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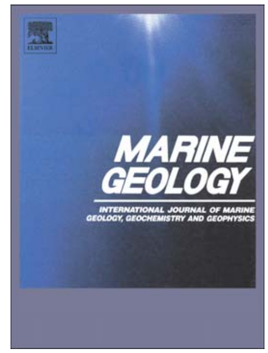

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Clay mineral provenance of sediments in the southern Bellingshausen Sea reveals drainage changes of the West Antarctic Ice Sheet during the Late Quaternary

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Abstract

The Belgica Trough and the adjacent Belgica Trough Mouth Fan in the southern Bellingshausen Sea (Pacific sector of the Southern Ocean) mark the location of a major outlet for the West Antarctic Ice Sheet during the Late Quaternary. The drainage basin of an ice stream that advanced through Belgica Trough across the shelf during the last glacial period comprised an area exceeding 200,000 km^2 in the West Antarctic hinterland. Previous studies, mainly based on marine-geophysical data from the continental shelf and slope, focused on the bathymetry and seafloor bedforms, and the reconstruction of associated depositional processes and ice-drainage patterns. In contrast, there was only sparse information from seabed sediments recovered by coring. In this paper, we present lithological and clay mineralogical data of 21 sediment cores collected from the shelf and slope of the southern Bellingshausen Sea. Most cores recovered three lithological units, which can be attributed to facies types deposited under glacial, transitional and seasonally open-marine conditions. The clay mineral assemblages document coinciding changes in provenance. The relationship between the clay mineral assemblages in the subglacial and proglacial sediments on the shelf and the glacial diamictons on the slope confirms that a grounded ice stream advanced through Belgica Trough to the shelf break during the past, thereby depositing detritus eroded in the West Antarctic hinterland as soft till on the shelf and as glaciogenic debris flows on the slope. The thinness of the transitional and seasonally open-marine sediments in the cores suggests that this ice advance occurred during the last glacial period. Clay mineralogical, acoustic sub-bottom and seismic data furthermore demonstrate that the palaeo-ice stream probably reworked old sedimentary strata, including older tills, on the shelf and incorporated this debris into its till bed. The geographical heterogeneity of the clay mineral assemblages in the sub- and proglacial diamictons and gravelly deposits indicates that they were eroded from underlying sedimentary strata of different ages. These strata may have been deposited during either different phases of the last glacial period or different glacial and interglacial periods. Additionally, the clay mineralogical heterogeneity of the soft tills recovered on the shelf suggests that the drainage area of the palaeo-ice stream flowing through Belgica Trough changed through time.

Keywords: Late Quaternary, West Antarctic Ice Sheet; ice stream; Bellingshausen Sea; clay mineralogy; continental margin; diamicton.

1. Introduction

The southern Bellingshausen Sea (Fig. 1) is a poorly-studied area on the Pacific continental margin of Antarctica, but was a major outlet for ice drainage from West Antarctica during the past (Ó Cofaigh et al., 2005a). The area was investigated in detail during cruise JR104 on RRS *James Clark Ross* in 2004. Multibeam swath bathymetric data and sub-bottom acoustic profiles revealed the existence of a major glacial trough ("Belgica Trough") on the shelf and an associated trough mouth fan ("Belgica TMF") on the adjacent slope (Ó Cofaigh et al., 2005a; Dowdeswell et al., 2008; Noormets et al., 2009). Distinct seabed morphological features on the shelf, such as mega-scale glacial lineations, drumlins and grounding-zone wedges, indicate that Belgica Trough was the former pathway of a grounded ice stream, which had advanced onto the outer shelf and probably to the shelf break during the last glacial period (Ó Cofaigh et al., 2005a; cf. Wellner et al., 2001). Moreover, the orientation of the subglacial bedforms suggested that the ice stream was fed by grounded ice draining through Eltanin Bay, located directly to the south of Belgica Trough, and Ronne Entrance, located between southwestern Alexander Island and the English Coast (Fig. 1). These results implied that ice flow into the southern Bellingshausen Sea drained more than 200,000 km^2 of the West Antarctic hinterland and, in contrast to the present ice drainage pattern, played a significant role for ice drainage from the largely marine-based West Antarctic Ice Sheet (WAIS) during the Late Quaternary (Ó Cofaigh et al., 2005a).

