Glacial dynamics of the West Antarctic Ice Sheet in the southern Bellingshausen Sea during the last glacial cycle

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Abstract

A major glacial trough ("Belgica Trough") on the continental shelf in the southern Bellingshausen Sea acted as an important outlet for ice draining the West Antarctic Ice Sheet during the last glacial maximum (LGM). Mega-scale glacial lineations, drumlins and grounding-zone wedges indicate that Belgica Trough represents the former pathway of a grounded ice stream, which advanced to the shelf break during the LGM and which was fed by ice draining through Eltanin Bay and Ronne Entrance. Here we present the preliminary results of sedimentological investigations carried out on 26 sediment cores recovered from the shelf and slope. This unique dataset allows the identification of various facies types that reflect the different phases of grounded ice advance, retreat, and post-glacial onset of seasonal open-water conditions. We will reconstruct the complex processes of erosion, transport and (re-)deposition controlling sedimentation on the margin and the timing of ice sheet retreat from the shelf.

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Introduction

The West Antarctic Ice Sheet (WAIS; Fig. 1) is considered as the most vulnerable part of the Antarctic ice sheet, because it is largely grounded below sea level (e.g. Oppenheimer, 1998). Its complete disintegration would raise global sea level by ~5 m. Therefore, the knowledge of the past and current mass balance of the WAIS is crucial for an accurate estimation of future sea-level rise (Vaughan & Arthern, 2007). Recently, some parts of the WAIS have shown dramatic signs for a negative mass balance, including thinning, flow acceleration and grounding-line retreat of glaciers (e.g. Vaughan & Arthern, 2007). It is unclear, however, if the WAIS is still responding to climatic changes following the Last Glacial Maximum (LGM) (Larter et al., 2007). Marine sediments recovered from the Ross Sea embayment suggest that ice retreat there has progressed since about 20 ka and may eventually result in a complete collapse of the WAIS within the next 4,000-7,000 years (Bindschadler, 1998). In response to the present global warming the WAIS could even disintegrate during the next 500-700 years (Oppenheimer, 1998). Most predictions about the future behavior of the WAIS are based on the chronology of the ice-front and grounding-line retreat and ice-sheet thinning during recent times. The deglaciation history of the WAIS since the LGM is mainly reconstructed from studying and dating subglacial and glaciomarine sediments from the embayments in the Ross, Amundsen, and Weddell seas, which form the main exit gates for ice draining the WAIS today (e.g. Bindschadler, 1998; Lowe & Anderson, 2002).

The southern Bellingshausen Sea is a poorly studied area of the West Antarctic continental margin, but was investigated during cruise JR104 with RRS *James Clark Ross* in 2004 (Fig. 1). Multibeam swath bathymetric data and sub-bottom acoustic profiles revealed the existence of a major glacial trough ("Belgica Trough") and of an associated trough mouth fan ("Belgica TMF") on the adjacent slope. Distinct seabed morphological features on the shelf, such as mega-scale glacial lineations, drumlins and grounding-zone wedges, give evidence that Belgica Trough represents the former pathway of a grounded ice stream, which had advanced to the shelf break during the LGM (Ó Cofaigh et al., 2005). Moreover, the orientation of the subglacial bedforms suggested that the ice stream was fed by grounded ice draining through Eltanin Bay and Ronne Entrance. These results revealed that, in contrast to the present drainage pattern of the WAIS, ice flow into the southern Bellingshausen Sea played a significant role in the past. First results of studies on three sediment cores recovered from the continental margin in the southern Bellingshausen Sea during a previous cruise with RV *Polarstern* confirmed grounded ice advance to the shelf break and deposition of glaciogenic debris flows (GDFs) on the western part of the Belgica TMF (Hillenbrand et al., 2005). While the mineralogical composition of a deformation till recovered from the shelf corroborated supply of glaciogenic detritus from Eltanin Bay, the mineralogical composition of the GDFs on the continental slope pointed to major supply of subglacial debris via Ronne Entrance (Hillenbrand et al., 2005). The latter finding is in conflict with the orientation of subglacial bedforms on the shelf indicating that ice flowing into Belgica Trough was mainly fed by ice draining through Eltanin Bay with only a minor contribution from ice draining through Ronne Entrance (Ó Cofaigh et al., 2005). Until now, no reliable age models for the cores collected from the southern Bellingshausen Sea were available (Hillenbrand et al., 2005).

