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Late Quaternary record of sea-level changes in the Antarctic

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

The variations in 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 and of the numerical models show that the Antarctic ice sheet follows glacial events in the northern hemisphere by teleconnections of sea level.

Key words Antarctic sea levels – Glacial Changes – Quaternary – Polar ice sheets

Introduction

In the geological past, the volume of ice on the earth has undergone important changes. The global eustatic sea level is controlled directly by the amount of ice stored in the polar ice sheets. During the Palaeogene, and even more so during the Neogene, ice masses have been the predominant factor influencing sea level. During the Quaternary period, the earth's climate has alternated between warmer intervals similar to the present, and ice ages when the global 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 behaviour of the great ice sheets (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 10^2-10^4 years, which has to be taken into account when dealing with palaeoglaciological and sea-level reconstructions from marine sediments.

The correlation between the waxing and waning of the ice sheets in the northern and southern hemispheres has been a matter of discussion since the beginning of this century (Denton and Hughes, 1981), with the Antarctic ice sheets being the major problem. The ice and ocean in the Antarctic region 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, i.e. 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 extensive mantle of sea ice. This makes the ice sheet shrink during glacials (Scott, 1905). In this particular case the Antarctic ice sheet may act contrary 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

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lead to thickening. Conversely, decreasing accumulation rates make 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 ice surging, 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 in the northern hemisphere (Wilson, 1964). In this instance the Antarctic region 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 and 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 a; 1986 b), 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 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 extent of the Antarctic ice sheet is crucial for the understanding of the link between the ice sheets in the northern and southern hemispheres and sea level. From a glacial dynamic point of view, the interactions with sea level and the resulting reconstructions is a complex matter, but modelling and 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; Barker and Kennett et al., 1990; Barron and Larsen et al., 1991) and gravity and piston coring in the Southern Ocean have provided a number of sediment cores of excellent quality from the shelf and slope of the Antarctic continent. These have improved our knowledge of the sedimentation processes on the margin with regard to the understanding of the behaviour of the Antarctic ice sheet during natural climatic change (Grobe, 1986; Melles, 1991; Fütterer and Melles, 1990; Grobe and Mackensen, 1992).

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 are dicussed in the following 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

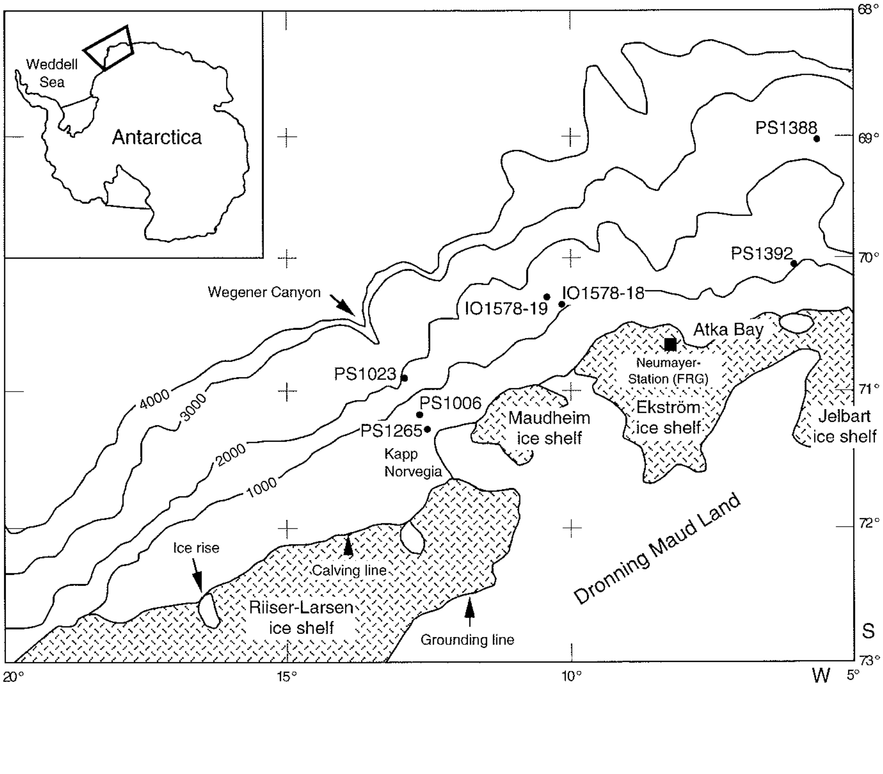


Fig. 1. Study area at the Antarctic continental margin in the eastern Weddell Sea with sample locations