First results of studies on three sediment cores collected from the continental margin in the southern Bellingshausen Sea during cruise ANT-XI/3 with RV

Polarstern in 1994 confirmed grounded ice advance onto the outer shelf and deposition of diamictons interpreted as glaciogenic debris flows (GDFs) on the western part of the Belgica TMF (Hillenbrand et al., 2005). While the clay mineralogical composition of a glacial diamicton recovered from the shelf (site PS2533-2; location see Fig. 1) corroborated supply of glaciogenic detritus from Eltanin Bay, the clay mineralogical composition of the GDFs on the continental slope (sites PS2538-2 and PS2540-3; locations see Fig. 1) pointed to major supply of subglacial debris via Ronne Entrance (Hillenbrand et al., 2005). The latter finding is surprising, because the orientation of subglacial bedforms on the shelf indicates that ice flowing into Belgica Trough was mainly fed by ice draining the WAIS through Eltanin Bay with a smaller contribution from ice draining the Antarctic Peninsula Ice Sheet through Ronne Entrance (Ó Cofaigh et al., 2005a).

In this paper, we present a large clay mineralogical dataset compiled from surface seabed samples and 21 sediment cores recovered from the southern Bellingshausen Sea during cruises JR104 and ANT-XI/3 (Supplementary Table). We relate the clay mineralogical composition of the sediments to different environmental conditions affecting deposition on the shelf and slope since the last glacial period. Moreover, we infer variations in past ice-drainage patterns from changes in sediment provenance. Subglacial sediment dispersal reconstructed from provenance data has been studied in detail for palaeo-ice sheets on the Northern Hemisphere (for a review see Clark, 1987). These studies used mainly mineralogical, petrological or geochemical indicator concentrations in tills, for example erratics from a particular well-known rock source, to determine transport distances (e.g. Clark, 1987; Dyke & Morris, 1988; Klassen, 2001). The indicator concentrations usually decrease exponentially or linearly with distance from the source (Clark, 1987; Klassen, 2001), forming so-called dispersal trains (e.g. Dyke & Prest, 1987; Dyke & Morris, 1988). The length of these dispersal trains varies between a few kilometres and 1,000 kilometres (e.g. Clark, 1987; Dyke et al., 2002). Topography, basal ice velocity and initial concentration of englacial debris have been recognized as primary factors promoting subglacial sediment dispersal over long distances (Clark, 1987; Dyke & Prest, 1987; Dyke & Morris, 1988; Klassen, 2001). In our study area, mountain valleys are restricted to the Antarctic Peninsula, and thus we can assume that a palaeo-ice stream advancing across the shelf of the southern Bellingshausen Sea transported debris predominantly at its base. Given the topography of Belgica Trough and relatively high palaeo-ice flow speed, which is inferred from the mega-scale glacial lineations present within the trough, we can expect subglacial dispersal trains to be in the order of a hundred to hundreds of kilometres (cf. Clark, 1987; Dyke & Morris, 1988).

2. Material and methods

Undisturbed sediments from the seafloor surface (recovered with box and multiple corers) and long sediment cores (recovered with a gravity corer) were collected during cruises JR104 with RRS *James Clark Ross* in 2004 and ANT-XI/3 with RV *Polarstern* in 1994 (Miller & Grobe, 1996; Fig. 1, Supplementary Table). The sediment cores were described visually and using X-radiographs.

Shear strength was measured on the split cores using a hand-held shear vane and a shear vane HAAKE Rotovisco 1500M, respectively.

The clay fraction (<2 µm) was separated from the bulk sediment in settling tubes. Relative clay mineral contents in the surface sediment samples and in cores PS2533-2, PS2538-2 and PS2540-3 were determined with X-ray diffraction according to the procedures and methods described in detail by Ehrmann et al. (1992) and Petschick et al. (1996). All other clay samples were processed as follows: Clay (40 mg) was dispersed in an ultrasonic bath and mixed with 1 mL of an internal standard consisting of a 1% MoS_2 suspension. The samples were mounted as texturally oriented aggregates by rapidly filtering the suspension through a membrane filter of 0.15-µm pore width. The filter cakes were dried at 50°C and mounted on aluminum tiles. They were exposed to ethylene glycol vapor at a temperature of 50°C for at least 18 hr immediately before the X-ray analyses. The measurements were conducted on an automated powder diffractometer system Rigaku MiniFlex with CoKα radiation (30 kV, 15mA). The samples were X-rayed in the range 3°-40°2θ with a scan speed of 0.02°2θ/s. Additionally, the range 28°-30.5°2θ was measured with a step size of 0.01°2θ/s in order to better resolve the (002) kaolinite peak and the (004) chlorite peak. The X-ray diffractograms were evaluated on an Apple Macintosh personal computer using the “MacDiff” program (freeware available from http://servermac.geologie.uni-frankfurt.de/HomePage.html).

