off Chiloé no OMZ was found and the oxygen levels in the near bottom water layer varied between 1.3 ml L^{-1} in 160 m water depth to a maximum of 2.8 ml L^{-1} in 500 m on the upper slope.

Taxonomic composition of macrozoobenthos - A total of 129 species/morphotypes belonging to 9 major taxa were collected during this survey. The total number of species increased from north to south and was shown to differ significantly between the three study areas (Fig. 7.13.1); no significant differences, however, became evident between increasing water depths and total species numbers. Annelida (Polychaeta and Oligochaeta) with 84 species/morphotypes were the most abundant group in all three locations.

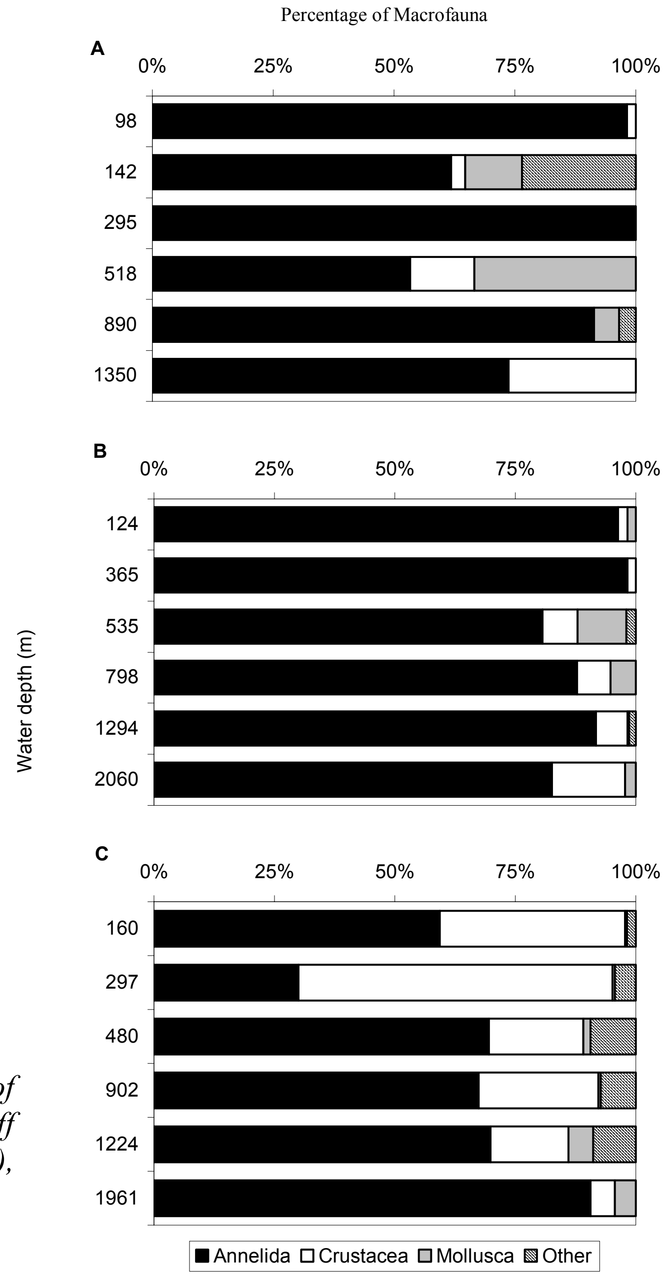

Fig. 7.13.1 Taxonomic composition of the macrozoobenthos sampled off Antofagasta (A), Concepcion (B), and Chiloé (C).

The OMZ stations in 98 and 142 m depth off Antofagasta were dominated by polychaetes and oligochaetes, contributing 90 – 100% to the total macrofauna. *Magelona phyllisae* (2,442 ind m^{-2}) and oligochaeta sp. A (1,100 ind m^{-2}) were the most abundant species in the OMZ, followed by *Cirratulus cirratus* (442 ind m^{-2}) and *Levensenia gracilis* (458 ind m^{-2}), although the latter also occurred outside the OMZ.