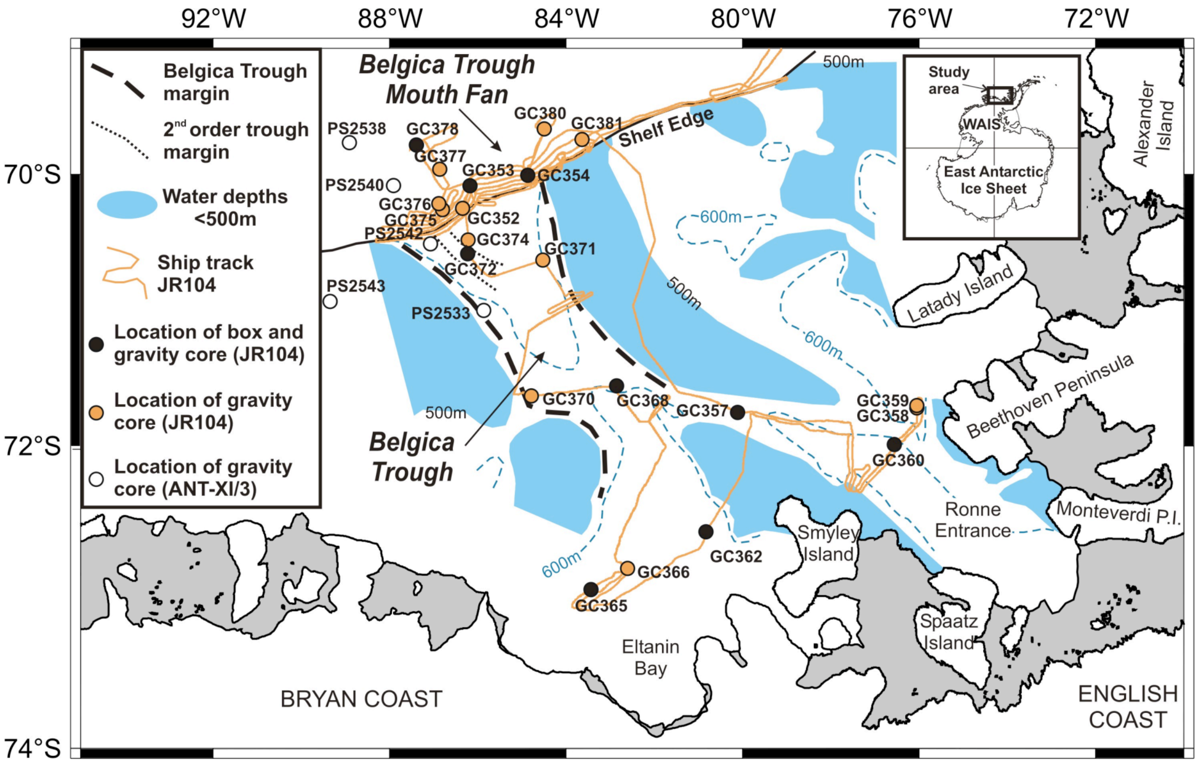

Figure 1. Map of the southern Bellingshausen Sea with ship track of cruise JR104 with RRS *James Clark Ross* and core locations of cruises JR104 and ANT-XI/3 with RV *Polarstern* (modified from Ó Cofaigh et al., 2005).