Our study concentrates on the main clay mineral groups smectite, illite, chlorite, and kaolinite. These clay minerals were identified by their basal reflections at ~17 Å (smectite), 10 and 5 Å (illite), 14.2, 7, 4.72, and 3.54 Å (chlorite), and 7 and 3.57 Å (kaolinite). Semiquantitative evaluations of the mineral assemblages were made on the integrated peak areas. The relative percentages of smectite, illite, chlorite, and kaolinite were determined using empirically estimated weighting factors (Biscaye, 1964, 1965; Brindley & Brown, 1980). No effort was made to quantify mixed-layer clay minerals.

All data and core photographs are available from the PANGAEA world data center under http://doi.pangaea.de/**[XXX]**.

3. Results

3.1. Clay mineral distribution in the surface sediments

The main clay mineral component in surface sediment samples from Eltanin Bay is illite (54-70%) with significantly less chlorite (24-27%), only minor amounts of smectite (5-16%) and traces of kaolinite (1-4%) (Fig. 2). In comparison, surface sediments in Ronne Entrance contain more smectite (22-51%), less illite (26-47%) and similar contents of both chlorite (20-28%) and kaolinite (2-4%). Clay minerals in the sediments on the outer shelf and continental slope are dominated by illite (44-61%) with similar contents of smectite (13-27%) and chlorite (23-29%) and low contents of kaolinite (2-6%). A slight enrichment of chlorite (≤ 33%) is observed on the lower slope.

3.2. Lithological units

Most cores from the continental shelf and slope in the southern Bellingshausen Sea recovered three lithological units (Fig. 3; Supplementary Figure). In the following we describe these units from bottom to top.

3.2.1. Lower lithological unit

The sediments at the base of cores GC365, GC366 and GC362 from around Eltanin Bay, core GC368 from the middle shelf and core GC371 from the outer shelf in Belgica Trough consist of 0.45-2.1m thick, lithogenic, olive grey to dark brown massive to stratified gravelly sandy mud and muddy diamictons with relatively low shear strength (≤12 kPa) (Fig. 3a, Supplementary Figure). The lower units in cores GC359 and GC360 from the inner shelf, cores GC357 and GC370 from the middle shelf, cores PS2533-2, GC372, GC374, PS2542-2, PS2543-1 from the outer shelf, core GC352 from the uppermost continental slope, cores PS2540-3, PS2538-2 and GC378 (above 2.24m core depth) from the western Belgica TMF, and core GC381 from the slope east of Belgica TMF consist of 0.85-3.8m thick, grey, massive, lithogenic muddy diamictons (Figs. 3b-e, 3g-i, 3k, Supplementary Figure). The diamictons in the cores from the shelf exhibit relatively high shear strength values that often increase downcore to values between 14 and 35 kPa. In the lithologically similar muddy diamictons of the cores from the continental slope the shear strength also often increases downcore to values between 8 and 30 kPa.

3.2.2. Middle lithological unit

The muddy diamictons and gravelly sandy muds on the shelf are overlain by 0.1-1.0m thick, structureless to laminated, lithogenic, gravel-bearing sandy muds and muddy sands with relatively low shear strength ≤11 kPa (Figs. 3a-h, Supplementary Figure). Only in the gravelly sandy mud of core GC372 relatively high shear strength values (up to 17 kPa) are observed. The diamictons on the western Belgica TMF are capped by 0.2-0.3m thick laminated to stratified lithogenic muds intercalated with silty to sandy layers characterised by enhanced shear strength values (up to 22 kPa) and occasionally normal grading (cores PS2538-2 and PS2540-3). In core GC381 the middle unit consists of a 0.2m thick, lithogenic sandy gravel with an erosional basis (Fig. 3k). Core GC380 from the eastern Belgica TMF recovered a 3.5m thick sequence of lithogenic sandy silt and clay laminae (Fig. 3j), which extends to the base of this core.

3.2.3. Upper lithological unit

The sediments overlying the middle unit on the inner shelf consist of 0.2-0.8m thick olive to brownish, bioturbated diatomaceous muds with low concentrations of iceberg-rafted debris (IRD) and low shear strength (≤5 kPa) (Fig. 3a-c, Supplementary Figure). The upper unit on the middle to outer shelf and on the slope consists of 0.1-0.4m thick, brown, bioturbated, planktonic foraminifera-bearing muds, which also exhibit low shear strength values (Fig. 3d-k, Supplementary Figure). Manganese-coated pebbles representing IRD are often scattered on the seabed of the outer shelf and upper slope. At site GC378 on the slope the sequence of a lithogenic sandy mud and an overlying bioturbated foraminifera-bearing mud is repeated between 2.65m and 2.24m core depth (Supplementary Figure).

