The memory of the polar oceans

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5th of February 1983, -5°C air temperature, -1.2°C water temperature, a strong wind from the Antarctic ice cap blew over remnants of the winter sea ice: it was midsummer in the Southern Ocean. The new German research vessel *Polarstern* was on its maiden voyage in the Antarctic. The impressive ship was on station off Kapp Norvegia, a prominent landmark of the coastline in the northeastern Weddell Sea. The ice shelf edge glistened in the sun and provided a perfect scenery for the *Polarstern*'s debut in recovering its first sediment core from the Antarctic continental slope at a water depth of 2796 m. Twenty five years on, the *Polarstern* has collected almost 2000 sediment cores from the polar oceans and provided valuable geological surveys for international research projects, such as the Ocean Drilling Program. Since this cold February day in 1983, much progress has been made in our understanding of the connection between ice sheet dynamics and geological and climate processes in the polar regions.

Polar ocean history in the Cenozoic – entering the ice age

The history of the polar regions during the Cenozoic period i.e. the last 65 million years (Ma) nicely documents the Earths transition from "greenhouse" climate conditions to the Pleistocene icehouse world. Climate cooling started at the mid-Cenozoic climax of high atmospheric concentrations of greenhouse gases (such as carbon dioxide and methane), high sea level, and the absence of large ice sheets. It ended up in the ice ages of the Pleistocene with considerable bipolar glaciation and widespread permafrost in Siberia since about 2 Ma, overprinted by repeated short-term fluctuations of cold glacial and warmer interglacial stages and stadials multimillennial to centennial times scales. The longterm growth and storage of continental ice is reflected in a corresponding sea level fall throughout the Cenozoic and high frequency sea level fluctuations in response to the short-period buildup and collapse of ice sheets.

The northern and southern polar regions differ significantly in terms of land-water distribution as well as in their glacial and geological history. The important steps in shaping the Antarctic ring ocean were the separation of Tasmania from the Antarctic continent and the opening of the Drake Passage between South America and the Antarctic Peninsula. Today, Antarctica is covered by an ice sheet up to 4000 m thick. The weight of the ice masses, in conjunction with glacial erosion of shelf sediments during past ice ages, is the reason why the Antarctic shelf is 200-300 m deeper than the shelves of all other continents.

In contrast to the circular Southern Ocean, the Arctic Ocean is located within a deep-sea basin surrounded by continents with broad shelf areas. The Arctic Basin is connected to the Pacific and the Atlantic via two small gateways and divided by the Lomonosov Ridge into the Eurasian and the Amerasian Basins. The Eurasian Basin started opening at the Cretaceous/Tertiary boundary at about 65 Ma. The Amerasian Basin formed through complex tectonic movements of the seafloor probably since the earliest Cretaceous at ca. 140 Ma, which provided enough time to build up sediment coverage of up to 2000 m thickness. Latest evidence from deep-sea drilling shows that during its early stage, the Arctic Basin might have been occupied by a large lake-like water body with oceanographic features comparable to the modern Baltic Sea. The opening of the Fram Strait in the early Miocene connected the Arctic Ocean to the North Atlantic at about 17.5 Ma.