Preliminary results and discussion

New sedimentological data

Within the last couple of years numerous sedimentological analyses have been carried out on additional surface sediment samples and marine sediment cores recovered during JR104 (Fig. 1) sheding new light on the depositional processes, the patterns of grounded ice flow and the history of ice retreat from the shelf in the southern Bellingshausen Sea. These studies included core logging (by visual description and x-raying), measurement of physical properties (magnetic susceptibility, sediment density, water content, shear strength), grain-size analysis, determination of organic and inorganic carbon content, analysis of clay mineral assemblages, and AMS ^{14}C dating of calcareous (micro-)fossils and the acid-insoluble fraction of the bulk organic matter (AIO).

Shelf and slope sediments as indicators for (paleo-)environmental conditions

Sedimentary sequences recovered in the southern Bellingshausen Sea document a whole suite of (sub-)glacial and glaciomarine environmental settings. The basal units in the gravity cores from the western Belgica TMF, from the outer and middle shelf, and from Ronne Entrance consist of thick, grey, massive, lithogenic diamictons (e.g core GC374, Fig. 2). The diamictons on the continental slope represent GDFs consisting of the detritus initially delivered by the grounded ice stream to the shelf edge during the LGM. In contrast, the lithologically similar diamictons in Belgica Trough and Ronne Entrance are interpreted as deformation tills, which were deposited directly at the base of the grounded ice stream, and as sub-ice shelf diamictons, which were deposited subsequently to the retreat of the grounding line. Sediment core GC371 from the iceberg-soured outer Belgica Trough recovered a soft diamicton that is interpreted as an iceberg turbate. The basal sediments in cores from Eltanin Bay consist of grey-olive, lithogenic, massive to stratified gravelly muddy sands deposited as GDFs or iceberg-rafted sediments. In the cores from the eastern part of Belgica TMF the basal GDFs are overlain by thin, lithogenic gravelly sands interpreted as grain-flow deposits. Core GC380 was collected from an area of the eastern Belgica TMF, where gullies and channels are incised into the upper slope. GC380 recovered a thick sequence consisting of lithogenic sandy silt and clay laminae, which were probably deposited by turbidity currents. Sedimentation of the sandy-silt/clay couplets by meltwater plumes seems to be less likely.

The GDFs on the western Belgica TMF are capped by lithogenic muds with silty to sandy layers interpreted as distal turbidites. The soft diamictons on the shelf are overlain by thin-bedded, structureless to laminated, lithogenic, gravelly to sandy muds (Fig. 2), which were probably deposited in the vicinity of the grounding line during the transition from subglacial to glaciomarine conditions. Sedimentation during deglaciation is also inferred for the distal turbidites on the slope. Post-glacial sedimentation in the southern Bellingshausen Sea is dominated by brown, bioturbated, planktonic foraminifera-bearing muds occurring on the slope and on the outer to middle shelf (Fig. 2). Manganese-coated pebbles representing iceberg-rafted debris (IRD) are often scattered on the seabed of the outer shelf and upper slope and point to low sedimentation rates (<1 cm/kyr). On the inner shelf post-glacial sediments consist of olive to brown, bioturbated diatomaceous muds with low IRD concentrations. Both the foraminifera- and the diatom-bearing sediments document plankton production in a seasonally open-marine setting. Contents of lithogenic sand and (calcareous) foraminifera tests in the surface sediments and their AMS ^{14}C ages increase from the inner shelf to the upper slope. This pattern probably results from current-induced winnowing of the fine-grained particles. At present, an oceanographic front, the southern boundary of the Antarctic Circumpolar Current, runs along the shelf break of the southern Bellingshausen Sea (Orsi et al., 1995). We assume that this front repeatedly swept across the upper slope and outer shelf during the past, thereby winnowing the seabed sediments. In contrast to the outer shelf, the sedimentation rates on the inner shelf are relatively high, which is indicated by the low concentration of IRD and the lack of manganese coating of pebbles.