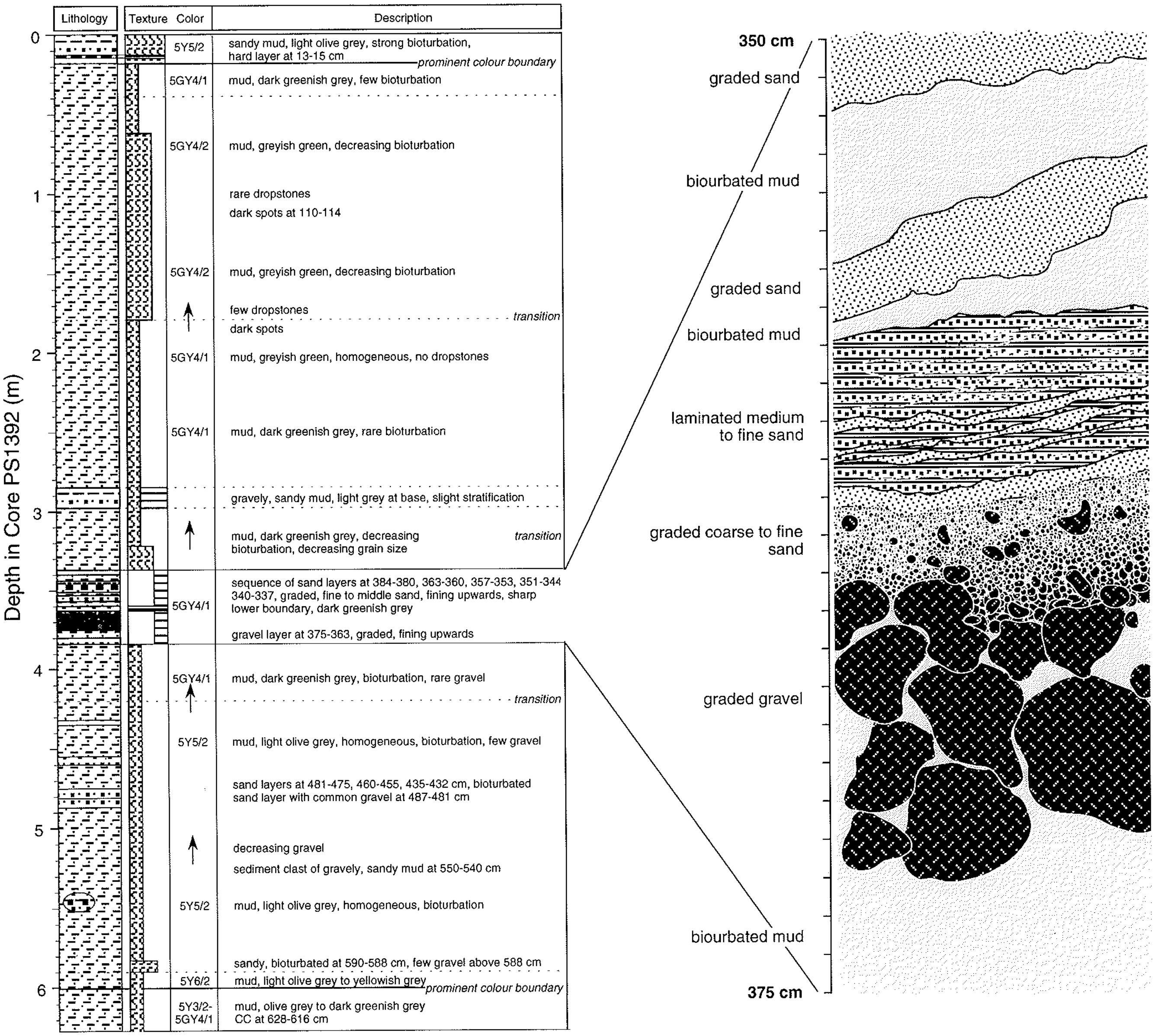
the coastal areas fully grounded, ice sheet extending to the edge of the continental shelf (Hughes, 1975; Denton et al., 1979; Huybrechts, 1992). In this paper we present the first sedimentological evidence within the Southern Ocean for those modelled glacial processes.

Environmental settings and methods

Continental margin bathymetry

The southernmost Atlantic between the East Antarctic continent and the Antarctic Peninsula is the Weddell Sea (Fig. 1). The distinct morphology of the Antarctic continental margin in the eastern part of the Weddell Sea off Dronning 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 (Fig. 6): (1) the partly overdeepened continental shelf (down to 500 m water depth) has a distinct shelf break, followed seawards 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 1 700 and 1 200 m. The bench is 50 – 100 km wide, dipping seaward by 1.5° to about 3 000 m water depth. The steep lower slope (4)

Fig. 2. Lithological description of core PS1392 off Jelbert ice shelf. Enlargement of section at 350 – 375 cm shows a sequence of sand layers of different grain size, mostly fining upwards sequences. The gravel layer at the base is also graded. This sequence is the proximal part of a turbidite which was triggered by ice advances to the shelf edge during glacial maximum sea-level lowstand



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. 2 and 6).

