The record of sea level changes in the Antarctic

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Zusammenfassung

Die spätquartären Sedimente am antarktischen Kontinentalhang im Bereich des östlichen Weddellmeeres sind für Rekonstruktionen der Paläoumweltbedingungen gut geeignet. Zwei ausgewählte Kerne vom oberen Hangbereich, die einen Zeitraum von 300 ka erfassen, wurden detailiert sedimentologisch analysiert. Die Alterseinstufungen basieren auf einer Lithostratigraphie, die mit einer Sauerstoffisotopenkurve korreliert werden konnte. Die Ergebnisse aus den Analysen der Tonmineralvergesellschaftungen, Korngrößenverteilungen und Sedimentstrukturen zeigen erstmals im marinen Bereich eine Fazies, die eindeutig darauf hinweist, daß sich der antarktische Eisschild im Glazial bis zur Schelfkante ausgedehnt hat.

Die Veränderungen von Ausdehnung und Volumen des Eisschildes wurden auch in numerischen Modellen simuliert. Veränderungen der Akkumulationsraten und der Eistemperatur spielen eine nur untergeordnete Rolle; das Modell zeigt, daß die Veränderungen vorwiegend durch eustatische Meeresspiegelschwankungen angetrieben werden und sich der Eisschild im letzten Glazial bis zur Schelfkante ausgedehnt hat. Dieser Zusammenhang impliziert, daß die maximale Eisausdehnung direkt mit dem Umfang und der Dauer einer glazialen Meeresspiegelabsenkung gekoppelt ist. Die Ergebnisse der sedimentologischen Untersuchungen, wie auch der Modellierung zeigen, daß Veränderungen des antarktischen Eisschildes allein von den Glazialstadien auf der Nordhalbkugel über den Meeresspiegel gesteuert wird.

Abstract

The late Quaternary sediment sequence of the continental margin in the eastern Weddell Sea are well suited for paleoenvironmental reconstructions. Two cores from the upper slope including the sedimentary record of the last 300 kyr, have been sedimentologically investigated in detail. Age models are based on a lithostratigraphy, correlated with a stable isotope record. As a result of a detailed analysis in particular of the clay mineral composition, grain size distributions and structures, the sedimentary record is the first marine evidence that the Antarctic ice sheet extended to the shelf edge during the last glacial.

The variations of volume and size of the ice sheet were also simulated in numerical models. Changes in accumulation rate and ice temperature are of some importance, but the model revealed that fluctuations are primarily driven by changes in eustatic sea-level and that the ice edge extended to the shelf edge during the last glacial maximum. This causal relationship implies that the maximum ice extension strongly depends on the magnitude and duration of the sea-level depression during a glacial period. The results of the sedimentological investigations as well as of the numerical models show that the Antarctic ice sheet follows glacial events on the northern hemisphere by means of sea-level teleconnections.

Introduction

In the geological past the volume of ice on Earth has undergone quite important changes. The global eustatic sea level is controlled directly by the quantity of ice stored in the polar ice sheets. In particular during the Paleogene and even more during the Neogene, ice masses have had a predominant influence on sea level. During the Quaternary period, the Earth´s climate has altered between warmer intervals similar to the present, and ice ages when the ice volume was considerably larger, possibly by a factor of 2.5 during the last glacial maximum. The resulting sea level changes of between 50 and 150 m during a glacial cycle were a direct result of the behavior of the great ice sheets (a.o. Denton and Hughes, 1981).

The critical relationships between ice masses and climate have become a major concern. Ice sheets do not simply respond to climatic change but are active components; there exist strong couplings between ice sheets, the atmosphere, the oceans, and the lithosphere. In addition, ice sheets tend to interact with the climate on long time scales of between 102-104 years, which has to be taken into account when dealing with paleoglaciological and sea level reconstructions from marine sediments.

The correlation between the waxing and waning of the ice sheets on the northern and southern hemispheres has been a matter of discussion since the beginning of this century, with the Antarctic ice sheet being the major problem. Ice and ocean in Antarctica influence the climate on Earth in a variety of ways and, in turn, changes in the global environment lead to fluctuations of the ice cover and thus sea level.

Generally speaking, there are three principal ways by which the Antarctic ice sheet responds to global climatic changes, namely by fluctuations in air temperature, precipitation rate, and sea level. During glacial periods less precipitation is generated above the ice sheet as a result of the lower water-vapour carrying capacity of the colder air, and the decreased evaporation in the Southern Ocean due to the closed sea ice cover. This makes the ice sheet shrink during glacials (Scott, 1905). In this particular case the Antarctic ice sheet may act in contrast to the Arctic glaciations.

Secondly, changes in snow accumulation rate and surface temperature have an influence on the ice sheet's thermal regime. Colder ice deforms less easily which will lead to a thickening. Conversely, decreasing accumulation rates makes cold ice advection towards the basal shear layers less effective, providing heat to induce basal melting. It has been suggested that this could lead to an ice surge, thereby creating a huge ice shelf in the Southern Ocean. The resulting increase in reflected solar radiation would then lead to the temperature drop needed to initiate the ice sheets on the northern hemisphere (Wilson, 1964). In this case the Antarctic triggers ice ages.

Hollin (1962) postulated the idea that glacial-interglacial expansions and contractions of the Antarctic ice sheet might be largely controlled by world-wide sea level changes, rather than by climatic changes. During times of extensive glaciation in the northern hemisphere, the eustatic lowering of the sea-level would lower the Antarctic grounding line and displace it northwards, allowing the ice sheet to expand onto the present continental shelf. This view has also been expressed elsewhere (Thomas & Bentley, 1978; Stuiver et al., 1981; Denton et al, 1989), but still awaits thorough experimental verification. If correct, it would fit the concept of the globally interlocked ice sheet system of Denton et al. (1986), where sea level changes provide the direct mechanism linking the Antarctic ice sheet to the northern glacial cycles.

In discussing this hypothesis, however, a distinction has to be made between the terrestrial East Antarctic ice sheet and the marine West Antarctic ice sheet. The reason for making this distinction is directly linked to the subglacial bed topography. In West Antarctica, the bedrock between the grounding line and the edge of the continental platform is generally rather flat, making the position of the grounding line very sensitive to changes in relative water depth. A change in eustatic sea level, for example, would cause an immediate shift of the grounding line in order to preserve hydrostatic equilibrium (Huybrechts, 1992). However, it is important to realize that grounding-line migration may also occur because of local changes in ice thickness. This is illustrated by the fact that in its effect on grounding lines, a 100 m thickening of the ice is equivalent to that of a 90 m lowering of sea level.

A reconstruction of the last glacial maximum (LGM) extent of the Antarctic ice sheet is crucial for the understanding of the link between the ice sheets on the northern and southern hemispheres and sea level. From a glacial dynamic point of view, the interactions with sea level and the resulting reconstruction is a complex matter, but modelling as well as the investigation of sediment samples have contributed to some new outcomes. During the last decade enhanced marine geological work with conventional drilling (ODP Legs 113, 119) and gravity and piston coring in the Southern Ocean has provided a number of sediment cores of excellent quality from shelf and slope of the Antarctic continent. These have improved our knowledge about the sedimentation processes on the margin with regard to the understanding of the behavior of the Antarctic ice sheet during natural climatic change

(Grobe, 1986, Grobe & Mackensen, 1992; Melles, 1991; Fütterer & Melles, 1990).

Sea level changes exercise a major influence on sedimentation processes on the Antarctic continental margin as well as on the amount of terrigenous detritus and the way it is delivered to the Southern Ocean. Sediment distribution and composition originating at the continental margin, can be traced further north into the area of the Antarctic Polar Frontal Zone. Processes and products of sea level variations which can be best investigated close to the continent, will be discussed in the following text in relation to the late Pleistocene climatic cycles.

Most of the models simulating the conditions during the last glacial maximum yield an enlarged and in most of the coastal areas fully grounded ice sheet extending to the edge of the continental shelf (Hughes, 1975; Denton et al., 1979; Huybrechts, 1992). In our paper we present the first sedimentological evidence within the Southern Ocean for those modelled glacial processes.

Environmental settings and methods

Continental margin bathymetry

The southernmost Atlantic between the East Antarctic Continent and the Antarctic Peninsula is called the Weddell Sea (Fig. 1). The distinct morphology of the Antarctic continental margin in the eastern part of the Weddell Sea off Queen Maud Land is largely responsible for the accumulation of undisturbed sediment sequences close to the continent, providing good conditions for the reconstruction of processes which are related to changes in the sedimentary environment. The margin can be divided into five major morphological units: (1) the partly overdeepened continental shelf (down to 500 m water depth) has a distinct shelf break, followed seaward by (2) a very steep and narrow upper continental slope with inclinations of up to 16°. The transition zone to a gently inclined midslope bench (3) occurs from west to east in decreasing water depths between 1700 m to 1200 m. The bench is 50 to 100 km wide, dipping seaward by 1.5° to about 3000 m water depth. The steep lower slope (4) locally shows inclinations of up to 30° (Fütterer et al., 1990). The continental rise (5) ends in the Weddell abyssal plain at about 4400 m water depth (Fig. 7).