3.3. Down-core variations of clay mineral assemblages

3.3.1. Assemblages in the lower lithological unit

The clay mineral assemblages in the lower unit are remarkably homogenous at any particular core site with contents of smectite (1-34%), illite (28-69%), chlorite (23-38%) and kaolinite (4-15%) exhibiting hardly any down-core variation (Figs. 3, 4, Supplementary Figure). Illite plus smectite or illite form the dominant clay mineralogical components at most sites. Only the assemblage in the diamicton of core GC359 is dominated by chlorite and illlite (Group A in Fig. 5). The clay mineral composition of the lower unit in the cores from the shelf varies significantly between the sites. This variability is in remarkable contrast to the clay mineral distribution in the surface sediments (Fig. 2). Additionally, the kaolinite contents in the lower unit at both the shelf and the slope sites are generally higher than in the surface sediments (Fig. 4).

With the exception of site GC372, the muddy diamictons and gravelly sandy muds in Eltanin Bay, the western Belgica Trough and at site PS2543-1 are characterised by relatively high illite concentrations (Group B in Fig. 5), but also within Group B the illite contents vary between the individual sites without exhibiting a clear geographical pattern. The lower unit in cores from the eastern Belgica Trough, the uppermost slope (site GC352) and site GC372 show high smectite contents coinciding with low illite concentrations (Group C in Fig. 5). Apart from core GC372, the chlorite contents are slightly enhanced in Group C when compared to Group B. Similar to Group B, the concentrations of the individual clay minerals vary between the sites of Group C without showing a clear geographical relationship. The highest smectite contents in the diamictons of Group C occur at site GC372, which is located in a smaller, second-order trough incised into the outer Belgica Trough (Fig. 1), and site GC357 (Fig. 5). The clay mineral assemblages in the lower unit from the Belgica TMF are relatively uniform with the smectite contents slightly increasing from east to west (Group D in Fig. 5).

3.3.2. Assemblages in the middle lithological unit

In general, the average contents of smectite (1-43%), illite (31-68%), chlorite (18-38%) and kaolinite (3-10%) in the sediments of the middle unit are not much different from those in the lower unit (Fig. 6). However, within the middle unit on the shelf the clay mineral composition changes from an assemblage similar to that in the lower unit to an assemblage resembling that in the upper unit (Figs. 3, Supplementary Figure). In comparison to the assemblages in the lower unit, the assemblages in the middle unit of Groups A, B and C show more overlap (Fig. 7). Group A is still slightly enriched in chlorite, Group B is still slightly enriched in illite, and Group C is still slightly enriched in smectite (Fig. 7). At most core sites on the southern Bellingshausen Sea shelf (e.g. GC366, GC359, PS2533-2, PS2542-2, GC374) the clay mineral composition changed gradually. However, at some sites (e.g. GC357, GC360, GC371) the clay mineral assemblage of the middle unit differs from those in the lower and upper units.

Similar to the clay mineral assemblages in the lower unit, those in the middle unit of Group D represent a mixture between Group B and C (Fig. 7). On the western Belgica TMF the clay mineralogy of the middle unit exhibits an initial increase in smectite contents (up to 52% in core GC378) followed by a decrease to smectite concentrations more typical of the upper unit (Figs. 2, 3i-k, Supplementary Figure). On the shelf, similarly high smectite concentrations were only observed in the lower unit of core GC372.

3.3.3. Assemblages in the upper lithological unit

The concentrations of smectite (19-33%), illite (34-55%) and chlorite (21-31%) in the upper unit are similar to those in the surface sediments (Figs. 2, 8). Only the kaolinite contents (5-9%) are slightly higher. The clay mineral assemblages within Groups A, B, C and D vary less than in the middle and lower units (Fig. 9). Moreover, the differences in clay mineral composition between the different groups are less pronounced (Fig. 9). Nevertheless, the upper unit of core GC372 and Group B, which comprises the cores on the shelf west of the Belgica Trough axis, are characterised by a clay mineral assemblage enriched in illite, whereas the sediments in most cores of Group C, which comprises the sites on the shelf east of the Belgica Trough axis, exhibit higher contents of smectite (Fig. 9). The smectite contents at both sites GC359 and GC360 are higher in the upper unit than in the middle unit.