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 thought to have been an important conveyor channel for sediment transport to the deep sea, especially during a glacial sea-level lowstand (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 (Fig. 1) are the optimum sites where sediments eroded from the shelf are 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 Ross and Filchner-Ronne ice shelves; and (3) the East Antarctic ice sheet. The East Antarctic ice sheet is the largest of the three, comprising 85% of the total Antarctic ice sheet volume. Detailed morphometric features of this ice sheet, the world's largest with a total ice volume of 30×10^6 km^3, have been provided by Drewry et al. (1982). Removal of the East Antarctic ice sheet would raise the world-wide sea level by about 60 m. The corresponding figure for the West Antarctic ice sheet is only 6 m, not only because the ice sheet is smaller, but also because much of it is grounded below sea level, thus already displacing ocean water (Huybrechts, 1992). In addition, grounding below sea level makes the West Anarctic ic 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 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 Filchner-Ronne 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.

Table 1. Position, water depth and core length of sediment cores. PS = Polarstern; IO = Islas Orcadas

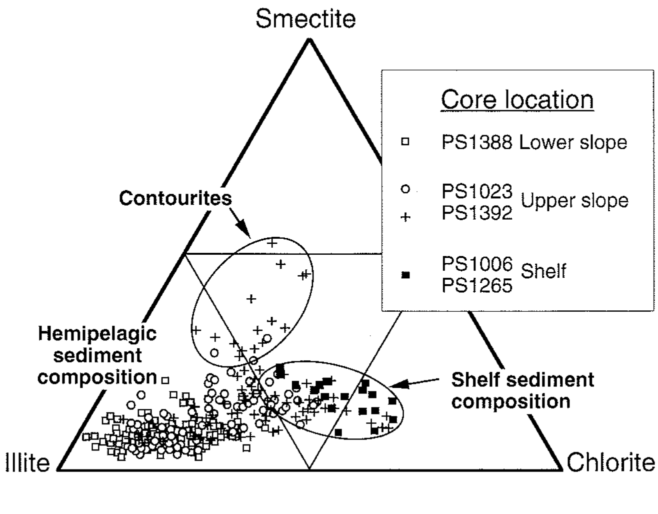
Core	Latitude	Longitude	Depth (m)	Length (cm)	No. of samples
PS1023	71°08.4′ S	13°36.2′ W	1826	688	85
PS1388	69°02.0′ S	05°53.0′ W	2517	1238	141
PS1392	70°11.8′ S	06°43.5′ W	1794	630	81
PS1006	71°29.6′ S	13°16.3′ W	234	55	9
PS1265	71°21.1′ S	13°24.5′ W	229	26	5
IO1578-18	70°33.6′ S	10°10.9′ W	1039	131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

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 (Fütterer, 1987; 1989; Fütterer and Schrems, 1991) during transects made both perpendicular and parallel to the depth contours. Two sediment cores, which include the last climatic cycle (about 200 ka), 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; Table 1). The cores were described and sediment slabs were X-rayed for a better description of structures and were sampled with a mean sampling interval of 10 cm. Samples were analysed for carbon, grain size, clay minerals, ice-rafted debris, components of the coarse

Fig. 3. Ternary diagram illustrating the important clay minerals of the slope and shelf sediments. Hemipelagic sediments are dominated by illite; contourites contain more current derived smectite. Higher values of chlorite are typical of the shelf sediments, a composition which can also be found in slope sediments if they were delivered from the shelf (e.g. turbidite sequence in Fig. 2)