The continental slope is deeply dissected by canyon systems, such as the Wegener Canyon off Kapp Norvegia (Fig. 1) with gullies cutting into the upper slope and shelf. The canyon is supposed to be an important conveyor channel for sediment transport to the deep sea especially during a glacial sea-level low-stand (Fütterer et al., 1990).

A detailed knowledge of the slope morphology was crucial for the sampling of this specific facies. From a morphological point of view the core locations of PS1023 and PS1392 are the best places to find sediments eroded from the shelf, transported a short but steep way down the slope, and deposited where a sudden decrease of the slope inclination occurs.

Ice sheet

The Antarctic ice sheet can be divided into three distinct parts: (1) the ice on the Antarctic Peninsula which mainly consists of many individual glaciers, (2) the West Antarctic ice sheet including the two large ice shelves named after Filchner and Ross, and (3) the East Antarctic Ice Sheet, with 85 % of the volume the largest part. Detailed morphometric features of this ice sheet, the world's largest with a total ice volume of 30 million km3, have been given in Drewry et al. (1982). Melting of the East Antarctic ice sheet would raise world-wide sea level by about 60 m. The corresponding figure for the West Antarctic is only 6 m, not because the ice sheet is smaller, but also because much of it is grounded below sea level thus displacing ocean water (Huybrechts, 1992). In addition, grounding below sea level makes the West Antarctic ice sheet more sensitive to disintegration triggered by a sea-level rise.

Ice shelves

The continental ice which is discharged towards the margins in the form of large ice streams, ends in ice shelves at least about 250 m thick. Ice shelves are the marginal parts of the Antarctic ice sheet between the grounding line and the calving line, and float in equilibrium with the ocean water above the continental shelf. Ice shelves are unique to the

Antarctic, where about half of the coastal perimeter consists of ice shelves and glacier tongues. Apart from the two largest ice shelves, the Ronne-Filchner and Ross Ice Shelves, mostly in the eastern Weddell Sea about 2000 km of the coastline are made up by ice shelves of a smaller size (Riiser-Larsen, Maudheim, Ekström, Jelbart, Fig. 1). These ice shelves are often fringed by ice rises or, towards their lateral margins, by parts of the coastline where the grounding line coincides with the calving line. Those points act as stabilizing pivots and thus contribute to the size and extent of the ice shelves. Because of the morphology of the slope and the glaciological setting of the ice sheet margin, the sedimentary record and environment of the investigation area are well suited for the reconstruction of processes related to sea level.

Sampling and methods

Sediment cores were recovered by gravity corer during expeditions of the German polar research vessel POLARSTERN (a.o. Fütterer, 1987, 1989, 1991) on transects perpendicular and parallel to the depth contours. Two sediment cores, which include the last climatic cycle, have been chosen for the discussion of sea-level related processes at the ice sheet margin. The sites are located on the uppermost part of the bench, well below the upper steep slope (Fig. 1). (PS1023, 71° 8.4´ S, 13° 36.2´ W, 1826 m, 6.88 m; PS1392, 70° 11.8´ S, 6° 43.5´ W, 1794 m, 6.30 m).

The cores were described (Figs. 2, 3) and sampled with a mean sampling interval of 10 cm. Samples were analyzed for carbon, silica, grain-size, clay minerals, ice-rafted debris, and stable oxygen and carbon isotopes on planktonic foraminifera. Sediment slabs were X-rayed for a better description of structures. Sedimentological data were produced using standard methods (Grobe et al., 1990). For the description of distinct sediment sequences two cores from a profile of the Ara Islas Orcadas Cruise 1578 were included (Fig. 1; IO1578-18, 70°33.6´ S, 10° 10.9´ W, 1039 m, 1.31 m; IO1578-19, 70° 32.4´ S, 10° 16.4´ W, 1339 m, 4.99 m; Kaharoeddin et al., 1980). The interpretation of the mineralogical composition of the slope sediments was supported by the clay mineral data of two short cores from the shelf off Kapp Norvegia (Fig. 1; PS1006, 71° 29.6´ S, 13° 16.3´ W, 234 m, 55 cm; PS1265, 71° 21.1´ S, 13° 24.5´ W, 229 m, 26 cm; Grobe, 1986).

Sedimentary record

Shelf sediments

During an interglacial sea-level high stand similar to present conditions, a residual sediment including all grain sizes is deposited on the shelf. One third of the facies is gravel (> 2 mm), sand is distributed through all subfractions without any changes. With decreasing grain size the <63mm-fraction is increasingly winnowed by the Antarctic Coastal Current (ACC) leaving behind a clay content of only about 10 %. A patchy high biological benthic productivity contributes to an opal content mainly by sponge spicules (Voss, 1990), and some carbonate by bryozoans and molluscs (Anderson et al., 1983).

Grain size distribution, biogenous content and texture of the sediment are typical for a residual glacial marine sediment as defined by Anderson et al. (1980). This sediment is deposited during high sea level off and below an ice shelf. Similar sediments were described at other localities from the Antarctic shelf around the Weddell Sea (Anderson et al., 1981; Elverhoi & Roaldset, 1983; Kaharoeddin et al., 1980). Far away from the ice front, where ice rafting is minor, a soft silty clay with abundant diatoms overlaying a stiff diamictite was found in the Ross Sea area. The diamictite is outcropping on swells and highs due to common erosion by grounded ice during a sea-level low stand (Drewry, 1979). There was disagreement about the age of this unit, but compared to other occurrences of diamictites on the shelf, it was most probably deposited during the last glacial maximum.

Similar sedimentary successions were found on the Weddell Sea shelf, where a stiff pebbly mud is overlain by a thin veneer of soft pebbly mud (Elverhoi, 1981), which was described at all sites as olive gray (5Y3/2, Rock Color Chart). The thickness of the residual glacial marine sediment was described as being up to one meter, and mean sedimentation rates were calculated between 0 and 3 cm/ka depending on the sedimentary conditions (Elverhoi & Roaldset, 1983; Grobe, 1986). Peak values in sedimentation rates are closely related to the rise of sea level during glacial terminations. The residual sediment facies was recovered and investigated in Cores PS1006 and PS1265 on the shelf (Fig. 1).

Due to the high gravel content of the shelf sediments it is hard to get long sediment cores with a coring device working by gravity. But in some longer cores a textural and mineralogical homogeneous diamictite was recovered below the residual glacial marine sediment, which was interpreted as being deposited by grounded ice (orthotill; Harland et al., 1966). The facies is characterized by a higher content of fine material, bad sorting, missing biogenous content, and a dark gray (N3, 5Y2/1) color (Harland et al., 1966; Anderson, 1972; Gravenor et al., 1984); it is also over-compacted (Elverhoi & Roaldset, 1983; Anderson, 1972). In the case that the gravel content allowed deeper penetration, in some areas the facies change between the residual glacial marine sediment and the orthotill was mapped by a sediment echosounding system (Grobe, 1986).

Slope sediments

Important evidence for the reconstruction of glacial erosion on the shelf and the concurrent sedimentation processes is provided by the sedimentary sequence of the upper continental slope. As an example Cores PS1023 and PS1392 will be described in detail, because both core locations are situated on the uppermost continental bench well below the upper steep slope. These are areas of high accumulation during downslope sediment transport by gravity.

Core PS1023 is located off Kapp Norvegia (Fig. 1). Due to the absence of an ice shelf at this site, terrigenous detritus from the continent is directly delivered to the continental shelf and slope. The sediments are mainly of the typical glacio-marine facies, as found in all locations in the eastern Weddell Sea. The olive gray (5GY4/1-2) mud contains a varying amount of sand, and some gravels are scattered throughout the core. The biogenous content consists of calcareous and arenacous foraminifera, radiolaria, diatoms, and a few sponge spicules. The siliceous particles are concentrated in distinct horizons. Sharp lithologic boundaries at 341 and 34 cm, where the color changes from greenish gray to light gray, indicate significant changes of the sedimentary environment. In between the color changes more gradually.

Below the sharp boundaries the color is dark greenish gray to dark gray, which is uncommon to sediments of this area. As can be observed in the X-radiographs, in particular the grain size within this unit changes rapidly between a homogeneous silty clay and a graded silty sand (e.g. 183-155 cm, Fig. 2). Any bioturbation is missing. Gravels are scattered throughout but also appear concentrated in distinct horizons. The coarse fraction (< 500 mm) of samples from these horizons contains a high amount of gravel and rock fragments, which have a similar composition as the rocks found on the adjacent shelf. In contrast the crystalline rocks found in the remaining part of this core or in other cores from the deeper slope, are of granitic or gneissic composition, which is typical to most of East Antarctica. A second horizon with similar mineralogical composition, color and texture occured in PS1023 between 403 and 377 cm.