The uppermost two stations off Concepción (124 – 365 m) were dominated by polychaetes, which made up 96 – 98% of the total macrofauna. The percentage of polychaetes was lower at the 535 m (80 %) and 2060 m (82%) stations, where crustaceans and mollusks gained importance. The small-bodied polychaetes *C. chilensis* (5,884 ind m^{-2}) and *P. pinnata* (5,042 ind m^{-2}) were the most important species in the 124 m station within the OMZ. Contrasting, the polychaetes *Paramphinome australis*, Fauvelopsidae sp. A, *Maldane sarsi,* and the amphipod Ampeliscidae sp. A showed high densities at stations beneath the OMZ.

Off Chiloé, polychaetes and custaceans were found in high numbers in the 160 m station, making up 60 and 38 % of the total macrofauna, respectively (Fig. 7.13.1). Contrasting, amphipods and ostracods together formed 60 % of the total macrofauna at the 297 m station. At the deeper stations polychaetes contributed between 62 to 90% to the total macrofauna, with *Aphelochaeta monolaris, Aricidea strelsovi,* and *Maldane amphiglypta* being the most important species.

<u>Macrobenthic density and biomass</u> - Densities of the macrofauna in the three areas under study showed the tendency of decreasing values with increasing depth, although these differences were not always significant. Comparison of the different areas exhibited significantly higher density values off Concepción than off Antofagasta and Chiloé (Fig. 7.13.2). Off Antofagasta macrofauna densities were highest in the 98 and 295 m stations within the OMZ (4,025 – 3,408 ind m^{-2}), decreasing to low values of 104 - 483 ind. m^{-2} in deeper stations; *a posteriori* test revealed significant differences between the 98 – 295 m station in the OMZ and the other stations. Off Concepción the density at the 124 m station (13,808 ind. m^{-2}) was exceptional due to the high contribution of the two small polychaetes *Cossura chilensis* and *Paraprionospio pinnata.* The lowest density (483 ind m^{-2}) was found at the 365 m station. The 124 m station differed significantly from all other stations. The macrobenthic densities off Chiloé were highest at the 160 m station (3,466 ind m^{-2}), but *a posteriori* test revealed significant differences only between the two shallowest shelf stations and the 480 and 1961 m stations.