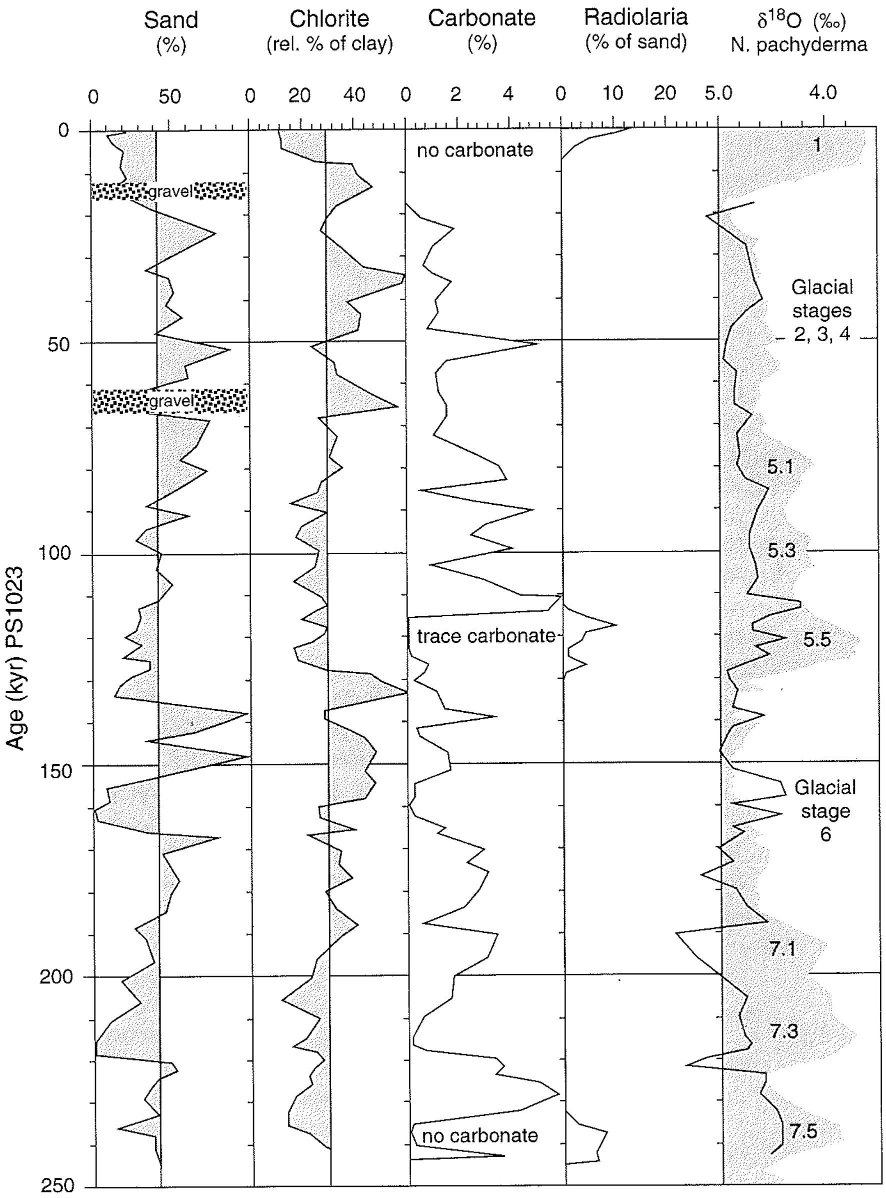


Fig. 4. Sedimentological parameters of core PS1023 plotted versus time. Glacial intervals are shaded light grey. For comparison the $\delta^{18}O$ record is plotted with the chronostratigraphy of Martinson et al. (1987). The data are altered through diagenetic processes. An age model was obtained by lithological correlation with core PS1388 according to Grobe and Mackensen (1992)

fraction and stable oxygen and carbon isotopes on planktonic foraminifera. 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; Table 1; 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, Table 1; Grobe, 1986).

Sedimentary record

Shelf sediments

During an interglacial sea-level highstand similar to present day conditions, residual sediment with a wide range of grain sizes is deposited on the shelf. One third of the facies is gravel (>2 mm) and sand is evenly distributed through all subfractions. With decreasing grain size, the <63 μm fraction is increasingly winnowed by the Antarctic coastal current, leaving a residual clay content of only about 10%. A patchy high biological benthic productivity contributes to an opal content (mainly sponge spicules; Voss, 1988) and some carbonates (bryozoans and molluscs; Anderson et al., 1983).

The 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 have been described at other localities from the Antarctic shelf around the Weddell Sea (Kaharoeddin et al., 1980; Anderson et al., 1981; Elverhoi and Roaldset, 1983). In the Ross Sea area at sites far away from the ice front where ice rafting is minor, a soft silty clay with abundant diatoms overlies a stiff diamictite. The diamictite crops out on swells and highs due to common erosion by grounded ice during a sea-level lowstand (Drewry, 1979). There has been disagreement about the age of this unit, but compared with other occurrences of diamictites on the shelf, it is assumed that it was probably deposited during the last glacial maximum.

On the Weddell Sea shelf a stiff pebbly mud is overlain by a thin veneer of a soft pebbly olive grey mud (Elverhoi, 1981). The residual glacial marine sediment was described as being up to 1 m thick, and the mean sedimentation rates were calculated as between 0 and 3 cm/ka depending on the sedimentary conditions (Elverhoi and 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).

Owing to the high gravel content of the shelf sediments it is difficult to recover long sediment cores by gravity coring. However, in some longer cores a texturaly and mineralogically 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, poor sorting, missing biogenic components and a dark grey (N3, 5Y2/1) colour (Harland et al., 1966; Anderson, 1972; Gravenor et al., 1984); it is also over-compacted (Anderson, 1972; Elverhoi and Roaldset, 1983). In some areas the facies change between the residual glacial marine sediment and the orthotill was mapped by subbottom profiling (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 slope bench well below the upper steep slope. These are areas of high accumulation sedimentation during gravity transport.

Core PS1023 is located off Kapp Norvegia (Fig. 1). Owing to the absence of an ice shelf at this site, terrigenous detritus from the continent is delivered directly to the continental shelf and slope. The sediments are mainly of the typical glaciomarine facies, as found in all locations in the eastern Weddell Sea. The olive grey (5GY4/1-2) mud contains a variable amount of sand and some gravel scattered throughout the core. The biogenic components are calcareous and arenacous foraminifers, radiolaria, diatoms and a few sponge spicules. The siliceous particles are concentrated in distinct horizons. Sharp lithological boundaries at 341 and 34 cm, where the colour changes from greenish grey to light grey, indicate significant changes in the sedimentary environment. Between the colour changes variations are gradational.