4. Discussion

4.1. Clay minerals in surface sediments: Relation to source rocks and proxies for transport paths

The analysis of clay mineral assemblages in surface sediments recovered proximal to the coast provides clues on source areas in the Antarctic hinterland, and thus helps to decipher transport pathways farther offshore. The dominance of illite in Eltanin Bay (Fig. 2) is likely to reflect the supply of detritus from plutonic rocks underlying the Bryan Coast, because clay mineral assemblages in soils formed on granitic rocks in that region mainly contain illite (Vennum &

Nejedly, 1990). The relative enrichment of smectite in the surface sediment samples in Ronne Entrance (Fig. 2) probably originates in the additional supply of lithogenic detritus derived from volcanic rocks cropping out on Beethoven Peninsula, western Alexander Island (Hole et al., 1991; Smellie, 1999). A few volcanic rocks also crop out along the English Coast (Smellie, 1999), and soils formed on them were shown to differ from soils formed on their granitic counterparts by the presence of smectite (Vennum & Nejedly, 1990). However, the volcanic rocks on Beethoven Peninsula seem to be the most important source for the higher smectite contents in surface sediments from Ronne Entrance, because sample PS2528-1 recovered from near its coast exhibits the highest smectite concentration (51%) in the whole study area (Fig. 2).

Clay minerals in the sediments on the outer shelf and continental slope form a mixed assemblage (Fig. 2), pointing to supply of detritus from both Ronne Entrance and Eltanin Bay by marine currents and iceberg rafting. The slight enrichment of chlorite on the lower slope is caused by supply of fine-grained detritus from the mainland of the Antarctic Peninsula via a bottom current flowing westward along the base of the slope (Hillenbrand et al., 2003, 2005).

4.2. Depositional environments of the lithological units

4.2.1. Lower lithological unit: Glacial facies

The gravelly sandy muds and muddy diamictons in the lower unit at sites GC365, GC366 and GC362 from around Eltanin Bay and core GC368 from the middle shelf in Belgica Trough exhibit low shear strength (≤10 kPa) (Fig. 3a, Supplementary Figure). Such lithologies and shear strength values are typical for GDFs, iceberg-rafted sediments or sediments deposited proximal to the grounding line of an ice shelf (e.g. Domack et al., 1999; Licht et al., 1999; Evans & Pudsey, 2002; Hillenbrand et al., 2005). We interpret the sediments of the lower unit at sites GC365 and GC366 as GDFs, because site GC365 is located within and site GC366 at the flank of a deep inner-shelf basin in Eltanin Bay (Fig. 1). At these sites we can expect gravitational down-slope transport, particularly during times of high lateral sediment supply, for example, when a grounding line was located nearby. In contrast, cores GC362 and GC368 were recovered from areas of lower relief topography. Therefore, we interpret the diamicton and the gravelly sediments at these two sites as iceberg-rafted sediments or sub-ice shelf diamictons. However, we cannot rule out their deposition as a soft till at the base of the grounded ice stream, which was present in Belgica Trough during the last glacial period (Ó Cofaigh et al., 2005a; Dowdeswell et al., 2008).

Core GC371 was collected from the outer shelf within Belgica Trough (Fig. 1), where multibeam swath bathymetric data revealed iceberg furrows (Ó Cofaigh et al., 2005a). Sediment cores collected from the iceberg-ploughed outer shelf around West Antarctica frequently recovered diamictons that resemble the lower unit in core GC371 and are interpreted as iceberg turbates (e.g. Lowe & Anderson, 2002; Evans et al., 2005; Heroy & Anderson, 2005). In accordance with these authors we interpret the muddy diamicton at site GC371 as an iceberg turbate resulting from iceberg scouring.

The diamictons in the lower unit of cores GC359 and GC360 from the inner shelf, cores GC357 and GC370 from the middle shelf and cores PS2533-2, GC372, GC374, PS2542-2, PS2543-1 from the outer shelf are characterised by relatively high shear strength, which increases downcore. Thus, the diamictons at those core sites resemble soft tills reported from other parts of the Antarctic shelf (e.g. Licht et al., 1996, 1999; Anderson, 1999; Domack et al., 1999; Evans & Pudsey, 2002; Evans et al., 2005; Ó Cofaigh et al., 2005b). We interpret them as soft tills deposited directly at the base of a grounded ice stream that had advanced across the shelf during the last glacial period (Ó Cofaigh et al., 2005a; Hillenbrand et al., 2005). Our interpretation is corroborated by the fact that most of the cores were recovered from shelf areas showing glacial lineations formed at the ice-stream bed (Ó Cofaigh et al., 2005a). The upper parts of those diamictons, however, may be sub-ice shelf diamictons that were deposited proximal to the grounding line during ice-stream retreat (cf. Licht et al., 1999; Domack et al., 1999; Evans & Pudsey, 2002; Hillenbrand et al., 2005).

The diamictons in the lower unit of core GC352 from the uppermost continental slope, cores PS2540-3, PS2538-2 and GC378 (above 2.24m core depth) from the western Belgica TMF, and core GC381 from the slope east of Belgica TMF also exhibit relatively high shear strength values that often increase down-core. The water depths of these core sites exceed 700m (see Supplementary Table). Therefore, we interpret the diamictons on the slope as GDFs that consist of the detritus delivered by the grounded ice stream to the shelf edge during the last glacial period (cf. Kurtz & Anderson, 1979; Wright & Anderson, 1982; Dowdeswell et al., 2004a, 2006a, 2008; Hillenbrand et al., 2005).