The development of Arctic glaciation throughout the Cenozoic, from some

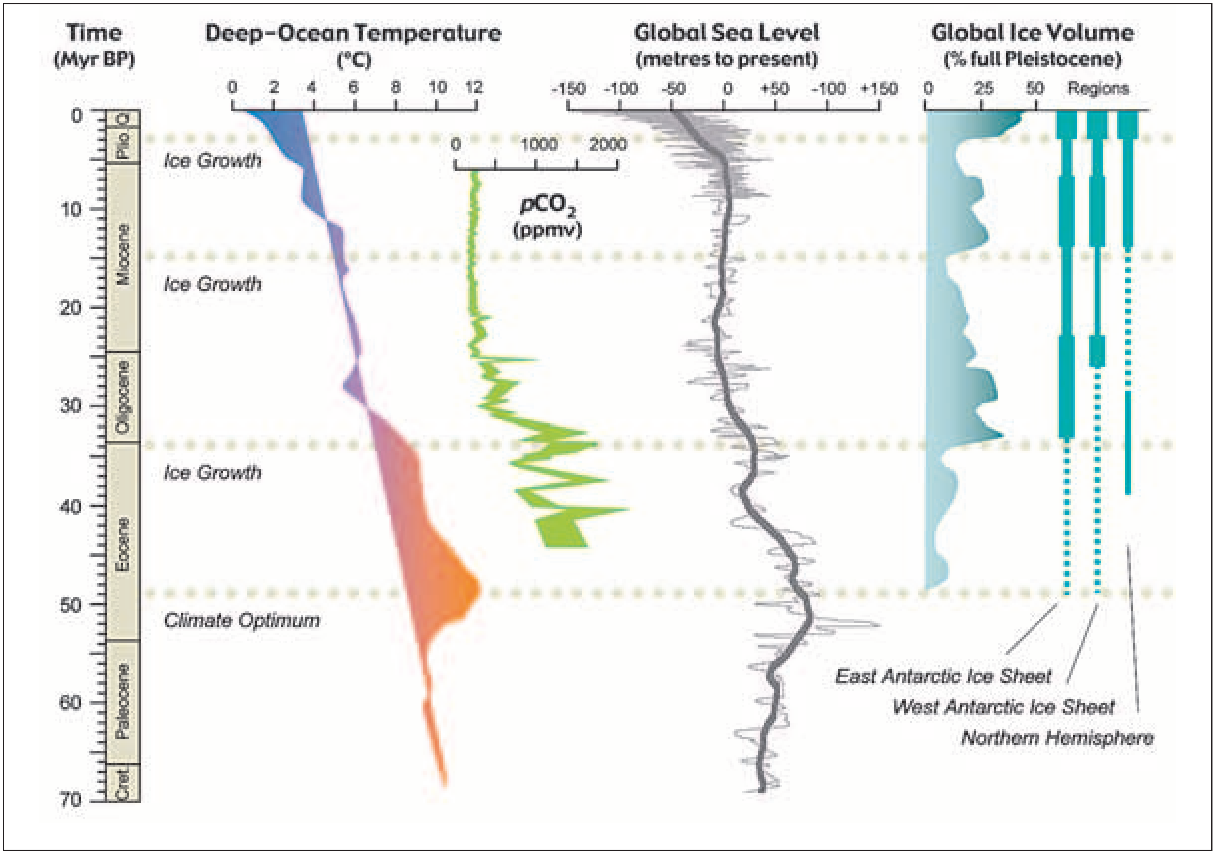


Fig. 1:
Climate development from the early Cenozoic greenhouse to the late Cenozoic icehouse world, documented by changes in deep-ocean temperature (Lear et al., 2000), the decline of atmospheric carbon dioxide (Pagani et al., 2005), global sea-level fluctuations (Miller et al., 2005), and changes in global ice volume (Lear et al., 2000). After the climate optimum in the early Eocene three distinct steps of climate cooling and ice-sheet growth occurred around the Eocene-Oligocene boundary at 34 Ma, in the middle Miocene after 15 Ma, and in the late Pliocene after 2.7 Ma.