Below the sharp boundaries the colour is dark greenish grey to dark grey, which is uncommon in sediments of this area. As can be observed in the X-radiographs, within this unit the grain size in particular changes rapidly between a homogeneous silty clay and a graded silty sand showing no bioturbation. Gravels are scattered throughout, but also appear to be concentrated in distinct horizons. The coarse fraction (<500 µm) of samples from these horizons contains a high amount of gravel and rock fragments, which have a similar petrography to 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, a characteristic rock of the crystalline basement in most of East Antarctica. A second horizon with similar mineralogical composition, colour and texture occurs 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 even more pronounced sedimentary structures indicating gravitational sediment transport downslope. The bioturbated mud in core PS1392 (Fig. 2) is similar to that 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 occurs, starting with gravel up to 4 cm in diameter. The gravel grades upwards into coarse sand, which again grades into fine sand followed by a sequence of laminated medium to fine sand. The uppermost part ends at a depth of about 350 cm as an alternating sequence of bioturbated mud and graded sand layers (Fig. 2). The turbidites are almost bare of biogeneous components in the two cores.

At the continental slope off the eastern boundary of the Maudheim ice shelf at a water depth of 1 339 m, a similar sequence has been described in the 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 1 039 m, core IO1578-18 is located on the upper steep slope of the continental margin. It contains sand of a dark grey (N3) colour, 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 colour (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 that of the shelf sediments investigated in cores PS1006 and PS1265 (Fig. 3). The mineralogy and petrology of the shelf sediments can be directly correlated with the petrographical composition of the rocks of the adjacent hinterland (Dreimanis and Vagners, 1969). In the area investigated here this means that all terrigenous material deposited on the shelf is delivered from Queen Maud Land, where the classification in petrographical provinces shows mainly Mesozoic, in most instances Jurassic, basalts with different degrees of alteration (Oskierski, 1988; Peters, 1989). 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 is 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 and missing microfossils may indicate the exclusively terrigenous origin. The high chlorite to illite ratio, the mineralogical composition and the high incidence of rock fragments and gravel suggest a relation with the residual glaciomarine sediments on the shelf. This is supported by observations of the petrology of the gravel. Sediment colours described from different core locations on the shelf close by (Kaharoeddin et al., 1980; Anderson et al., 1981; Elverhoi and Roaldset, 1983) correspond well with the typical olive grey colour of the turbiditic facies (N3-5Y3/2).

Lithostratigraphy

The facies described in the preceding section are obviously turbidites composed of shelf sediments. To correlate the facies with distinct changes of sea level, a stratigraphy which allows 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 palaeoenvironments is that they suffer from high resolution chronostratigraphic control due to the paucity of biogenic carbonate. This is the reason why cores from south of the Antarctic polar front were not included in recent Quaternary chronostratigraphic schemes (Imbrie et al., 1984; Martinson et al., 1987).

Trace to rare amounts of carbonate, mainly consisting of the planktonic foraminifer *Neogloboquadrina pachyderma,* were found on the Antarctic continental margin around the Weddell Sea in a water depth of between 2000 and 4000 m (Anderson, 1972; Grobe, 1986; Barker and Kennett et al., 1990; Mackensen et al., 1990). Thus in this area we were able to establish a first oxygen 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 30 cores in the area of investigation have shown that in most of the cores interpretation of the isotopic data still 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, which has until now been only poorly explained (Figs. 4 and 5).

Owing to severe problems with most of the isotopic data, a lithostratigraphy was developed as a tool for correlating and dating the Late Pleistocene sediment sequences at the East Antarctic continental slope (Grobe and Mackensen, 1992). Comparison of the isotopic record with some lithological parameters and biogenic constituents has shown that significant changes occur at distinct times of global climatic change. These variations can be correlated between cores and were found to be