4.2.2. Middle lithological unit: Transitional facies

The sediments of the middle unit in the cores from the southern Bellingshausen Sea shelf have a coarse-grained texture and are lacking biogenic components and bioturbation. These criteria indicate their deposition in the vicinity of a grounding line during the transition from subglacial/sub-ice shelf (proximal to the grounding line) to more glaciomarine conditions (distal to the grounding line) under ice-shelf or perennial sea-ice coverage. Our interpretation is consistent with the interpretation of similar sediments deposited elsewhere on the Antarctic shelf during the last deglaciation (e.g. Domack et al., 1999; Licht et al., 1999; Evans & Pudsey, 2002).

The sediments in the middle unit of the cores from the continental slope show lithological characteristics (e.g. normal grading), which are typical for distal turbidites (cf. Hillenbrand et al., 2005). Gravitational down-slope transport is also indicated by the middle unit of core GC381 that consists of sandy gravel with an erosional basis (Fig. 3k). We interpret this coarse-grained sediment as a grain-flow deposit. In contrast, formation by current winnowing seems to be unlikely, because a strong along-slope current should also have affected other sites on the upper slope (e.g. GC378 and PS2540-3 located at similar water depths), where no sandy gravel is observed. Core GC380 was collected from an area of the eastern Belgica TMF, where gullies and channels are incised into the upper slope (Dowdeswell et al., 2008; Noormets et al., 2009). The thick sequence of lithogenic sandy silt and clay laminae (Fig. 3j) recovered at this site resembles levee sediments reported from other parts of the Antarctic continental slope (e.g. Weddell Sea, Diekmann & Kuhn, 1997). Therefore, we interpret the laminated sequence in core GC380 as an over-spill deposit formed by turbidity currents travelling down-slope through a channel located <1 km to the SE. Given their stratigraphic position and composition, we suggest that the sedimentation of the distal turbidites and the grain-flow deposit on the slope of the southern Bellingshausen Sea occurred during the last deglaciation.

4.2.3. Upper lithological unit: Post-glacial facies

The presence of significant concentrations of diatoms and foraminifera, the bioturbation and the IRD content of the sediments in the upper unit of cores from the Bellingshausen Sea shelf and slope document a seasonally open-marine setting with plankton production (cf. Licht et al., 1996, 1999; Domack et al., 1999; Evans & Pudsey, 2002; Lowe & Anderson, 2002; Evans et al., 2005; Ó Cofaigh et al., 2005b). We assign the deposition of these sediments to the present interglacial period. The manganese-coated pebbles on the outer shelf and upper slope suggest low sedimentation rates (<1 cm/kyr). The combined thickness of the middle and upper unit in most cores from the shelf and slope is less than 0.8m (Fig. 3; Supplementary Figure). This thin cover suggests that the last time, when a grounded ice stream advanced through Belgica Trough to the shelf break, was indeed the last glacial period (cf. Hillenbrand et al., 2005; Ó Cofaigh et al., 2005).

The lower foraminifera-bearing mud of core GC378, which resembles the sediments of the upper unit at this site, was probably deposited during the interglacial period of Marine Isotope Stage (MIS) 5 (ca. 130-72 ka). A disseminated tephra layer found in this lower foraminifera-bearing mud corroborates a MIS 5 age (Hillenbrand et al., 2008). Correspondingly, the lithogenic sandy mud underlying the lower foraminifera-bearing mud at site

GC378 was probably deposited during the transition from the penultimate glacial period of MIS 6 (ca. 191-130 ka) to MIS 5.

4.3. Variations of clay mineral assemblages through time

4.3.1. Assemblages in the glacial facies

The remarkably uniform clay mineral assemblages in the soft tills, sub-ice shelf diamictons and the GDFs at any particular core site (Fig. 3, Supplementary Figure) documents intense mixing of eroded detritus during subglacial transport and during re-deposition of the glaciogenic debris in front of the grounding line of the ice stream. However, the clay mineral composition of the sub- and proglacial shelf sediments varies significantly between the core sites and, in contrast to the clay mineral assemblages in the surface sediments (Fig. 2), does not show a clear relation to source rocks in the hinterland or transport pathways (Fig. 4). We do not observe consistent geographical trends in changes of the clay mineral assemblages along the reconstructed flow lines of the Belgica palaeo-ice stream (Fig. 1).