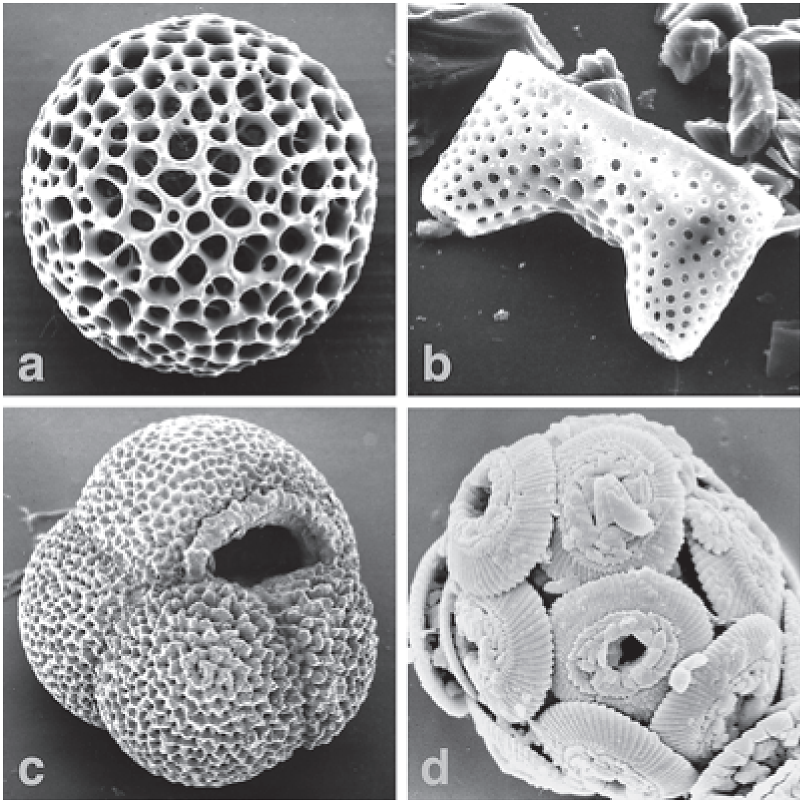


Fig. 2:
Major biogeneous components contributing to marine sediments are the remains of single-celled plankton and benthos organisms. The hard shells are made out of silica (opal) e.g. radiolaria (a, ø=350 µm) and diatoms (b, ø=50 µm) or out of calcium carbonate e.g. foraminifera (c, ø=400 µm) and coccoliths (d, ø=15 µm).Photos: AWI.

small glaciers and ice caps to a nearly complete coverage with a thick ice sheet, is excitingly complex. Consensus still exists that major ice sheet growth on the continents surrounding the Arctic Ocean began not earlier than late Pliocene around 2.7 Ma, and that these ice sheets oscillated in size during the glacial-interglacial cycles of the Plio-Pleistocene. However, new compelling geological evidence documents the presence of a continental ice sheet in Greenland already during the Eocene and Oligocene, in analogy to Antarctica. In the Arctic Ocean, the detection of ice-rafted rock pieces in sediments deposited at 45 Ma supports the presence of Arctic continental ice masses in the Eocene. The same marine record indicates strong cooling and the onset of seasonal sea ice coverage of the Arctic Ocean at 15 Ma, coinciding with a cooling pulse in the Antarctic region.

On the Antarctic continent, ice began to accumulate after the early Eocene climate optimum from 53 to 49 Ma ago. A major ice sheet expansion occurred at 34 Ma, when grounded ice advanced to the coasts around East Antarctica and entered the Southern Ocean. Further increases in Antarctic ice volume, which included the formation of the West Antarctic Ice Sheet, occurred in the middle Miocene after 15 Ma and in the late Pliocene between 3.2 Ma and 2.7 Ma. Phases of partial Antarctic ice sheet decay took place during the early Miocene and possibly the middle Pliocene.

In conclusion, it seems that the Cenozoic transition from the greenhouse to the icehouse world was a synchronous and bipolar phenomenon. Glaciation

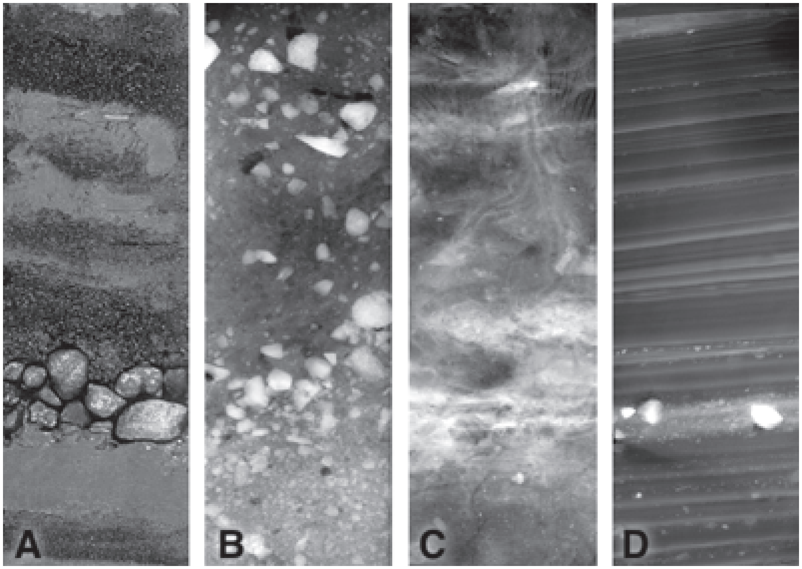


Fig. 3:
X-ray images of sediment types from the polar oceans: (A) sediment from the Antarctic con-tinental margin with layers of gravel and sand documenting advances of the ice sheet to the outer shelf, i.e. a proximal turbidite; (B) shelf sediments with a high amount of gravel; (C) sediment strongly bioturbated by benthic organisms living in and from the sediment; (D) laminated sediment deposited under closed ice coverage (width of each image is 10 cm). Photos: AWI.