Core PS1392 is located off the eastern boundary of the Ekström Ice Shelf, at a location where it is limited by an ice rise (Fig. 1). The slope morphology in this area is responsible for the deposition of an even more pronounced sedimentary structure indicating gravitational sediment transport downslope. The bioturbated mud in Core PS1392 is similar to the one found in PS1023 and in other cores of the slope (Grobe et al., 1990). At a depth of 372 cm the base of a sequence of proximal turbidites was found starting with gravels of up to 4 cm in diameter (Fig. 3). The gravel is grading upwards into coarse sand which again grades into fine sand followed by a sequence of laminated medium to fine sand. The uppermost part ending at a depth of about 350 cm, is an alternating sequence of bioturbated mud and graded sand layers. The turbidites are almost bare of biogenous particles in both cores.

At the continental slope off the eastern boundary of the Maudheim Ice Shelf at a water depth of 1339 m, a similar sequence was described in Islas Orcadas Core 1578-19 (Fig. 1) at a sediment depth of 180-149 cm (Kaharoeddin et al., 1980). The horizon consists of fine to medium sand interspersed with mud layers. Some boundaries are sharp and have irregular contacts. Close by, in a water depth of 1039 m, Core IO1578-18 is located at the upper steep slope of the continental margin. It has recovered sand of a dark gray (N3) color, fining upwards between 40 cm and the top. Between 131 and 40 cm the core consists of a sequence of poorly sorted pebbles and sedimentary clasts with interbedded mud of the same color (Kaharoeddin et al., 1980).

The clay mineral composition of the turbidites in Cores PS1023 and PS1392 shows a low illite content and corresponding peak values in chlorite, which are about twice as high as in the normal hemipelagic sediments. The clay mineral association is very similar to the one of the shelf sediments investigated in Cores PS1006 and PS1265 (Fig. 4). The mineralogy and petrology of the shelf sediments can directly be correlated with the petrographical composition of the rocks of the adjacent hinterland (Dreimanis & Vagners, 1969). In the investigation area this means that all terrigenous material deposited on the shelf is directly delivered from Queen Maud Land where the classification in petrographical provinces shows mainly Mesozoic, in most cases Jurassic basalts with different degrees of alteration (a.o. Peters, 1989; Oskierski, 1988). The source of chlorite may thus be the basic to ultrabasic rocks, where weathered olivine and pyroxene have formed chlorite.

The best example of a sediment unit which was gravitationally transported downslope and deposited in a typical proximal turbidite, was found in Core PS1392. At other locations additional indications may help to identify the shelf sediment units on the slope: the typical texture shows the absence of any bioturbation and/or graded bedding; a missing microfossil content may indicate the terrigenous origin. The high chlorite/illite ratio, the mineralogical composition, and the high amount of rock fragments and gravel suggests a relation with the residual glacio-marine sediments on the shelf, which is also supported by the petrology of the gravel. Sediment colors described from different core locations on the shelf close by (Anderson et al., 1981; Kaharoeddin et al., 1980; Elverhøi and Roaldset, 1983) correspond well to the typical olive gray color of the turbiditic facies (N3-5Y3/2).

Lithostratigraphy

The facies described are obviously turbidites composed of shelf sediments. To correlate the facies with distinct changes of sea level, a stratigraphy allowing the resolution of climatic stages and, as far as possible, events and terminations, is crucial. The problem with all interpretations of southern high latitude glacial and interglacial paleoenvironments is that they mostly suffer from the lack of a detailed stratigraphy due to the paucity of biogenic carbonate. This is the reason why cores from south of the Antarctic Polar Front were not included in the Quaternary chronostratigraphies (Martinson et al., 1987; Imbrie et al., 1984).

Rare carbonate, mainly consisting of the planktonic foraminifer Neogloboquadrina pachyderma, was found at the Antarctic continental margin around the Weddell Sea in a water depth of between 2000 and 4000 m (Anderson, 1972; Grobe, 1986; Barker & Kennett et al., 1990; Mackensen et al., 1990). Because today's masspectrometers produce acceptable results already with two tests, we were able to establish a first stable isotopic record for the late Quaternary on sediments from the Weddell Sea which could be correlated with the standard chronostratigraphy (Fig. 1, Core PS1388, Mackensen et al., 1989).

Further measurements of stable oxygen isotopes on some thirty cores in the investigation area have shown that in most of the cores interpretation of the data remains difficult. Diagenetic dissolution within the sedimentary column has altered the isotopic composition of the tests towards higher values by selectively removing the isotopically lighter carbonate, presumably as a result of the low carbonate content (Grobe et al., 1990). Cores PS1023 and PS1394 provide examples of this alteration (Figs. 5, 6).

Due to severe problems with most of the isotopic data, a lithostratigraphy was developed as a tool for dating the late Pleistocene sediments (Grobe & Mackensen, 1992). Comparison of the isotopic record with some lithological parameters as well as biogenic constituents has shown that significant changes occur at distinct times of global climatic change. Those variations can be correlated between cores, and were found to be similar in all sediments with similar sedimentation rates around the Weddell Sea. The new lithostratigraphy was produced by dating prominent lithologic changes in correlation with the isotope stratigraphy of Core PS1388. Age models for Cores PS0123 and PS1392 are based on this lithostratigraphy.

Carbonate and opal were plotted together with the content of sand and the most important clay mineral chlorite versus time for a detailed interpretation of the glacial and interglacial deposits (Figs. 5, 6). The occurrence of radiolaria indicates a high productivity during peak warm times, e.g. isotopic events 1, 5.5, and 7.5. At the same time, carbonate is dissolved due to the rise of the CCD. From moderate to enhanced glacial conditions (e.g. stages/events, 5.4-2) carbonate was found throughout both cores in slightly decreasing values. The corresponding terrigenous parameters show significant changes with the climatic deterioration. At the end of stage 5 with the onset of the glacial the amount of chlorite increases by roughly 25 % in Core PS1392 reaching peak values during stage 4 (Fig. 6). Stages 3 and 2 are characterized by a sequence of proximal turbidites, one of which is graded from gravel to fine silt. The corresponding clay mineral association may be hard to interpret due to the very low percentages of clay (2-5 %). With the onset of glacial termination 1, the sediment consists of mud when sand values decrease to 1-2 %. A further peak value in chlorite of up to 40 % is found during the termination prior to the final decrease to 10-20 % which is typical of interglacial conditions.

A similar distribution of the biogenic and terrigenic parameters can be observed in Core PS1023 (Fig. 5). During glacial stage 6 as well as in stages 2 to 4 an increase in chlorite with peak values during the beginning of the glacial is followed by graded sand layers. Gravel was found to be concentrated in layers during stage 4. A higher amount of gravel was also found during termination 1. When the coarse fraction has diminished to a few percent, a further chlorite maximum of up to 45-60 % occurs during the terminations. Also in Core PS1023 the normal interglacial chlorite content during events 1, 5.5 and 7.5 is about 10 %.

Response of the depositional environment to sea level changes

Interpretation of the late Pleistocene sediment sequence of Cores PS1023 and PS1392 from the upper continental slope can be used to reconstruct the distinct glacio-marine environments during a climatic cycle, and to synthesize a general relationship between sediment facies and sea-level changes.

Interglacial
One of the most important climatic events for the sedimentary conditions on the upper slope is the transition from a glacial to an interglacial period. A substantial change in the sedimentation process is triggered by a rising sea-level, which causes marginal parts of the Antarctic ice sheet to float. The recession of the grounding line produces broad ice shelves with a high amount of basal debris still incorporated at their base. Within a short geological time the size of the ice shelves is reduced by intense calving processes. The retreat of the ice margin may last several thousand years. Additionally, the increase in the flux of warmer North Atlantic Deep Water (NADW) to the Circumpolar Deep Water (CDW) with the onset of an interglacial may promote the melting of ice shelves and icebergs.

The basal debris is transported by the icebergs off the shelf, and contributes mainly to the sedimentation on the slope. The terrigenous sedimentation will reach its normal interglacial stage, when the postglacial ice shelves reach a stationary configuration. The transport of a huge amount of sediment by ice-rafting is the main process during the initial phase of an interglacial, and is responsible for an increase in sedimentation rates by an order of magnitude above that of glacial conditions. A high content of gravel and chlorite in the sediments document the sediment transfer from the shelf to the slope. Because those processes are directly linked to the behavior of the Antarctic ice sheet, their might be a response time of 10 to 15 kyr between sea-level rise, the changing mass budget of the ice sheet and the sedimentary record. The final change in the sedimentary environment from processes mainly controlled by the recession of the ice shelves to stable sedimentary conditions during interglacial stages 1 and 5 occurs at the climatic optimum, indicated by a sharp lithologic and color boundary in the sediment. Beginning with this stage, the shelf acts as a trap for most of the sediments delivered by the continental ice, resulting in a significant decrease in sedimentation rates at the slope.