4.3.1.1. Inner shelf north of Ronne Entrance (Group A)

Site GC359 (and site GC358) north of Ronne Entrance differ from the other core sites on the shelf, because streamlined subglacial bedforms observed in multibeam swath bathymetry data clearly indicate that directly to the west of Beethoven Peninsula grounded ice flowed towards NNW and not into Belgica Trough (Fig. 1; Ó Cofaigh et al., 2005a). The mainland of the Antarctic Peninsula is well known as a source for clay enriched in chlorite and illite (Hillenbrand & Ehrmann, 2002; Hillenbrand et al., 2003). Hence, the high chlorite and illite contents in the diamicton at site GC359 (Group A in Fig. 5), which contrast with the high smectite concentrations in modern surface sediments (Fig. 2), and the orientation of subglacial streamlined bedforms in the vicinity of this site (Fig. 1) indicate that ice originating from the Antarctic Peninsula Ice Sheet drained through Ronne Entrance towards the outer shelf.

4.3.1.2. Eltanin Bay and western Belgica Trough (Group B)

The relatively high illite concentrations in the muddy diamictons and gravelly sandy muds of Group B cores can be attributed to the high supply of detritus originating from Eltanin Bay, which was deposited as a till at the base of the Belgica palaeo-ice stream or as sub-ice shelf diamicton/glaciogenic debris flow proximal to the grounding line (Fig. 10; cf. Hillenbrand et al., 2005). However, the illite contents in the diamictons of Group B vary between the individual sites without exhibiting a clear geographical pattern. This heterogeneity is surprising given the expected length of subglacial dispersal trains in the order of hundreds of kilometres.

4.3.1.3. Eastern Belgica Trough (Group C)

Similar to Group B, the variability of clay mineral assemblages between the core sites of Group C points to relatively short subglacial dispersal trains (less than 100 kilometres). In contrast to Group B, the glacial diamictons and gravelly sandy muds of Group C have low illite, but high smectite concentrations. The distribution of modern surface sediments indicates that volcanic rocks on Beethoven Peninsula are a source for smectite-rich detritus (Fig. 2). However, the clay mineral assemblage in the glacial diamicton at site GC359 demonstrates that during the last glacial period any smectite signal from

Beethoven Peninsula was overprinted by chlorite- and illite-enriched glaciogenic debris originating from the Antarctic Peninsula mainland (Fig. 5). Therefore, smectite delivered from Beethoven Peninsula cannot explain the high smectite contents observed in the glacial diamictons of Group C.

Alternative sources for smectite-rich detritus are old sedimentary rocks and strata, which might occur on the shelf of the southern Bellingshausen Sea. For example, submarine outcrops of pre-Oligocene sedimentary strata have been described as important smectite sources for Cenozoic glaciomarine sediments from the Antarctic continental margin (e.g. Robert & Maillot, 1990; Hillenbrand & Ehrmann, 2003). If smectite-enriched sedimentary strata, including older tills derived from these strata, are present on the shelf of our study area, they were prone to erosion by grounded ice during glacial periods (Fig. 11). The hypothesis of the remobilisation of older sedimentary strata is supported by the observation that the kaolinite concentrations in the sub- and proglacial sediments of the lower unit are enhanced (Fig. 4), which indicates erosion of pre-Oligocene sedimentary rocks or tills containing detritus derived from these rocks (e.g. Ehrmann et al., 1992; Petschick et al., 1996; Hillenbrand et al., 2003).

The highest smectite contents in the diamictons of Group C occur at sites GC372 and GC357 (Fig. 5). Site GC372 is located in a smaller, second-order trough that is incised into the outer Belgica Trough (Fig. 1). When the clay mineral assemblage in the diamicton at site GC372 is compared to that of core PS2542-2, which is located in the second-order trough, too (Fig. 1), nearby cores GC374 and PS2533-2 (all three cores belong to Group B) and the modern near-coastal assemblages from Eltanin Bay and Ronne Entrance (Figs. 5, 12), it becomes obvious that i) no clear geographical relationship exists, and ii) the smectite content in the modern assemblage from Ronne Entrance is lower than in diamicton samples from core GC372. The latter finding suggests that Ronne Entrance is an unlikely source area for the glacial sediments at site GC372.