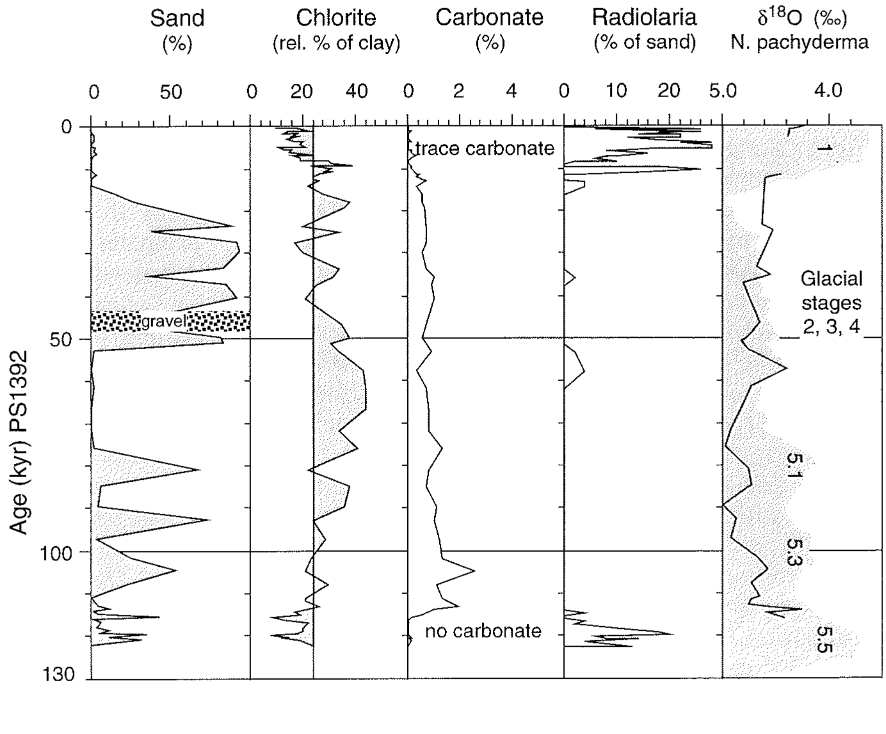


Fig. 5. Sedimentological parameters of core PS1392 plotted versus time. Sand and chlorite are the best indicators of gravitational downslope transport of shelf sediments. Gravel beds indicate advances of ice shelves, high values of chlorite indicate increasing sediment supply from the shelf to the slope. A high content of radiolaria in the sand fraction and traces of carbonate are indicative of high productivity during peak warm times. The $\delta^{18}O$ record as shown with the standard chronostratigraphy (Martinson et al., 1987) indicates that the data are altered through diagenetic processes

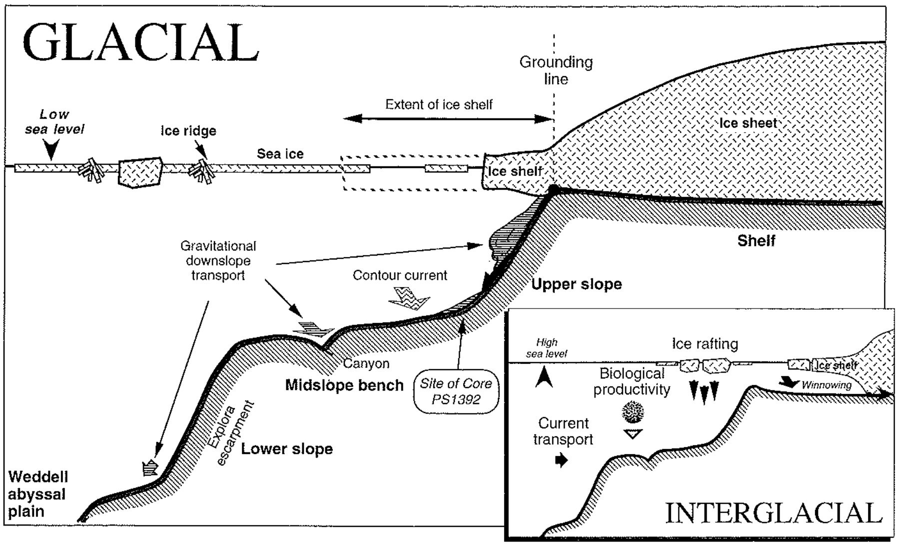


Fig. 6. Sketch of important sedimentation processes at the Antarctic continental margin during glacial/interglacial situations. Ice rafting, current transport and biological productivity are most important during interglacial periods, during glacial maxima gravitational downslope transport is the most important sedimentation process

similar in all sediment sequences around the Weddell Sea with similar sedimentation rates. The new lithostratigraphy was correlated by dating prominent lithological changes to the isotope stratigraphy of core PS1388. Age models for cores PS1023 and PS1392 are based on this lithostratigraphy.

The percentages of carbonate and radiolaria in the sand fraction 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. 4 and 5). We interprete the occurrence of radiolaria as indicating 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 carbonate compensation depth. From moderate to severe glacial conditions (e.g. stages/events, 5.4-2) carbonate was found throughout both cores in slightly decreasing amounts. The corresponding terrigenous parameters show significant changes with 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. 5). 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 of clay content (2–5%). With the onset of glacial termination 1, the sediment consists of mud and sand values decrease to 1–2%. A further peak value in chlorite of up to 40% is found during the termination before 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. 4). During glacial stage 6 and in stages 2–4 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 decreased to a few per cent, 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 glaciomarine 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 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 rapidly reduced by intense calving processes. The retreat of the ice margin lasts the time of the postglacial sea level rise. Additionally, the increase in the flux of warmer North Atlantic deep water to the circumpolar deep water 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 quasi-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 documentas the transfer of sediment from the shelf to the slope. 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 lithological and colour 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: biological productivity, current transport and ice rafting (Fig. 6). In the central Antarctic Ocean productivity is mainly controlled by light, which in turn is related to the sea ice cover. Hard parts of microfossils produced by this process amount to 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 the 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 tholeiitic 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 a granitic or gneissic composition of dropstones, gravel and sand fractions.