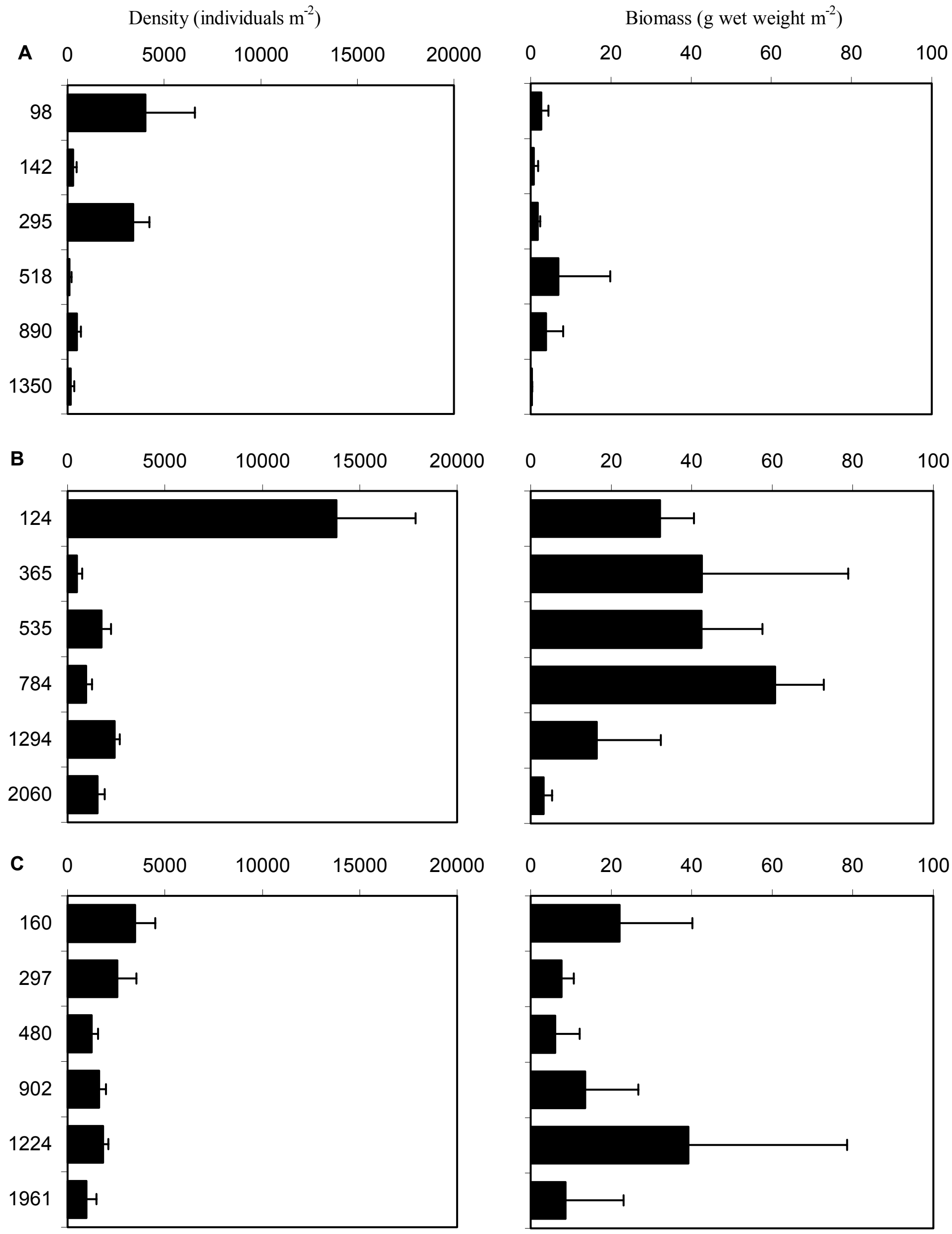

Fig. 7.13.2 Mean density and biomass (± SD) of macrozoobenthos sampled off Antofagasta (A), off Concepción (B), and Chiloé (C).

Biomass values did not show a clear depth dependence, although some station means differed significantly from others. Off Antofagasta highest biomass occurred at the 518 m station (6.92 wet weight m^{-2}) and lowest at the 1350 m station (0.25 wet weight m^{-2}; Fig. 2), but without any significant differences among stations. Off Concepción biomass was highest at the 784 m station (60.70 wet weight m^{-2}) and lowest at the 2060 m station (3.27 wet weight m^{-2}); this latter station differed significantly from all other stations. Off Chiloé macrofauna biomass was highest at the 1224 m station (39.35 g wet weight m^{-2}) and lowest at the 297 m station (3.03 g wet weight m^{-2}) without significant differences between stations.

The Nonmetrical Multi Dimensional Scaling analysis (NMDS) of organism densities of all samples collected revealed different station-groups (Fig. 7.13.3). Although off Antofagasta no clear pattern existed, probably due to substrate heterogeneity, significant differences between the OMZ stations and the deeper stations became evident. Contrasting, off Concepción clearly distinct stations-groups existed. The OMZ station was significantly distinguished from the shelf directly beneath the OMZ and from upper and lower slope stations, reflecting probably influence of different water masses. Off Chiloé NMDS analysis showed significant differences between the shelf stations – with the 480 m station separated from the two shallower shelf stations - upper slope stations, and lower slope stations. The multivariate index of dispersion reflected a high heterogeneity among cores at each station, however, without showing any dependence to water depth.