Three main processes contribute to the deposition of sediments at the continental slope during an interglacial: biogenous productivity, current transport and ice rafting (Fig. 7). Productivity is controlled by light which in turn is related to the sea ice coverage. Hard parts of microfossils produced by this process, make a content of 10-15 % of the bulk sediment. The ratio between the sedimentation from contour currents and ice rafting varies with the distinct climatic conditions and with the distance from the continent. For instance on shelf and upper slope, sediments are mainly derived from the hinterland of the investigation area, and thus originate from the bedrocks in Queen Maud Land. This is indicated by chlorite as the dominant clay mineral and tholeitic basalts found as dropstones and in the gravel fraction (Oskierski, 1988). On the lower slope ice rafting will produce sediments of a more "general East Antarctic composition" with mainly illite in clay and granitic or gneissic composition of dropstones, gravel and sand fractions.

Glacial
During glacial times the Antarctic Ice Sheet is indirectly coupled to global cooling by processes on the northern hemisphere. The expansion of the Antarctic ice sheet is mainly caused by the sea-level lowering resulting from the build-up of large ice sheets in Scandinavia, Siberia, and North America. During the transition from interglacial to glacial, the lowering of sea-level induces a seaward movement of the grounding line, and thus an enlargement of the grounded continental ice. Ice shelves are also displaced seaward and may finally float above the slope (Fig. 7).

With the Pleistocene sea-level changes the ice margins have oscillated several times across the entire continental shelf, and repeatedly the grounding lines coincided with the shelf edge. Grounding of ice shelves occured in parts of East as well as West Antarctica, but predominantly took place in areas with broad continental shelves. During the advances of the continental ice, the shelf was filled up with tillitic sediments. Similar depositional processes, which were not the result of sea-level changes, but were formed by ice advances during the cryospheric development of Antarctica, are represented by sequences of at least Miocene/Pliocene age, found off broad ice shelves (Hinz & Krause, 1982; Miller et al., 1990).

During a sea-level low stand the surficial shelf sediments become available for ice erosion and subsequent redistribution. Gravitational sediment transport is the most active mechanism (Fig. 7). Close to the continent, increasing transport down the slope triggered by the advancing ice edge, is responsible for a higher amount of coarse detritus, an increase in sedimentation rates, and changes in the composition of clay mineralogy. The beginning glacial is indicated in the sediments by an increase in chlorite which is mostly delivered from the shelf. Canyon systems such as the Wegener Canyon branching up to the shelf break, serve as preferred pathways for sediment transfer to the deep sea by turbidity currents. Thus, in particular during glacials deep sea terrigenous sedimentation is strongly influenced by ice-margin processes and preferred depositional areas in the deep sea like the Weddell Fan (Anderson et al.,1986) are fed with sediments.

The proximal turbidites in Cores PS1023 and PS1392 which indicate the coincidence of the grounding line with the shelf edge, are found at different times. In Core PS1023 an increase of sand and chlorite can already be found at stage boundary 5/4, the first gravel is found within stage 4. Also Core PS1392 shows an increase in chlorite at the boundary of isotopic stages 4 and 5 but turbidites occur not before stage 3. A more exact dating of the specific layers is not possible due to the missing of stratigraphic fix points in this part of the core.

From the results above it is obvious that turbiditic events, triggered by the advancing ice edge, will not happen synchronously at all parts of the continental margin because of to the different morphological settings of which the water depth of the shelf is the most important parameter varying between 200 and 500 m. In most parts of the Antarctic coastline, the shelf is significantly deeper than a shelf of a non-glaciated continent due to isostatic compensation to the load of the ice sheet on the continent. Also the size of the adjacent ice shelf, i.e. the distance between the calving line and the grounding line, and the distance and bedrock slope between the calving line and the shelf edge are morphological parameters which control the displacement of the grounding line during sea-level lowering. The final composition of the deposits at the slope and in the deep sea is related to sorting processes during transport down the slope, and thus depends on slope morphology and inclination.

Also in the southernmost Weddell Sea, off the broad Filchner Shelf, gravitational sedimentation processes were important to sediment redeposition at the slope most probably only during the last glacial (Melles, 1991). The coincidence of the ice margin with the shelf edge and the complete coverage of the shelf by grounded ice was believed to have occurred later than 31 kyr ago. The ice advance was accompanied by erosion of shelf sediments, and a high sediment transport from south to north. The erosional surface can be seen in the sediment echosoundings as an even, hard reflector. Turbidity currents, slumps, and slides were the result of an enhanced sediment redistribution at the upper continental slope. Peak values in sedimentation rates during sea level low stand north of the Filchner Trough are explained by the activity of the ice margin in addition to a concentration of ice flow lines in the trough (Melles, 1991).

Because sea-level lowering and ice advances are the triggers of turbiditic sedimentation, a huge amount of shelf sediments is delivered to the slope within the relatively short time of a glacial maximum. The combined action of processes as sea-level lowering, ice advance, turbidity currents and debris flows is responsible for current entrainment and distribution of a large amount of clay within the Southern Ocean. One of the most important processes is supposed to be the distribution of clay by thermohaline convection. Cold surface water of higher salinity produced in coastal polynyas, flows down the slope. It is responsible for the entrainment of suspended sediments which are made available at the shelf edge by the advancing ice (Melles, 1991). Further transport parallel to the slope is provided by contour currents (Fig. 7). At least parts of the fine fractions suspended by the different processes, will be entrained by currents and transported clockwise with the Weddell Gyre, and finally with the Circum Antarctic Current. The fine fractions are also transported to the north presumably by the Antarctic Bottom Water, and may influence the sediment composition in the South Atlantic.

At the Antarctic continental margin different environments were reconstructed and discussed, which have provided conditions for high accumulation rates of the fine, current derived material. During glacial maxima a thick and closed sea-ice cover off an ice shelf may develop and stay attached to the ice shelf. Stable sea-ice conditions increase the size of the ice shelf areas by stabilization of their margins and protect them against weakening by waves. The ice shelf expands on the slope and below, in a calm environment which is not influenced by any other transport processes, contourites are deposited, characterized by a high amount of current-derived smectite (Grobe, 1986; Grobe & Mackensen, 1992, Fig. 4).

On the other hand, deposits mainly consisting of clay and fine silt, were found in the vicinity of canyons. In the area north of the Filchner Trough spill-over sediments deposited at the margins of canyons by turbidity currents, were found with a thickness of several meters. The laminated units, which are similar in composition and structure to the contourites, were deposited during the intense redepositional and gravitational transport processes off the ice stream, which has filled the Filchner Trough during the last glacial sea-level low stand (Melles, 1991).

The deposition of similar deposits in the southeastern Weddell Sea off Halley Bay were found to be related to a channel system at the lower slope, which is also most active during glacials in producing levee sediments with sedimentation rates of up to 2.5 m/kyr during a glacial maximum. All clay deposits show excellent laminations in a thickness range of several hundred microns, which can be interpreted as a real varvity (Weber, 1992).

Response of the West and East Antarctic Ice Sheets to sea-level changes

Full agreement on the size and extent of the Antarctic ice sheet during the LGM has not yet been reached, and different reconstructions have been proposed. Most of the controversy revolves around the size of the marine ice sheet in West Antarctica. This ice sheet largely rests on a bedrock below sea-level, even if isostatic depression was not accounted for, and may have completely filled the continental shelf during maximum glaciation and sea-level low stand. There seems to be a general concensus that this was indeed the case in the Weddell Sea, but views still differ whether the shallow Ross Sea was completely land-ice covered, or there was only a minor expansion.

The maximum view was taken by Stuiver et al. (1981), who presented a LGM reconstruction of the Antarctic ice sheet as part of the CLIMAP project in the late 1970's. Their reconstruction was based on available geological data from ice-free areas in mountains adjacent to, and projecting through, the former expanded ice sheet. According to their tentative reconstruction, grounded ice expanded close to the edge of the continental shelves in both the Ross and Weddell Seas. This would have resulted in a unification of the East and West Antarctic ice sheets to form a radially symmetric ice cap in part overriding the Transantarctic Mountains. In East Antarctica the expansion of the marine margin to the shelf break could only have occurred over quite short distances (typically 75 to 90 km depending on bedrock slope) leading to a relatively minor interior thickening. The total ice volume during the LGM would have increased by about 10 x 106 km3 to 37.1 x 106 km3, which is equivalent to a 24.7 m sea-level fall.