Glacial

During glacial intervals the Antarctic ice sheet is indirectly coupled to global cooling by processes in the northern hemisphere. The expansion of the Antarctic ice sheet is mainly caused by the sea level lowering as a result of 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 seawards movement of the grounding line and thus an enlargement of the grounded continental ice. Ice shelves are also displaced seawards and may finally float above the slope (Fig. 6; Grobe and Mackensen, 1992).

With the Pleistocene sea-level changes the ice margins have oscillated several times across the entire continental shelf, repeatedly grounding at the shelf edge. Grounding of ice shelves occurred in parts of East as well as West Antarctica, but took place mostly in areas with broad continental shelves. During the advances of the continental ice till was deposited on the shelf. 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 and Krause, 1982; Miller et al., 1990).

During a sea-level lowstand the surficial shelf sediments become available for ice erosion and subsequent redistribution. Gravitational sediment transport is the most active mechanism (Fig. 6). 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 initial phase of the 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, which extend up to the shelf break, serve as preferred pathways for sediment transfer to the deep sea via turbidity currents. Thus during glacials deep sea terrigenous sedimentation is strongly influenced by ice-margin processes and preferred depositional areas in the deep sea such as 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 (Fig. 4). Core PS1392 also shows an increase in chlorite at the boundary of isotopic stages 4 and 5, but turbidites do not occur before stage 3. A more exact dating of the specific layers is not possible due to the lack of chronostratigraphic datums in this part of the core.

From these interpretations it is obvious that turbiditic events, triggered by the advancing ice edge, will not occur synchronously at all parts of the continental margin because of the different morphological settings, of which the water depth of the shelf is the most important parameter. The depth (200–500 m) is significantly deeper and more variable than the shelf of non-glaciated continents due to isostatic compensation to the load of the ice sheet. Other parameters controlling the displacement of the ice shelves during sea-level lowering are the distances between grounding line, calving line and shelf edge. 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-Ronne 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 after 31 ka ago. The ice advance was accompanied by the erosion of shelf sediments and a strong lateral sediment transport from south to north. The erosional surface can be seen in the sediment echo-soundings as an even, high amplitude 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 lowstand 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 volume of shelf sediments is delivered to the slope within the relatively short time of a glacial maximum. The combined action of processes such as sea-level lowering, ice advance, turbidity currents and debris flows are responsible for current entrainment and the 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. 6). At least part of the fine-grained material suspended by the various processes will be entrained by currents and transported cyclonally with the Weddell gyre, and finally with the Antarctic circumpolar current. The fine fractions are also transported to the north, presumably by the Antarctic bottom water, and may influence the composition of sediments in the South Atlantic.

Different environments have been reconstructed and discussed at the Antarctic continental margin, which have provided conditions for high accumulation rates of the fine, current-derived material. During glacial maxima a thick and extensive 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, in the calm environment below, which is not influenced by any other transport processes, contourites are deposited, characterized by a high amount of current-derived smectite (Grobe, 1986; Grobe and Mackensen, 1992; Fig. 3).

On the other hand, deposits consisting mainly 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 metres. The laminated units, which are similar in composition and structure to the contourites, were deposited during the intense redeposition and gravitational transport processes off the ice stream, which filled the Filchner Trough during the last glacial sea-level lowstand (Melles, 1991).

The deposition of similar deposits in the south-eastern 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/ka during a glacial maximum. All clay deposits show excellent laminations in a thickness range of several hundred micrometres, 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 last glacial maximum has not yet been reached, and various 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 lowstand. There seems to be a general consensus that this was indeed the case in the Weddell Sea, but views still differ as to whether the shallow Ross Sea was completely covered by an ice sheet, or if there was only a minor expansion.

The maximum view was taken by Stuiver et al. (1981), who presented a last glacial maximum reconstruction of the Antarctic ice sheet as part of the CLIMAP project in the late 1970s. 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 symmetrical 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 fairly short distances, which are typically 75 – 90 km depending on bedrock slope. This may lead to only a relatively minor interior thickening. The total ice volume during the would have increased by this expansion by about 10×10^6 km^3 to 37.1×10^6 km^3, which is equivalent to a 25 m fall in sea level. These model studies (Stuiver et al., 1981) are in contrast with some geological evidence, which indicate only limited ice expansion and a sea-level fall of 8 m (Drewry, 1979). Recent data for raised beaches imply either that the ice margins were even thinner and less extensive and that the contribution of ice expansion to the drop in sea level was only 0.2 – 2.5 m (Colhoun et al., 1992).

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, as a sea-level depression of 120 – 130 m sustained over more than 10000 years (an exceptional situation) would be needed for the ice shelf to fully ground in the Ross Sea. 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 30000 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 due to increased accumulation rates only after the end of the last glaciation (Raynaud and Whillans, 1982). These results do not favour the Stuiver et al. (1981) reconstruction, which requires a thickening of about 1700 m at Byrd Station during the Wisconsin maximum.