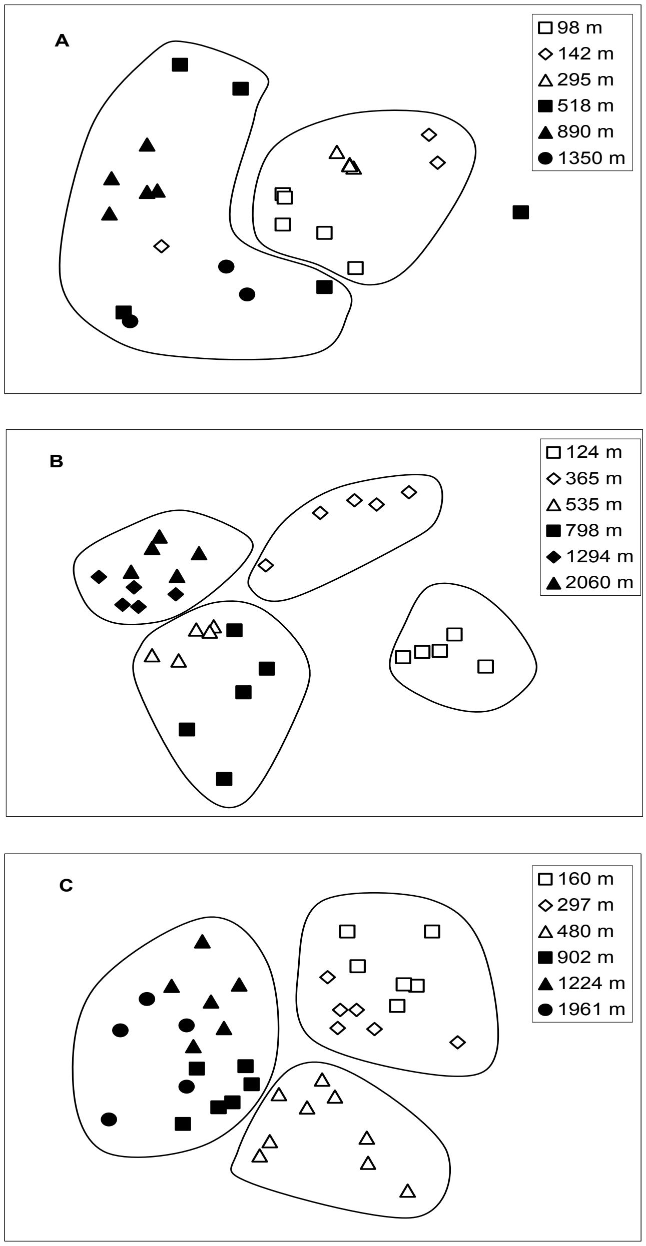

Fig. 7.13.3: NMDS ordination plots of macrozoobenthos sampled off Antofagasta (A), off Concepción (B), and Chiloé (C).

Conclusions - The PUCK–Expedition was a combination of geological and biological studies providing a wealth of biological and environmental data from the shelf and slope areas off north, central and southern Chile down to 2000 m water depth. Our results show that the shelf macrobenthic communities were affected locally by low oxygen saturations and sediment properties. In addition distinct differences became evident in the composition of the communities in different depths, which are probably related to different water masses, the boundaries of which coincide with the station depth ranges.

7.14) Taxonomic highlights of the PUCK expedition

First records to Chile and descriptions of the female of *Cymonomus menziesi* Garth, 1971 (Decapoda, Archaeobrachyura, Cymonomidae) - *Cymonomus menziesi* Garth, 1971 is cited for first time in Chilean waters. The specimens were obtained during a survey with R/V "Sonne", from AGT samples of one station at 500 m depth off Chiloe (Fig. 7.14.1). The female specimen of this species will be described, and preliminary aspects about its biology will be discussed. The presence of this species in this area almost 30 latitudinal degrees south from the original reported findings in 1000 m depth off Peru was rather unexpected.