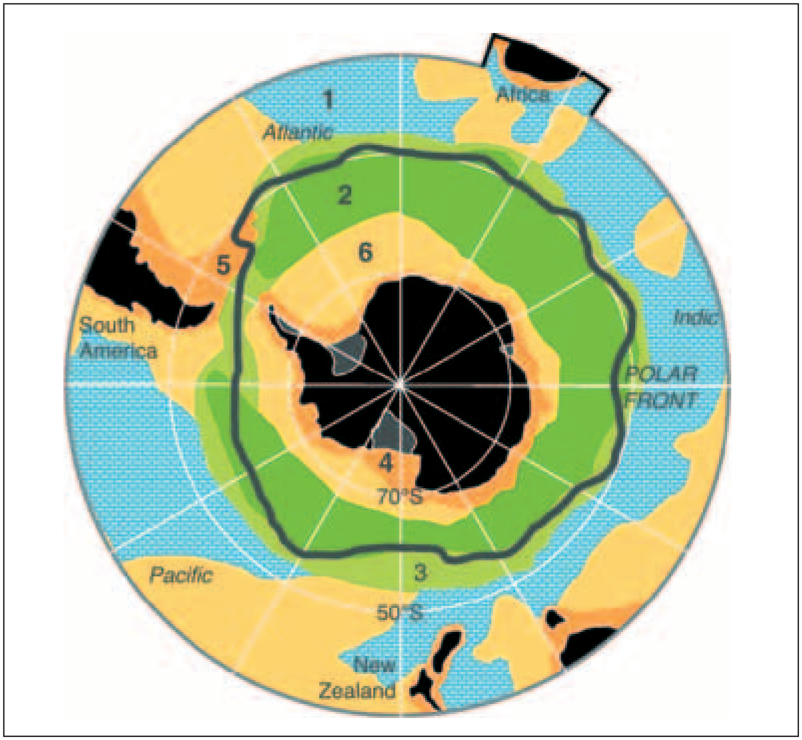


Fig. 4:
Spatial distribution of different types of marine sediments in the Southern Ocean (modified from Diekmann, 2007). The greenish area south of the Polar Front shows the extension of the subpolar opal belt where sediments have a significant portion of silicous plankton frustules. Sediments near Antarctica mainly consist of glacial debris in any grain size eroded and delivered by the Antarctic Ice. (1) Calcareous ooze/mud, (2/3)biosiliceous/mud, (4) coarse lithogenic sedi-ments, (5/6) lithogenic sand/mud.

proceeded in distinct steps and in parallel with global ocean cooling and the decrease of atmospheric greenhouse gases (Fig. 1). In the following case study from the Antarctic continental margin, we will demonstrate how marine geologists are able to recognise such environmental changes.

The memory of the sea

Sediments on the ocean floor archive a variety of environmental changes in their strata and preserve this record for millions of years for marine geologists to recover. Therefore, Seibold (1991) referred to marine sediments as the "memory of the sea". Marine sediments consist mostly of the weathering products from the continents that are transported by rivers, wind and ice. The rate of their deposition decreases from the coastal waters towards the deep ocean basins. Hard shells ("microfossils") of single-celled plants (diatoms, coccolithophorids) and animals (Radiolaria, Foraminifera) that grow as plankton in surface waters are components there (Fig. 2). Marine sediments record the various processes of sediment supply and formation. The record, however, is overprinted by redeposition induced by bottom current, dissolution of microfossils and bioturbation (stirring by benthic organisms). All those processes are controlled by climate and thus allow climate reconstruction through time, which is the key contribution of marine geology to the recent findings and discussions about Global Warming.