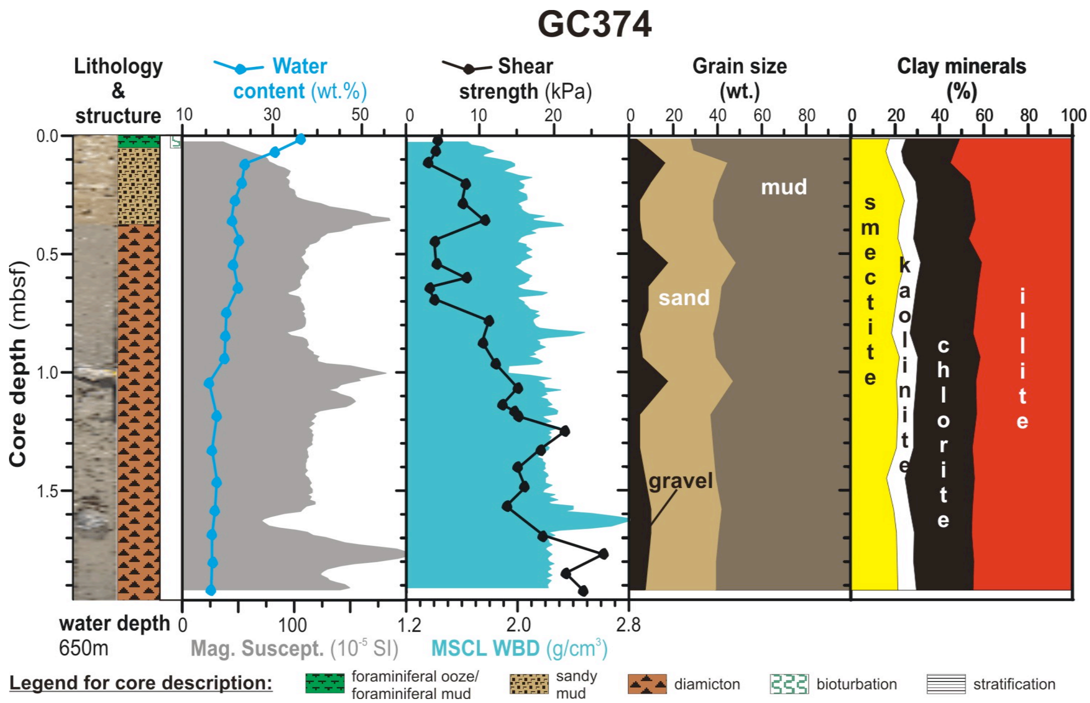

Figure 2. Lithology, physical properties (magnetic susceptibility, water content, shear strength, WBD =wet bulk density, measured with the MSCL =multi-sensor core logger), grain-size distribution and clay mineral composition of core GC374 (see Fig. 1 for site location).

Clay minerals as indicators of glacial and glaciomarine transport processes and pathways

The clay mineral assemblages in the deformation tills, the sub-ice shelf and iceberg-rafted diamictons, the GDFs and the laminated sequence at site GC380 are remarkably homogenous with contents of smectite, illite, chlorite and kaolinite exhibiting hardly any variations at a particular core site (Fig. 2). Like in the transitional and the post-glacial sediments, illite and smectite form the dominant clay mineralogical components in all cores. The clay mineral assemblages in the GDFs and turbidites from the Belgica TMF are relatively uniform with the smectite contents slightly increasing from east to west. However, the clay mineral contents in the sub-glacial sediments on the shelf vary significantly between core sites with no clear spatial pattern recognizable. This finding is surprising because the clay mineral distribution in the lithogenic fraction of the surface sediments shows a clear relation to both source rocks in the continental hinterland and modern transport pathways of the detritus (Hillenbrand et al., 2005). The modern supply of lithogenic material from the coast to the shelf and slope is assumed to be mainly controlled by wind and tidal driven currents and iceberg drift. The geographical heterogeneity of the clay mineral composition may indicate that the subglacial diamictons on the shelf have different ages. If during past glacial periods the ice stream flowing through Belgica Trough drained not always the same source rock area in the West Antarctic hinterland, the clay mineral composition of the corresponding subglacial deposits should reflect this variability. The catchment area of the ice stream may have changed geographically either within one (i.e. the last) glacial period or from one glacial period to another. Evidence for different ages of the subglacial diamictons recovered at sites PS2533, GC374 and GC372 comes from multibeam data and a seismic line across the western flank of outer Belgica Trough (Fig. 1). These data reveal a smaller, second-order trough incised into the main trough and a complex pattern with on-lapping and down-lapping near-seabed reflectors, which correspond to the cored deformation tills. However, we do not exclude the possibility that during the LGM the ice stream remobilised and reworked older sediments on its way across the shelf. Subglacial mixing of this old detritus with basal debris eroded in the West Antarctic hinterland within the deforming bed of the ice stream may explain the variability of the clay mineral assemblages in the subglacial sediments at the other core sites. Because most old shelf sediments are probably tills, also this scenario would imply that ice streams advancing across the shelf of the southern Bellingshausen Sea during past glacial periods drained not always the same catchment area.