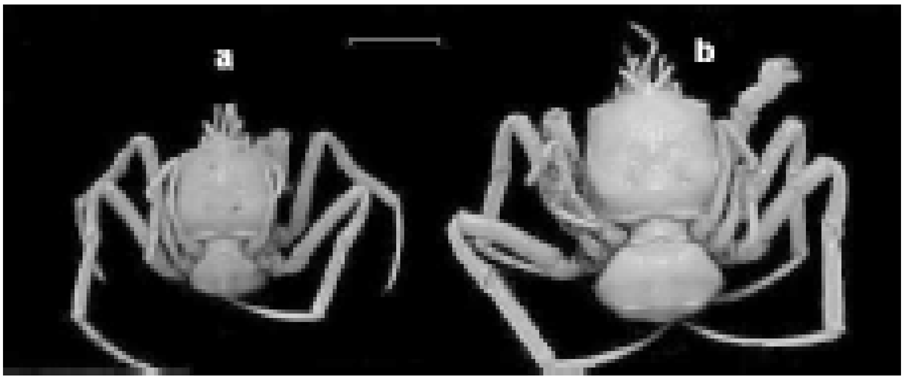

Fig. 7.14.1: Cymonomus menziesi *obtained from AGT samples of one station at 500 m depth off Chiloe.*

New records of shrimps (Decapoda; Caridea and Dendrobranchiata) in deep waters off Chile - Species of shrimps are revised based on bibliographic information and on specimens collected by Agassiz trawl (AGT) during the PUCK-SO 156 Expedition (2001) onboard R/V Sonne in three areas along Chilean coast; off Antofagasta (22° Lat. S), off Concepción (36°Lat. S) and off Chiloé (42° Lat. S) (Fig. 7.14.2). 111 specimens belonging to 12 species were collected, including three new records for the Chilean fauna; *Metacrangon procax, Nematocarcinus productus,* and *Merhyppolite* sp. aff. *M. american*. The presence of *Nematocarcinus lanceopes, Lebbeus antarticus, Pandalopsis ampla* and *Sclerocrangon atrox* in the collected material allows the extension of their distributional ranges from sub-Antarctic to temperate areas.

Fig. 7.14.2: Example for a shrimp species detected for the first time in Chilean waters.

8) Outlook

Usually the analysis of marine sediments is a quite time-consuming task and two years after a major expedition only the first final results are available. By the end of this project only a few scientific paper are already submitted or even published. However, the experience from the CHIPAL project (SO-102), the first cruise to the Chilean margin focussing on paleoenvironmental studies, showed that within a timeframe of ~ 5 years numerous scientific papers will be published with even more following in the subsequent years. Thus, to give an overview about which knowledge about the southern Peru-Chile Current and its history has been achieved by these two projects – PUCK and CHIPAL – all related references are listed below. The main output of scientific papers directly related to the PUCK project is expected in the forthcoming years.

<u>Publications related to the PUCK project (SO-156, marked by *) and the CHIPAL project (SO-102)</u>

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Additional output related to SO-156:

Poster presentations

Arntz, W., Gallardo, V.A., Gerdes, D., Montiel, A., Palma, M., Quiroga, E. & Texido, N. - Das Makrozoobenthos im Bereich der O_2- Minimumzone entlang der chilenischen Küste: Verteilungsmuster und Anpassungen. Statusseminar 2003 Meeresforschung mit FS Sonne, 12.-14.3.2003, Hamburg.

Romero, O. & Hebbeln, D. - Räumliche Variabilität der Produktivität im südlichen Peru-Chile Strom (SO-156): Geochemische Signale und silikatisches Phytoplankton in Oberflächensedimenten. Statusseminar 2003 Meeresforschung mit FS Sonne, 12.-14.3.2003, Hamburg.

Mohtadi, M. & Hebbeln, D. - Räumlich-zeitliche Entwicklung der Sedimentakkumulation entlang des chilenischen Kontinentalhanges seit dem letzten Glazial (SO-156). Statusseminar 2003 Meeresforschung mit FS Sonne, 12.-14.3.2003, Hamburg.