Ice is the dominant factor in the sedimentary processes in polar oceans. Sea-ice cover limits the light in surface water and the immediate input of nutrients by wind, both crucial for plankton growth. In the Arctic Ocean, sea ice also transports sediments supplied by rivers to the open ocean. The ice sheets and glaciers of Greenland and of Antarctica erode large amounts of rock debris from the underlying continent and deliver it to the sea. Calving icebergs act as rafts for the debris and release it when they melt, often far away from the source. During glacial periods, the global ice budget was enlarged by additional ice sheets in Europe and North America, which led to the formation of thick glaciomarine deposits in the adjacent oceans. Ice does not sort detritus during erosion and transport, and therefore those sediments contain particles with diameter size ranging from less than a micron to several metres(Fig. 3).

In the glaciated Arctic Ocean, sediment supply mainly depends on the input of terrigenous detritus. An almost permanent sea ice cover hampers plankton production, resulting in very low concentrations of microfossils in the underlying sediments. This lack of microfossils also hinders the exact dating of the Arctic marine records. In the Southern Ocean, the distribution of distinct marine sediment types shows a zonal pattern, dictated by oceanography and the distance from the continent (Fig. 4). The Antarctic coast is surrounded by a belt of unsorted sediments called diamictons that were deposited near to or even below the base of the ice sheet. Glaciomarine silty clay characterises the Antarctic continental margin, and its fine-grained fraction increases with distance from the shelf. Other shallow parts of the Southern Ocean are covered with calcareous ooze. Most of the seafloor in the deep-sea basins is covered with terrigenous clay because these basins are located below the "carbonate compensation depth" (CCD), at which calcareous microfossils are completely dissolved before reaching the seabed. At the Polar Frontal Zone (PFZ) (see Fahrbach et al., this book), the surface water is rich in nutrients providing food for a high primary production of diatoms. Consequently, the sediments below the PFZ consist of siliceous (opaline) diatom frustules, referred to as the Circumpolar Opal Belt.

The deposition of relatively high amounts of organic matter, a process which is called the "Biological Pump", removes carbon dioxide from the atmosphere (see Bathmann and Passow, this book). Paleoceanographic studies revealed a close relationship between variations in the deposition of diatoms in the Southern Ocean and global fluctuations of atmospheric carbon dioxide – as documented in Antarctic ice cores –

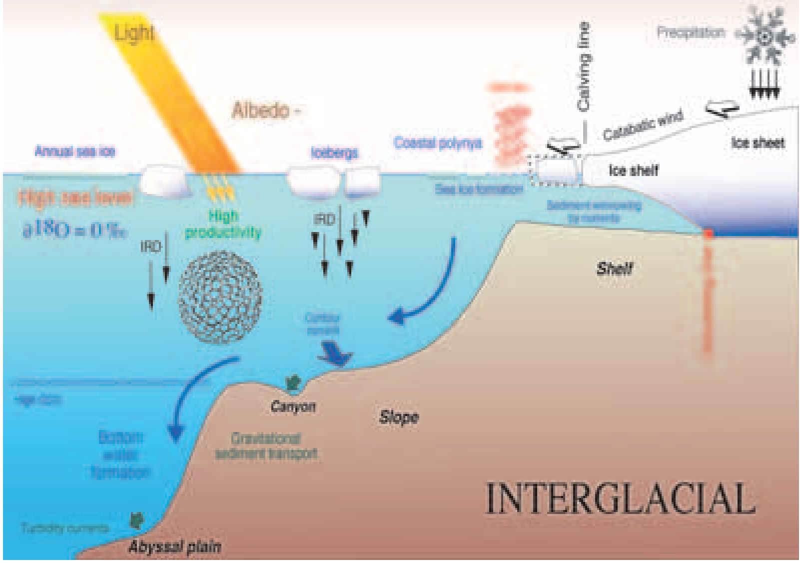


Fig. 6:
Sketch of glaciomarine sedimentation at the margin of an ice-covered continent during interglacials (a) and glacials (b).
a.During interglacials, sediment is eroded by the continental ice and rafted by icebergs. Sedimentation in the proximal areas of an ice-covered continent are dominated by ice- rafted debris (IRD), gravitational transport down the slope, supplemented by plankton shells and their hemipelagic sedimentation from the water column. A lower albedo during summer is due to a reduced sea-ice coverage which on the other hand allows a higher heat flux into the atmosphere and thus increased evaporation and precipitation.