In contrast Drewry (1979) argues that the CLIMAP reconstruction represents only one possible and probably extreme case. He proposed an alternative working hypothesis, in which he kept an expanded ice shelf regime over the major part of the Ross Sea throughout most of the last glaciation. This follows from bathymetric and glaciological considerations, since a sea-level depression of 120-130 m sustained over more than 10,000 years (an exceptional situation) would be needed for the ice shelf to fully ground in the Ross Sea. Limited support for Drewry's hypothesis is provided by marine sedimentary studies below the Ross Ice Shelf (Kellogg and Kellogg, 1981), but the most convincing evidence for a minimum West Antarctic ice sheet comes from the glaciology of the Byrd ice core. According to Whillans (1976) the surface elevation near Byrd Station shows only small changes over the last 30,000 years, if it is assumed that no flowline migration took place. Moreover, analysis of the air content in the Byrd core seems to indicate that the West Antarctic ice sheet was actually thinner during the last part of the recent ice age, and that a 200-250 m thickening occurred only after the end of the last glaciation (Raynaud and Whillans, 1982, who attribute this to increased accumulation rates). These results do not favour the Stuiver et al. (1981) reconstruction which requires a thickening of some 1700 m at Byrd Station during the Wisconsin maximum.

Since the theoretical CLIMAP reconstruction based in many places on little data, more geomorphological and glacial geological data have become available implying that some amendments are necessary. With respect to the Weddell Sea region it is obvious that the late Wisconsin ice sheet indeed extended to the edge of the continental shelf. In addition to the results presented in this paper, other findings support the theory of a fully ice covered shelf. Elverhøi (1981) describes sedimentological data which clearly suggest grounding of the Filchner-Ronne Ice Shelf down to a water depth of 500 m. Even the Filchner Trough down to -1000 m seems to have been covered by grounded ice, suggesting a considerable increase in ice thickness as well (Melles, 1991). Further support for widespread grounding is provided by the presence of fresh striations and erratics on nunataks. These have been found at elevations of up to 500 m above the current ice surfaces along the Orville Coast (Carrara, 1981), and the Lassitter Coast (Waitt, 1983). Both areas lie on the east side of the southern Antarctic Peninsula, adjacent to the Ronne Ice Shelf and the Weddell Sea respectively. Similar evidence for a thickening of 1000 to 2000 m has been reported at the head of the Filchner-Ronne Ice Shelf, based on trimline elevations in the Heritage Range, Ellsworth Mountains (Rutford et al, 1980).

Also in the Antarctic Peninsula area, Clapperton and Sugden (1982) postulate a late Wisconsin maximum ice cover in broad agreement with CLIMAP, although their geomorphologic observations did not support ice flowing from the Peninsula axis across Alexander Island to the edge of the continental shelf in the west. Rather, they believe that separate ice domes were centered over both Alexander Island and Palmer Land. Grounded ice probably expanded to the continental shelf break elsewhere in the Pacific sector as well. This is indicated by the presence of basal tills in such critical locations as Marguerite Bay along the Antarctic Peninsula (Kennedy and Anderson, 1989), and Pine Island Bay in the Amundsen Sea (Kellogg and Kellogg, 1987).

Further support for the theoretical CLIMAP reconstruction comes from additional, though still sparse evidence for Wisconsin margin positions in East Antarctica. Adamson and Pickard

(1983) reviewed data (mainly glacial striations) for a late Wisconsin advance of the ice sheet across the Vestfold Hills region, an oasis near the Australian Davis Station. The striations clearly indicate recent (25,000-10,000 years BP) overriding in a direction pointing radially outwards. Also submarine terminal moraines seaward of the Ninnis and Mertz outlet tongues are in good agreement with the Stuiver et al. reconstruction (Domack et al., 1989). Here, the ice sheet expanded over a distance of 150 km to a position where the water depth is some 400 m below contemporary sea level.

In contrast, it appears that the controversy which centered around the history of the marine ice sheet in the Ross Sea, is still not resolved. The available data are still open to a considerable degree of interpretation and at best only constrain a maximum and minimum reconstruction (Denton et al., 1989). The problem is that dated evidence on the sea floor is still lacking. The ice sheet margin therefore has to be estimated from the altitude of lateral moraines in the Transantarctic Mountains. Both the maximum and minimum reconstructions of Denton et al. (1989) depict little change (compared to the present) of the inland plateau surface adjacent to the Transantarctic Mountains. However, the major difference between the two reconstructions lies in the areal extent of grounded ice in the outer Ross Embayment. Here, the late glacial extent could have varied from a position close to the continental break to several ice lobes with low surface slopes covering only the inner embayment.

Data of total gas content from deep ice cores now seem to indicate that ice-surface elevations in interior East Antarctica at the LGM were little different from today. Even a thinning may have occurred in some areas (Anderson, 1991). This is assumed to be a direct consequence of lower accumulation rates. Based on 10Be concentrations in the Vostok ice core it has been declared that precipitation rates over the Antarctic plateau were roughly halved during the last glaciation (Yiou et al., 1985).

Different sections of the ice sheet margin may have moved out of phase with the Antarctic ice sheet as a whole. This is the case for the small local glaciers in the Dry Valley area of Victoria Land in the Transantarctic Mountains. These glaciers originate from a local dome, which is subject to different glacio-climatic controls than those affecting the bulk of the ice sheet. Unlike more complex behavior elsewhere, such a local dome essentially responds to changes in precipitation amounts. Since this precipitation comes primarily from air advected over the Ross Sea and regulated by such factors as seasonal ice cover and degree of open water, glacier advances only occur during the warmer interglacials. Conversely, the Victoria Land glaciers retreated during glacials mainly because of reduced precipitation rates, when on the other hand episodes of global sea-level depression caused expansion of ice across the continental shelf, and a thickening elsewhere (Drewry, 1980; Denton et al., 1991).

From the sedimentological record no direct information can be extracted about the thickness distribution of the Antarctic ice sheet during the LGM, which has to be derived from modeling studies. New results were recently obtained from a computer simulation of the ice sheet during the last climatic cycle (Huybrechts, 1992). In this study the total ice volume at 16 kyr BP was found to increase by 5 x 106 km3 to 31 x 106 km3, mainly due to spreading of grounded ice across the Ross and Weddell Seas (Fig. 8). This corresponds to a global sea-level drop of around 12 m, which is only half of the value obtained in the CLIMAP reconstruction. The discrepancy appears to be due to the more sophisticated modelling, the incorporation of thermomechanical coupling, and the inclusion of a more realistic forcing. Consistent with the more recent findings described above, however, the model confirms that surface elevations over the East Antarctic plateau were not higher at the LGM, and that grounding in the Ross basin was not entirely completed. This is attributed to the long response time scales involved. Though changes in accumulation rate and ice temperature were also of some importance, the model experiments revealed that fluctuations are primarily driven by changes in eustatic sea-level. This causal relationship implies that the maximum ice extent strongly depends on the magnitude and duration of the sea-level depression during the final stage of a glacial period. It furthermore supports the hypothesis that the Antarctic ice sheet basically follows glacial events in the northern hemisphere by means of sea-level teleconnections.

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Figure Captions:

Fig. 1. Investigation area at the Antarctic continental margin in the eastern Weddell Sea with gravity and piston core locations.

Fig. 2. Section of Core PS1023 between 155 and 183 cm, showing the only sequence of alternating layers of silty clay and silty sand with scattered gravel. Most of the sediment is intensively bioturbated.

Fig. 3. Description of Core PS1392. Blow up of section at 350 to 375 cm shows a sequence of sand layers of different grain size, mostly fining upwards. The gravel layer at the base is also graded.