Mohtadi, M. & Hebbeln, D. - Rekonstruktion der Paläoumweltbedingungen entlang des chilenischen Kontinentalhanges anhand planktischer Foraminiferen (SO-156). Statusseminar 2003 Meeresforschung mit FS Sonne, 12.-14.3.2003, Hamburg.

Mohtadi, M.; Hebbeln, D.; & Wefer, G. – Glacial/Interglacial Record of Planktic Foraminifera From the Upwelling Area off Chile. AGU-Fall Meeting, 09.12.2002, San Francisco, USA.

Hebbeln, D. – Coastal upwelling off Chile: Ocean productivity and surface sediments. AGU-Fall Meeting, 09.12.2002, San Francisco, USA.

Romero, O. & Hebbeln, D. - Räumliche Variabilität der Produktivität im südlichen Peru-Chile Strom: Geochemische Signale und silikatisches Phytoplankton. Margins Meeting. October 2001, Kiel, Germany.

Romero, O. & Hebbeln, D. - Effects of El Niño 1997-98 on siliceous phytoplankton Fluxes from two Coastal Upwelling Areas: Southern California and Northern Chile. AGU - ASLO Ocean Sciences Meeting. February 2002, Honolulu, Hawaii, USA.

Romero, O. & Hebbeln, D. - Surface sediment record of diatoms and biogenic opal in the southern Peru-Chile Current: controlling mechanisms and relationship with surface water productivity. 17th International Diatom Symposium. August 2002, Ottawa, Canada.

Treude, T., Kallmeyer, J., Wintersteller, P. & Niggemann, J. - Anaerobe Methanoxidation am chilenischen Kontinentalhang. Statusseminar 2003 Meeresforschung mit FS Sonne, 12.-14.3.2003, Hamburg.

Oral presentations

Hebbeln, D. & Projektteilnehmer - Wechselwirkungen zwischen Produktivität und Umweltbedingungen am chilenischen Kontinentalhang (PUCK – SO-156). Statusseminar 2003 Meeresforschung mit FS Sonne, 12.-14.3.2003, Hamburg, Germany.

Hebbeln, D. - Present and Past Sedimentation in the Southern Peru-Chile Current. Kolloquium, 15.8.2002, Departamento de Oceanografia, Universidad de Concepcion, Chile.

Hebbeln, D. - Seasonal and Interannual Variability of the Particle Flux in the Humboldt Current off Chile. International El Niño Symposium, 7.8-10.8.2002, Viña el Mar, Chile.

Romero, O., Mohtadi, M. & Hebbeln, D. - Productivity Variations off Northern Chile Through the Last 19,000 Years. AGU Chapman Conference, September 2003, Paros, Greece.

Mohtadi, M.; Romero, O.E.; & Hebbeln, D. - Changing Productivity off Northern Chile Through the Last 19,000 Years. AGU-EUG-joint assembly, 08.04.2003, Nizza, Frankreich.

Mohtadi, M. & Hebbeln, D. – Paleoproductivity off northern Chile through the last 40,000 years. Kolloquium, Departamento de Oceanografia, Universidad de Concepcion, 29.08.2003, Concepcion, Chile.

Mohtadi, M. & Hebbeln, D. – Mechanisms and history of the productivity along the Peru-Chile-Current for the last 40,000 years. Postgraduate seminar, Departamento de Oceanografia, Universidad de Concepcion, 26.09.2003, Concepcion, Chile.

Mohtadi, M. & Hebbeln, D. – Planktic foraminifera in Peru-Chile Current and their relevance for paleoclimatic reconstructions. Introductory course for marine sciences, 04.10.2001, Bremen.

Niggemann, J., Kallmeyer, J, Ferdelman, T. & Schubert, C. – Sulfatreduktionsraten und organisch geochemische Analysen von Oberflächensedimenten vor Chile (SO 156 PUCK). Statusseminar 2003 Meeresforschung mit FS Sonne, 12.-14.3.2003, Hamburg.