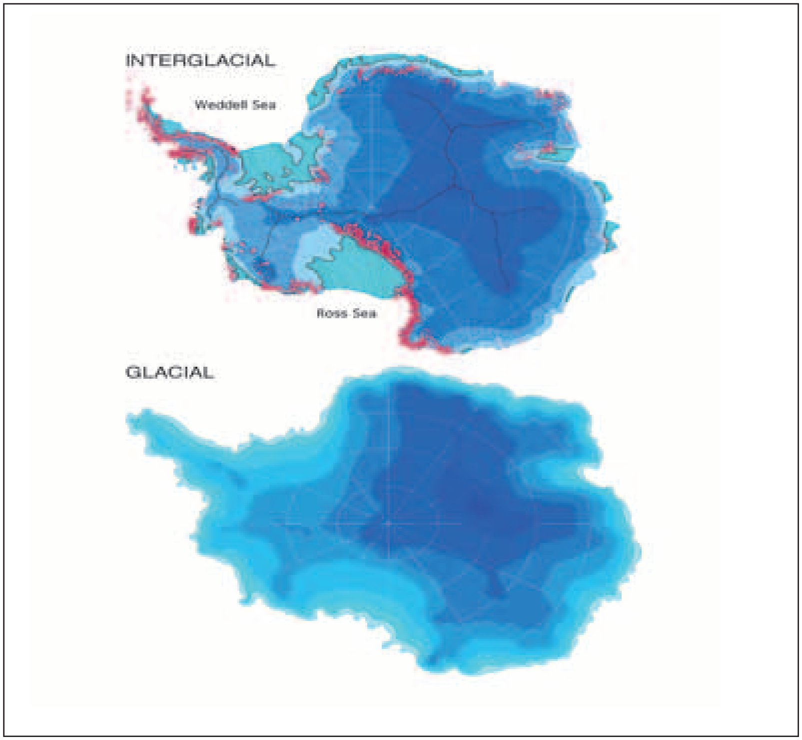
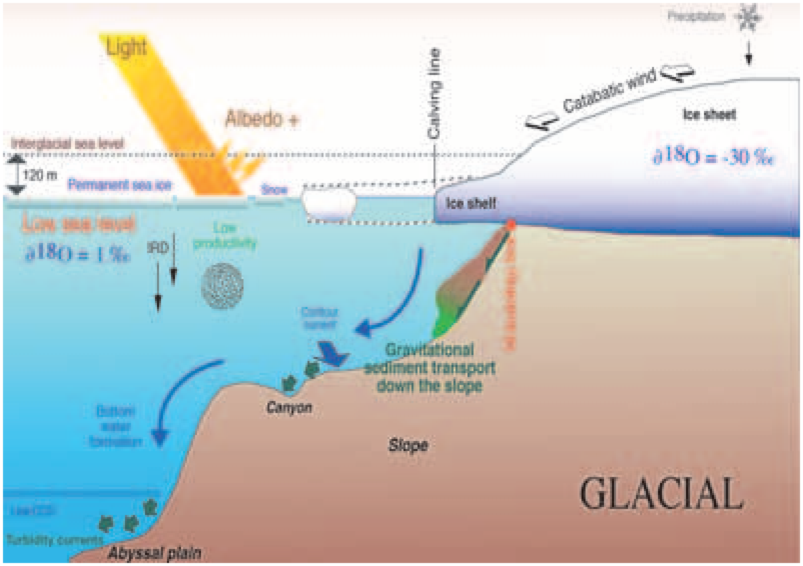


Fig. 5:
Minimum (upper, Interglacial) and maximum (lower, Glacial) extension of the Antarctic ice sheet during the Quaternary climatic cycles. Shaded blue indicate height steps of 500 m; in the upper graph, turquoise marginal areas are shelf ice, red areas are exposed continent not covered by ice, lines are flow lines (thin) and ice divides (thick).The glacial ice sheet mostly extends due to sea level. More marginal ice on the shelf is grounded and the ice sheet thickens due to increasing back pressure.



b. During glacials, gravitational sediment transport is dominant. A lower sea level pro-vides suitable conditions for bulldozed de-posits from the shelf by the advancing ice sheet. Primary production is reduced due to missing light in surface waters under permanent sea-ice cover-age which also prevents icebergs to calve and distribute their sediment loads.

for at least the last 800 thousand years (ka). Also on longer time scales, changes in biosiliceous opal sedimentation patterns were obviously coupled with global climate events, such as the mid-Miocene and late Pliocene cooling steps.