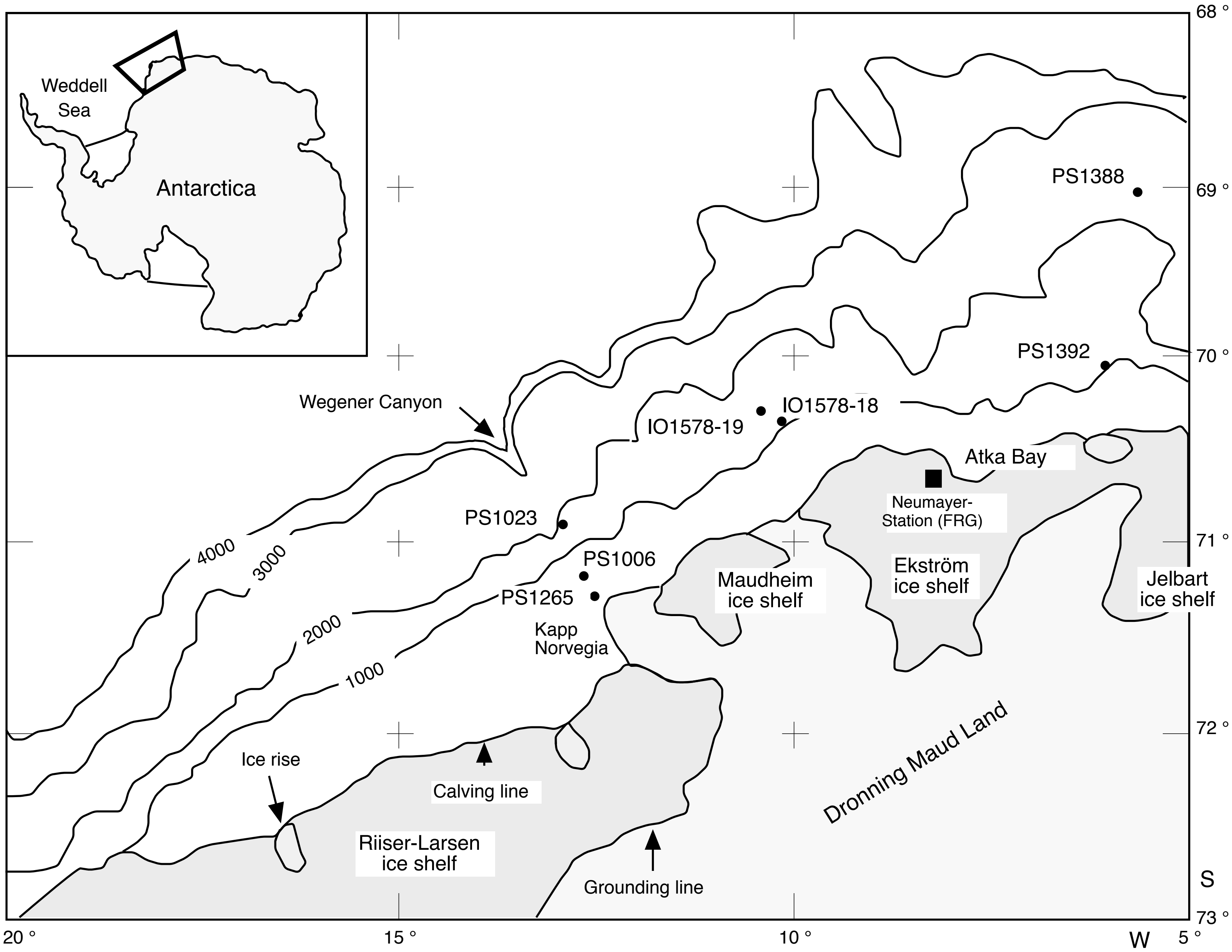
Fig. 4. Ternary diagram of the important clay minerals of the slope and shelf sediments. The hemipelagic sediments are dominated by illite, contourites contain more current derived smectite. Higher values of chlorite are typical to the shelf sediments, a composition which can also be found in sediments transported gravitationally down the slope triggered by the advancing ice edge.

Fig. 5. Sedimentological parameter of Core PS1023 plotted versus time. Oxygen isotopic data are altered through diagenetic processes and can only be interpreted by lithologic correlation with other cores (s. Grobe & Mackensen, 1992).

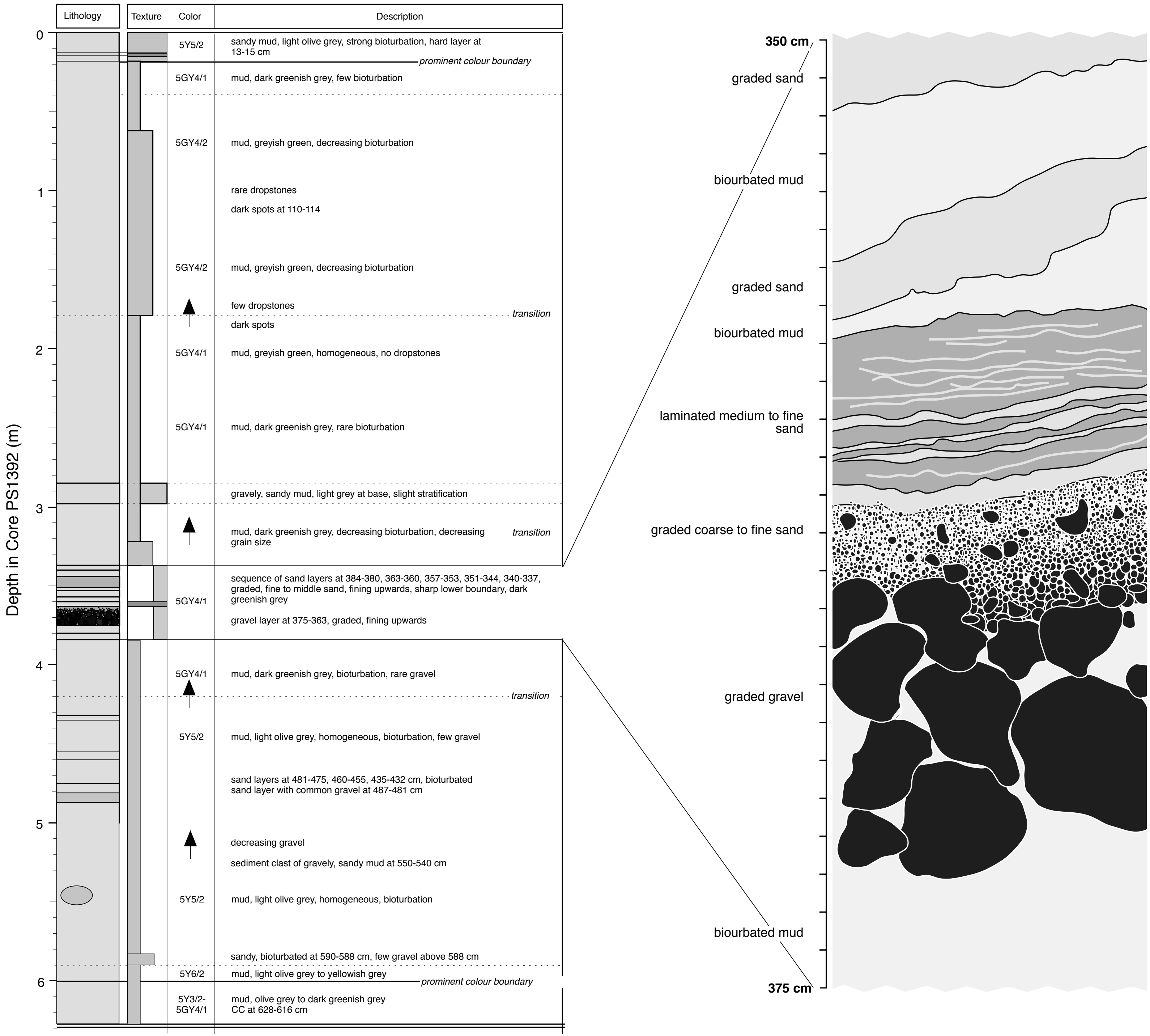
Fig. 6. Sedimentological parameter of Core PS1392 plotted versus time. Sand and chlorite were plotted as they are the best indicators to gravitational transport of shelf sediments down the slope. Gravel layers indicate ice advances, high values of chlorite indicate an increasing sediment supply form the shelf to the slope.

Fig. 7. Sketch of the most important sedimentation processes at the Antarctic slope during different climatic stages. Ice rafting, current transport and biological productivity are important during interglacial conditions, during glacial maxima gravitational transport down the slope is the most important sedimentation process.

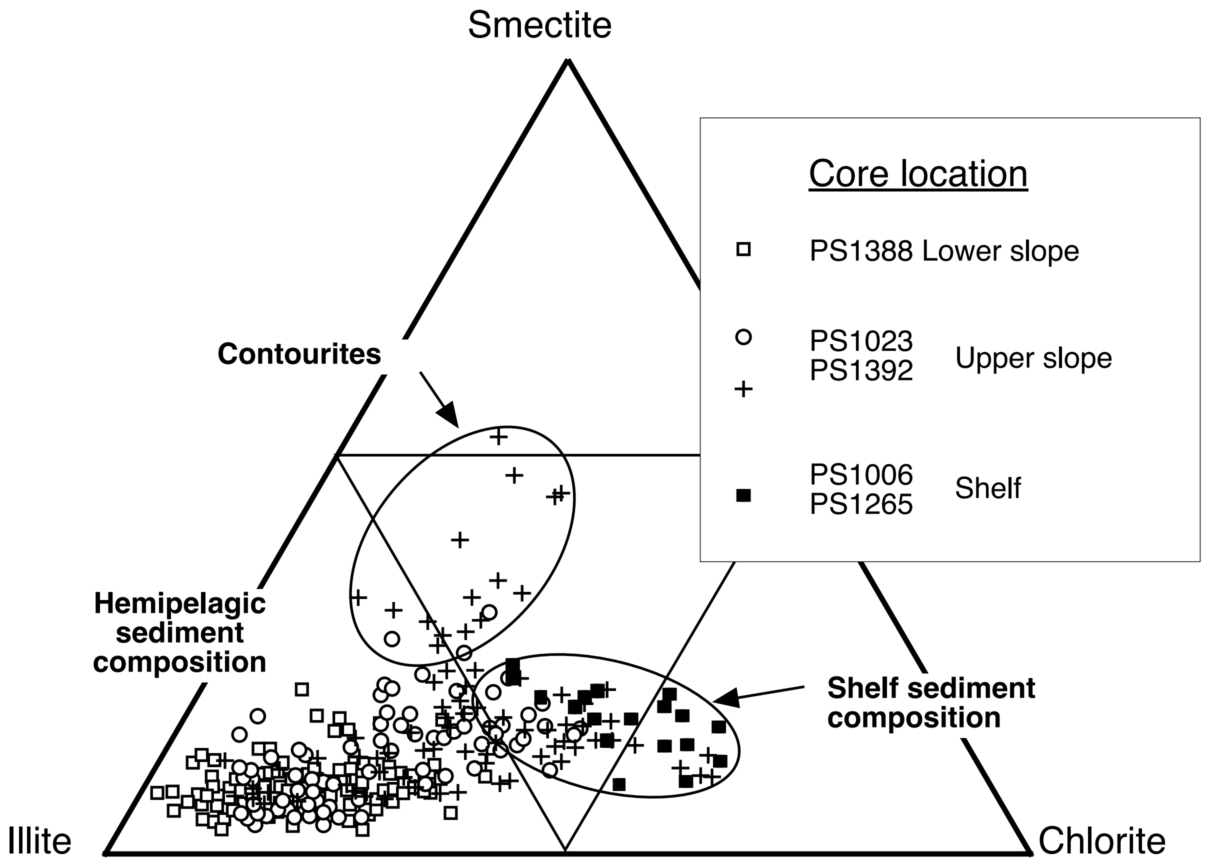
Fig. 8. Reconstruction of the Antarctic ice sheet during the last Glacial Maximum compared to the present ice sheet geometry. The right panel results from a computer simulation of the last glacial cycle with a numerical ice flow model, and takes into account transient effects and a climatic forcing derived from the Vostok ice core (Huybrechts, 1992). Shown are surface elevations in meter above present sea level.