Since the theoretical CLIMAP reconstruction, based in many places on little data, more marine 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. Elverhoi (1981) describes sedimentological data which clearly suggest grounding of the Filchner-Ronne ice shelf down to a water depth of about 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 (Melles, 1991).

Also in the Antarctic Peninsula area, Clapperton and Sugden (1982) postulate a Late Wisconsin maximum ice cover in broad agreement with CLIMAP, although their geomorphological observations do not support ice flowing from the Peninsula axis across Alexander Island to the edge of the continental shelf in the west. Instead, they believe that separate ice domes were centred 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 critical locations such as Marguerite Bay along the Antarctic Peninsula (Kennedy and Anderson, 1989) and Pine Island Bay in the Amundsen Sea (Kellogg and Kellogg, 1987).

In contrast, it appears that the controversy which centred 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 seafloor 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 with 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 for the total gas content from deep ice cores now seem to indicate that ice surface elevations in interior East Antarctica at the last glacial maximum were little different from today. A thinning may even have occurred in some areas (Anderson et al., 1991). This is assumed to be a direct consequence of lower accumulation rates. Based on ^{10}Be concentrations in the Vostok ice core it has been determined that precipitation rates over the East Antarctic plateau were roughly halved during the last glaciation (Yiou et al., 1985).

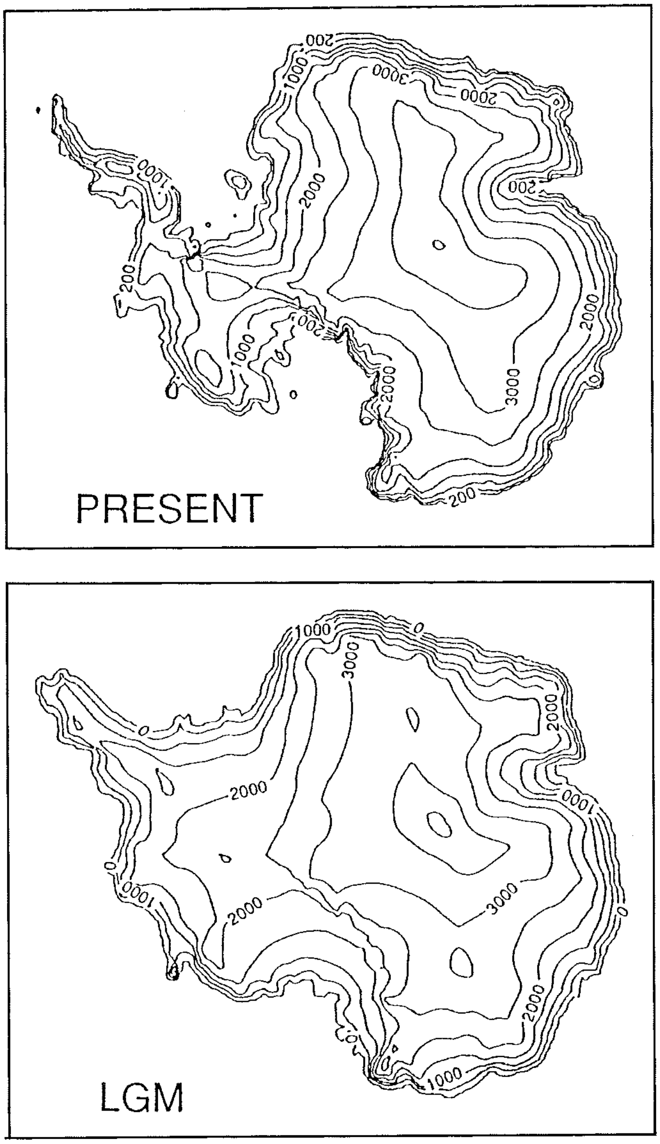


Fig. 7. Reconstruction of the Antarctic ice sheet during the last glacial maximum (LGM) compared with the present ice sheet geometry (without ice shelves). The last glacial maximum results from a computer simulation of the last glacial cycle with a numerical ice flow model. It takes into account transient effects and a climatic forcing derived from the Vostok ice core results (Huybrechts, 1992). Surface elevations are in metre above present sea level

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 glacioclimatic controls than those affecting the bulk of the ice sheet. Unlike more complex behaviour elsewhere, such a local dome essentially responds to changes in amounts of precipitation. As 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 the 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 last glacial maximum, which has to be derived from modelling studies. New results have been 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 ka BP was found to increase by 5×10^6 km^3 to 31×10^6 km^3, mainly due to spreading of grounded ice across the Ross and Weddell Seas (Fig. 7). 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, however, the model confirms that surface elevations over the East Antarctic plateau were not higher at the last glacial maximum, and that grounding in the Ross basin was not entirely completed. This is attributed to the long response time-scales involved. Although 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 sea-level teleconnections.

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