Messages from the plankton

Species assemblages and chemical composition of microfossil shells provide various parameters for paleoclimatic reconstructions (Mackensen et al. 2001; Abelmann et al. 2006). Biogenic components of marine sediments consist mainly of whole and fragmented tests of planktonic, and to a lesser extent, benthic organisms. Composition and richness of the assemblage of dead organisms on the seafloor change during the sedimentation due to processes in the water column, at the seafloor and finally within the seabed. Only this modified dead assemblage is preserved in the geological record sampled by the sediment corer. Additionally, the benthic infauna masks the original assemblage by bioturbation. Thus, geologists are forced to develop tools for the reconstruction of the original environment by unravelling those processes of alteration.

Ice ages in ice

In the twenty five years following the first retrieval of sediment cores by *Polarstern* near Kapp Norvegia, the geological approaches described above have yielded a good picture of the variability of climate related glaciomarine processes through-out the Quaternary. This period is characterised by dramatic climate changes induced by small variations in the geometry of the Earth's orbit, amplified by feedback mechanisms in the climate system. Considering the last few hundred thousand years, the recent two major glacial periods were interrupted by relatively short warm phases. The present warm interglacial stage, the Holocene, began approximately 11,000 years ago.

The coastal areas play a key role for sediment input and life cycles in the nearby oceans. As ice grounded on land flows across the coastline, it starts to float, thereby producing ice shelves or glacier tongues. Over 40% of the Antarctic continent is surrounded by floating ice shelves that calve tabular icebergs, typical for the Antarctic. A large quantity of terrigenous sediment particles follows this transport pathway of the ice, from erosion on the continent to deposition on the ocean floor. Sea ice, and further offshore, hydrographic zones and frontal systems influence plankton production and thus the biogenic components of the marine sediments. Ice sheets, sea ice, sea level and oceanographic systems vary in space and time at different frequencies and with different amplitudes, controlling and controlled by changes in the global climate system. The marine sediments provide a smoothed reflected image of those long-term variations.

In the following, we present a depositional model which illustrates the glaciomarine sedimentary processes and environments on the Antarctic continental margin during a glacial-interglacial cycle. The model is based on the investigation of a comprehensive suite of sediment cores from expeditions by the *Polarstern* and also considers oceanographic and glaciological conditions.

Interglacial situation

The strongest changes of sedimentary conditions occur during the short transition from a glacial to interglacial period. In response to ice sheet melting predominantly on the northern hemisphere, sea level rises by ca. 120 m within 10,000 years, which results in the "lift-off" of previously grounded parts of the Antarctic ice sheet, retreat of its grounding line and the enlargement of shelf areas towards the continent (Fig. 5 upper part). Iceberg calvings increase, and hence redeposition of shelf sediments by icebergs and transport of iceberg rafted debris to the deep sea.

In the interglacial (Fig 6a), sea-ice cover is subject to pronounced seasonal variations. In winter, sea ice covers 20 million km^2. During the short summer, it may shrink to just 4 million km^2. Light and nutrient supplies to the surface water layer during the summer trigger short-term but intense blooms of plankton, especially along the retreating sea ice margin.

Hence, the geological record of the interglacial climate optimum is characterised by sediments rich in biosiliceous microfossils. Calcareous foraminifera thrive in the surface waters as well. Their shells sink through the water column, but are dissolved quickly.

During warm times, the remineralisation of organic matter by bacteria is responsible for a high content of dissolved carbon dioxide in pore and bottom waters. This process promotes a shallowing of the CCD. Only siliceous microfossils are preserved in the sediments.