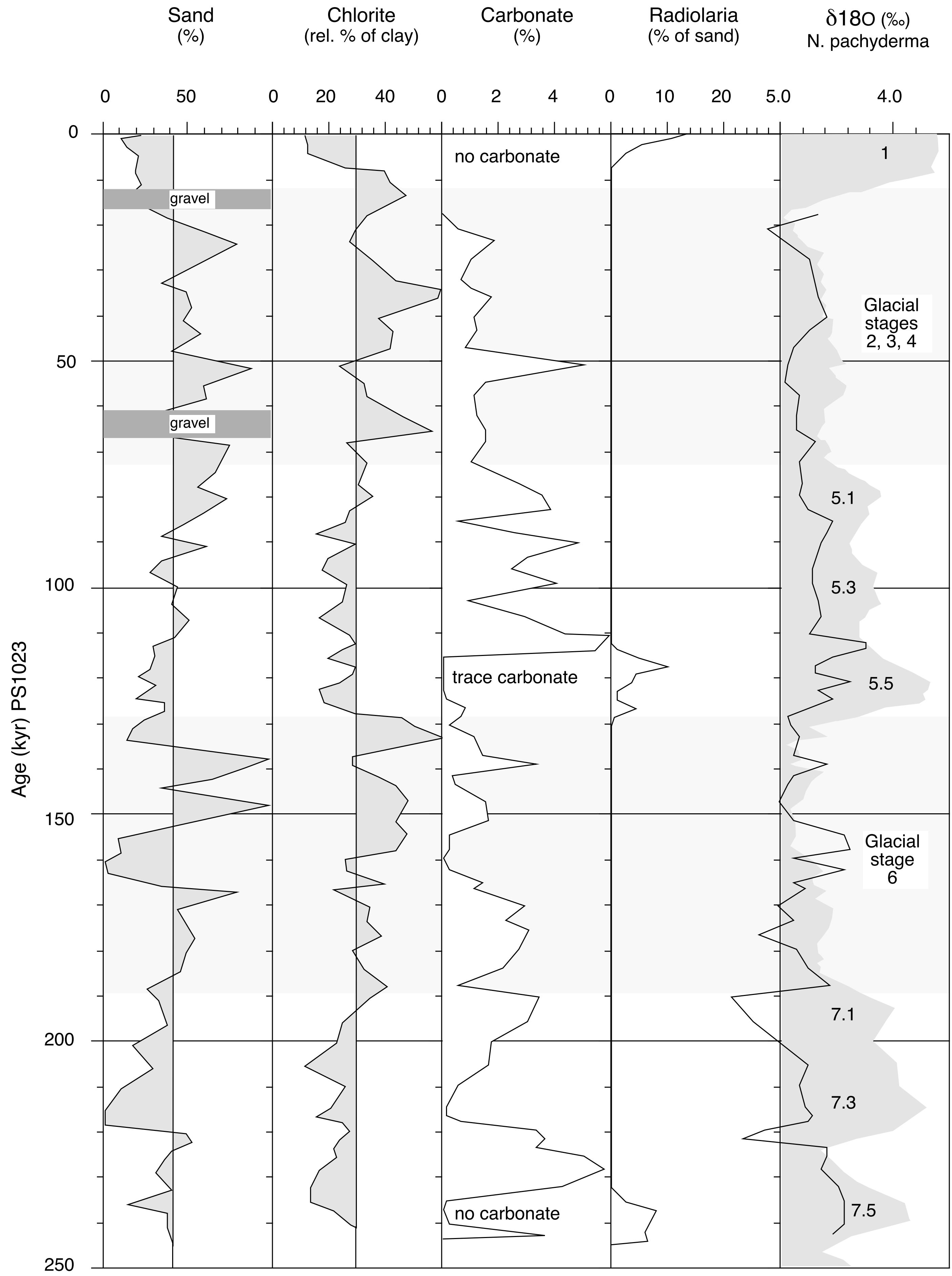
68 °
69 °
70 °
71 °
72 °
73 °
S
20 °
15 °
10 °
W
5 °
Weddell
Sea
Antarctica
PS1388
PS1392
Wegener Canyon
IO1578-18
IO1578-19
Atka Bay
Neumayer-
Station (FRG)
PS1023
4000
3000
2000
1000
PS1006
PS1265
Kapp
Norvegia
Maudheim
ice shelf
Ekström
ice shelf
Jelbart
ice shelf
Dronning Maud Land
Ice rise
Calving line
Riiser-Larsen
ice shelf
Grounding line