The clay mineral composition of the structureless to laminated sandy muds deposited subsequently to grounded ice retreat from the shelf changes from an assemblage similar to that in the subglacial sediments to an assemblage resembling that in the sediments deposited under seasonally open-water conditions (Fig. 2). When the grounding line was located proximal to a core site, the lithogenic detritus deposited at the site had the same clay mineralogical fingerprint as the subglacial debris. When the grounding line retreated further away from the core site, additional lithogenic detritus from a wider source area was supplied to the site by ocean currents. On the western part of the Belgica TMF the sandy mud unit marking the transition from GDF deposition to open-marine sedimentation exhibits an initial increase in smectite contents followed by a decrease to concentrations more typical for the post-glacial sediments. Similar smectite concentrations were only observed in the subglacial diamicton recovered at site GC372, which is located in the second-order trough. Therefore, we suggest that at the end of the last glacial period, when the grounding line had already retreated from the shelf break, primarily sediment eroded from the second-order trough was delivered to the western Belgica TMF, possibly by meltwater outbursts carving the second order-trough into the outer shelf.

Timing of ice retreat from the shelf

We obtained AMS ^{14}C ages on the AIO of six cores from the shelf (GC374, GC371, GC372, GC368, GC357, GC359, and GC366). We dated the subglacial diamicton, the basal and the top section of the sandy mud unit, and the surface sediment. At all core sites except GC371 the ^{14}C ages increase with core depth. Down-core ages at a particular site were corrected by subtracting the AIO age of the core top. We consider the ^{14}C age obtained from the upper section of the sandy mud unit, which marks the phase of ice retreat from a core site, to be the most reliable age for deglaciation because these sediments contain a clay mineral assemblage corresponding to that of the post-glacial sediments. In contrast, the basal section from the sandy mud unit contains a clay mineralogical fingerprint corresponding to that of the subglacial diamictons. Therefore, significant contamination of the lower section of the sandy mud unit with reworked fossil carbon is very likely. The assumption of contamination of AMS ^{14}C ages obtained from the lower section of the sandy mud is confirmed by the similarity of these ages with those of the underlying subglacial diamictons. The corrected AMS ^{14}C ages of the upper section of the sandy mud unit indicate the following deglaciation ages for the southern Bellingshausen Sea: outer shelf (GC374, GC371) ca. 26 ka, middle part of the shelf (GC368, GC357) ca. 19 ka, Eltanin Bay (GC366) ca. 12 ka, and Ronne Entrance (GC359) ca. 7 ka B.P.

Summary

Glacial and glaciomarine sediments recovered from the shelf and slope in the southern Bellingshausen Sea reveal that a grounded ice stream advanced through Belgica Trough to the shelf break during the last glacial period. The ice stream drained different source areas in the West Antarctic hinterland, eroded and reworked old shelf sediments, and deposited subglacial debris as deformation till at its base. Some of this subglacial debris was bulldozed across the shelf edge and re-deposited down-slope onto the Belgica TMF by debris flows and turbidites. The timing of post-LGM deglaciation of the shelf suggests an early onset and possibly continuation of WAIS retreat in the southern Bellingshausen Sea.

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