Benthic organisms benefit from a high food supply and cause intense bioturbation of the sediments. Bottom water production in areas with major ice shelves contributes to a distinct grain size distribution and mineralogical composition of the marine sediments, and thus generates a facies typical for warm periods. Strong "catabatic winds" originating from the interior Antarctic ice sheet blow sea ice offshore, thereby forming open-water leads near the coast called "coastal polynyas". The surface water within these polynyas freezes quickly, thereby continuously releasing highly saline seawater of low temperature. In a similar process, the salinity of seawater circulating under the ice shelves increases. The resulting water mass of high density flows down the slope and forms the Antarctic Bottom Water (AABW). This water mass is of crucial importance for the ventilation of the deep Atlantic Ocean and the global thermohaline circulation (see Fahrbach et al., this book).

Glacial situation

The mass budget of the Antarctic ice sheet is controlled by precipitation, air temperature and sea level. During glacial periods the precipitation diminishes due to lower temperatures and perennial sea ice coverage all around the continent preventing evaporation from the ocean surface. On the other hand, the severe drop in sea level as a result of the formation of ice sheets on the northern hemisphere causes a seaward migration of the grounding line of the Antarctic ice sheet enlarging the total area covered by continental ice. When grounded ice advances to the shelf break, it bulldozes large volumes of glacial sediment across the shelf edge, which then slides further downslope. Gully systems cut into the slope guide turbidity currents far into the deep sea. The calving of icebergs and thus sediment transport by ice rafting is reduced during glacial times.

During glacials, the extent of sea ice also increases (Fig. 5 lower part). Marine sediments from the Atlantic sector of the Southern Ocean document that the sea ice extent during glacial summer corresponded to the present maximum winter extent, the seasonal variations occurred further north in the PFZ which also shifted northwards (Mackensen et al. 2001). The reduced light and nutrient supply to the surface water under snow-covered sea ice strongly reduced plankton productivity, resulting in low contents or even lack of micro-fossils in the sediments (Fig. 6b).

The shutdown of plankton production during glacial maxima created hostile conditions for benthic life on the seafloor and resulted in the deposition of undisturbed, laminated sediments on the Antarctic continental margin. Bottom currents flowing along the bathymetric contours parallel to the slope delivered fine-grained terrigenous particles and deposited them as laminated clayey sequences.

The coverage of the Antarctic shelf with grounded ice and the permanent sea ice cover further offshore probably reduced the formation of bottom water masses because they prevented the processes responsible for AABW production (see above).

Life around the sediment

Glacial history and related processes of erosion and deposition have influenced life in the polar oceans. The major glaciation of Antarctica started at about 34 Ma allowing evolution sufficient time for fauna to adapt to a polar environment. A high diversity of distinct organism groups and the occurrence of several endemic species are presumably related to the long time span of isolation of the Antarctic ecosystem. This is also the main difference to the Arctic Ocean. Within the Quaternary the shelf seabed with its benthic fauna were completely reworked by the advancing ice. The habitat of the shallow water benthos was dramatically reduced or even extinguished. The history of changes in marine biodiversity has been described by Gutt in this book.

Numerous *Polarstern* expeditions have investigated the status of recolonisation of the Antarctic shelf during the Holocene. An impressive richness of species and high density of organisms were observed on many parts of the shelf and thus provide evidence that the bottom fauna has already recovered since the last glacial period (see Arntz and Gerdes, this book). Reconstruction of the paleoproductivity during climatic cycles is performed by studies on microfossil content, bioturbation and proxy parameters such as opal, carbonate, organic carbon and biogenic barium content of the sediments. The alternating facies produced by low plankton productivity during glacials and intense productivity during interglacial maxima is comparable to the seasonal variations bet ween polar winter and summer. Its geological reconstruction allows the quantification of the efficiency of the biological pump at high latitudes. This meachnism is most important for the transfer of organic matter to the deep sea. It extracts carbon dioxide from the global biogeochemical cycle by storing it within the seabed sediments for geological times (a.o. Abelmann et al. 2006, see also Assmy et al., this book)).

For further reading and information: The "Reports on Polar and Marine Research" issued by the Alfred Wegener Institute, including cruise reports of *Polarstern* expeditions and theses, as well as articles published in the journal "Polarforschung" are available in Open Access via: http://www.awi.de/en/infrastructure/library/awi_periodicals *Polarstern* expeditions with links to stations, data and abstracts of related publications ("Polarstern abstracts") are listed at http://www.awi.de/en/infrastructure/ships/polarstern/detailed_ expedition_schedule/