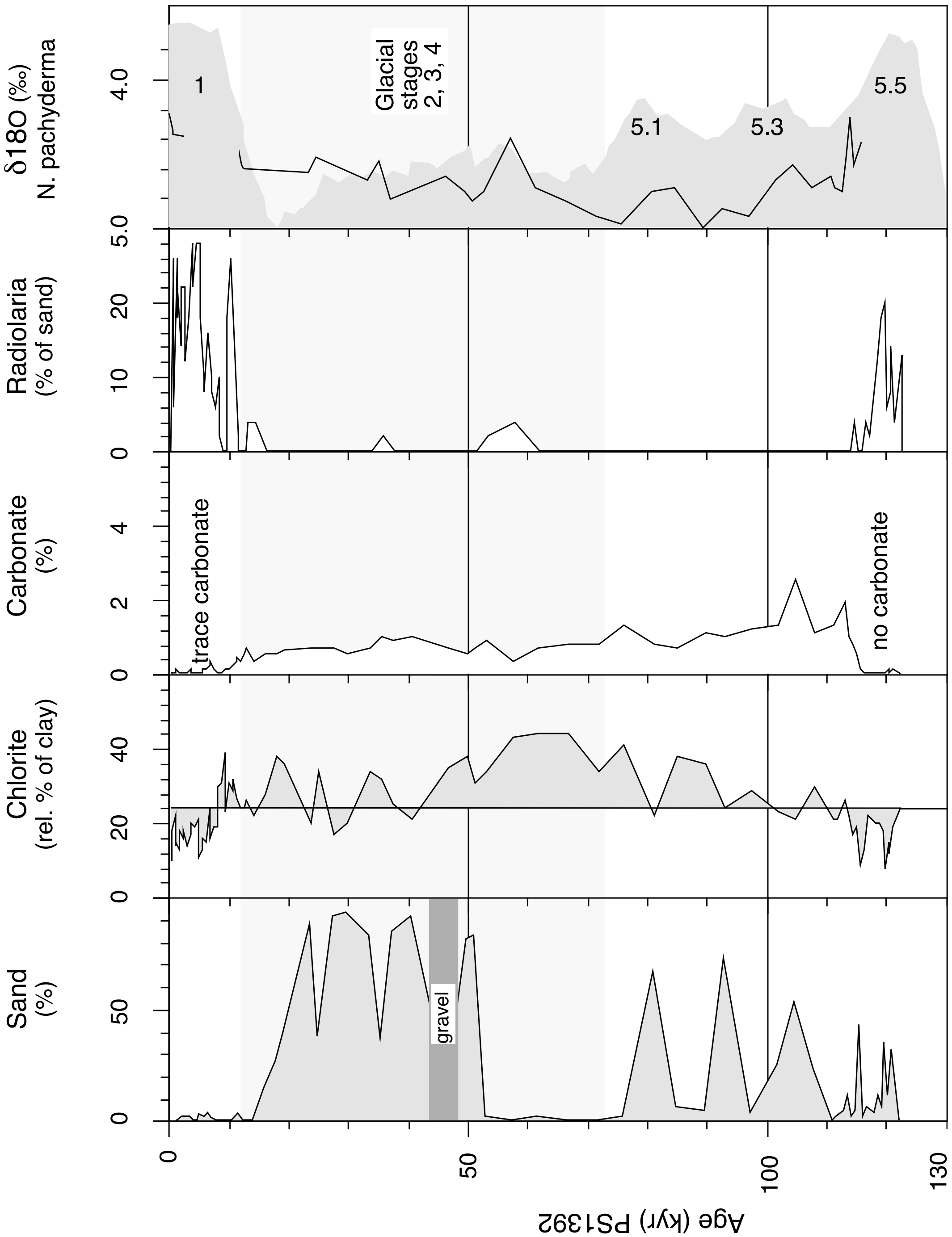
Lithology
Texture
Color
Description
Depth in Core PS1392 (m)
0
1
2
3
4
5
6
5Y5/2
sandy mud, light olive grey, strong bioturbation, hard layer at 13-15 cm
prominent colour boundary
5GY4/1
mud, dark greenish grey, few bioturbation
5GY4/2
mud, greyish green, decreasing bioturbation
rare dropstones
dark spots at 110-114
5GY4/2
mud, greyish green, decreasing bioturbation
few dropstones
transition
dark spots
5GY4/1
mud, greyish green, homogeneous, no dropstones
5GY4/1
mud, dark greenish grey, rare bioturbation
gravely, sandy mud, light grey at base, slight stratification
mud, dark greenish grey, decreasing bioturbation, decreasing grain size
transition
5GY4/1
sequence of sand layers at 384-380, 363-360, 357-353, 351-344, 340-337, graded, fine to middle sand, fining upwards, sharp lower boundary, dark greenish grey
gravel layer at 375-363, graded, fining upwards
5GY4/1
mud, dark greenish grey, bioturbation, rare gravel
transition
5Y5/2
mud, light olive grey, homogeneous, bioturbation, few gravel
sand layers at 481-475, 460-455, 435-432 cm, bioturbated
sand layer with common gravel at 487-481 cm
decreasing gravel
sediment clast of gravely, sandy mud at 550-540 cm
5Y5/2
mud, light olive grey, homogeneous, bioturbation
sandy, bioturbated at 590-588 cm, few gravel above 588 cm
5Y6/2
mud, light olive grey to yellowish grey
prominent colour boundary
5Y3/2-5GY4/1
mud, olive grey to dark greenish grey
CC at 628-616 cm
350 cm
graded sand
biourbated mud
graded sand
biourbated mud
laminated medium to fine sand
graded coarse to fine sand
graded gravel
biourbated mud
375 cm

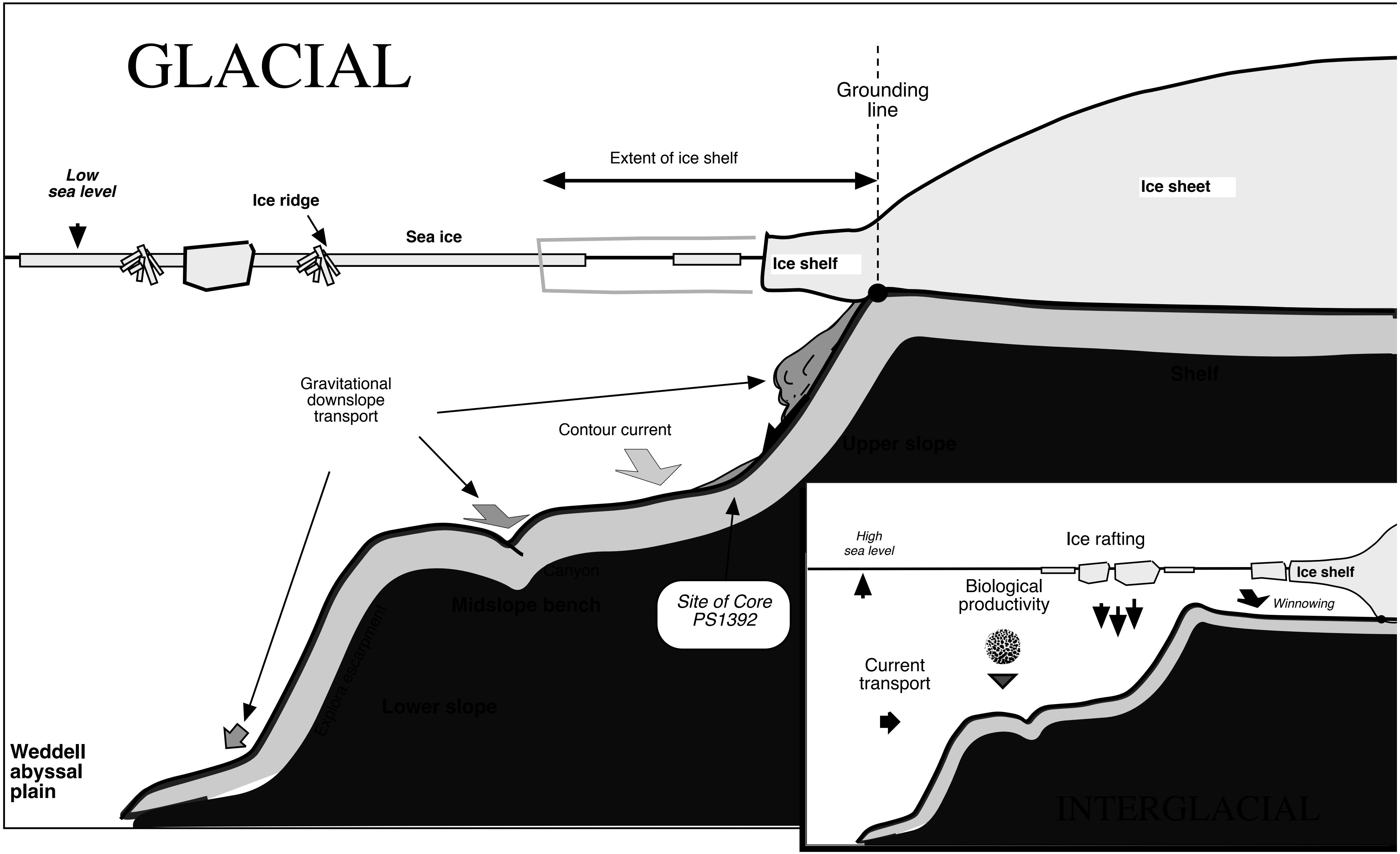


Smectite
Core location
PS1388 Lower slope
PS1023
PS1392
Upper slope
PS1006
PS1265
Shelf
Contourites
Hemipelagic sediment composition
Shelf sediment composition
Illite
Chlorite



Sand (%)
Chlorite (rel. % of clay)
Carbonate (%)
Radiolaria (% of sand)
δ18O (‰) N. pachyderma
Age (kyr) PS1023
gravel
gravel
no carbonate
trace carbonate
no carbonate
1
Glacial stages 2, 3, 4
5.1
5.3
5.5
Glacial stage 6
7.1
7.3
7.5


δ18O (‰)
N. pachyderma
Radiolaria
(% of sand)
Carbonate
(%)
Chlorite
(rel. % of clay)
Sand
(%)
Glacial
stages
2, 3, 4
1
5.1
5.3
5.5
trace carbonate
no carbonate
gravel
Age (kyr) PS1392
0
50
100
130
4.0
5.0
0
10
20
2
4
40



GLACIAL
Grounding line
Extent of ice shelf
Ice sheet
Low sea level
Ice ridge
Sea ice
Ice shelf
Shelf
Gravitational downslope transport
Contour current
Upper slope
Canyon
Midslope bench
Site of Core PS1392
Explora escarpment
Lower slope
Weddell abyssal plain
High sea level
Ice rafting
Ice shelf
Biological productivity
Winnowing
Current transport
INTERGLACIAL

Core	Latitude	Longitude	Depth (m)	Length (cm)	No of samples
PS1023	71° 08.4´ S	13° 36.2´ W	1826	688	85
PS1388	69° 02.0´ S	05° 53.0´ W	2517	1238	141
PS1392	70° 11.8´ S	06° 43.5´ W	1794	630	81
PS1006	71° 29.6´ S	13° 16.3´ W	234	55	9
PS1265	71° 21.1´ S	13° 24.5´ W	229	26	5
IO1578-18	70° 33.6´ S	10° 10.9´ W	1039	131	-
IO1578-19	70° 32.4´ S	10° 16.4´ W	1339	499	-

Tab.1 Grobe et al.