4.3.1.3.1. Evidence for subglacial reworking of older sedimentary strata

A single-channel seismic profile that crosses the western flank of Belgica Trough on the outer shelf, including the second-order trough (for location of seismic profile see Fig. 1), reveals downlap and onlap relationships between near-seabed sediment units indicating their diachronous deposition (Fig. 13). The acoustically transparent strata probably correspond to thick till bodies, which may underlie the recovered soft tills elsewhere in the study area. Our clay mineral data and the stratigraphical relationship visible in the seismic profile suggest that the Belgica Trough palaeo-ice stream remobilised and reworked older sediments on its way across the shelf, thereby incorporating the eroded material into its subglacial deformable bed and mixing it with basal debris eroded from the West Antarctic hinterland. Our findings are consistent with hypotheses of erosional and mixing processes suggested for other palaeo-ice streams on the West Antarctic shelf (cf. Evans et al., 2005; Ó Cofaigh et al., 2005b, 2007). One of these hypothesis assumes that soft tills in those areas are erosional products from underlying, highly consolidated stiff tills, which are characterised by shear strength values up to 100 kPa (Evans et al., 2005; Ó Cofaigh et al., 2005b, 2007).

The geometry of the seismic reflectors on the outer shelf in the southern Bellingshausen Sea indicates that the outer shelf cores probably recovered soft tills of different ages (Fig. 13). The presence of old tills near the seabed has important implications for the age interpretation of sub-seafloor till layers observed on the Antarctic shelf. Usually, these till layers, which cannot be directly dated, have been assigned to the last glacial maximum (e.g. Evans et al., 2005). Our results demonstrate that the till layers may also contain subglacial diamictons deposited during an earlier ice advance or even an earlier glacial period. However, this finding does not affect reconstructions of palaeo-ice sheet extent during the last glacial period, if it can be shown that subglacial bedforms associated with a glacial unconformity formed or were modified during the last glacial cycle.

4.3.1.3.2. Older sedimentary strata as a source for (sub-)glacial deposits

We suggest that the smectite enrichment in the muddy diamictons and gravelly sandy muds of the Group C cores originates in the subglacial erosion of old sedimentary strata. Such reworking of shelf sediments during full-glacial ice advances is a common feature on high-latitude continental shelves (e.g. Dowdeswell et al., 2007). Besides the seismic profile from the outer shelf (Fig. 13), acoustic sub-bottom profiles from various locations within Belgica Trough, for example near site GC357, which recovered a smectite-rich soft till (Figs. 3d, 4, 5), reveal a flat lying sub-seafloor reflector (Fig. 14). Similar sub-bottom reflectors were observed in other glacial troughs on the West Antarctic shelf (e.g. Dowdeswell et al., 2004b; Evans et al., 2005, 2006; Ó Cofaigh et al., 2005b). In sediment cores the sub-bottom reflector often corresponds to the lithological boundary between the upper soft till and the lower stiff till (Evans et al., 2005; Ó Cofaigh et al., 2005b, 2007). This stratigraphic relationship and the lithological characteristics of the tills have been considered in detail by Ó Cofaigh et al. (2007) who interpreted them as ‘‘hybrid’’ tills formed by a combination of subglacial sediment deformation and lodgement, and reflecting changes in basal effective pressure and/or glacial re-advance during the same glaciation.

Our gravity cores only recovered soft tills, but their clay mineralogical heterogeneity suggests that the sub-bottom reflector in the southern Bellingshausen Sea actually corresponds to a glacial unconformity with underlying older sediments even locally cropping out at the modern seabed (Fig. 14). This conclusion is corroborated by the observation that at some locations the flat sub-bottom reflector truncates deeper, dipping sub-bottom reflectors (Fig. 14). Within the study area, seaward dipping reflectors that underlie wedge-shaped sediment accumulations were originally interpreted as grounding-zone wedges (Ó Cofaigh et al., 2005a), in accordance with interpretations of similar features elsewhere on the Antarctic shelf (e.g. Dowdeswell et al., 2004b). However, there is no independent confirmation (e.g. by coring) for the origin of the dipping sub-bottom reflectors in the southern Bellingshausen Sea. We speculate that at least some of the dipping sub-bottom reflectors represent old sedimentary strata, which were eroded during ice stream advance across the shelf, and that the erosional detritus was advected into the active till bed (Fig. 11).

The clay mineral assemblage in the diamicton at site GC359 is dominated by illite and chlorite supplied from the Antarctic Peninsula, as we pointed out in 4.3.1.1. Glacial lineations document divergent palaeo-ice flow from Ronne Entrance to both site GC359 and site GC360 (Fig. 1), and thus we might expect enhanced chlorite and illite contents in the glacial diamicton at site GC360, too. However, the diamicton at site GC360 is characterised by significantly higher smectite and slightly higher kaolinite contents (Figs. 3b-c, 5), which are the highest kaolinite contents of all studied sediments (Figs. 4, 6, 8). No sub-bottom profiles that might indicate the presence of old sedimentary strata to the south of site GC360 are available from Ronne Entrance, but bathymetric data reveal water depths of >800 m on the inner shelf in Ronne Entrance, suggesting the presence of a deep basin (Fig. 1). The discrepancy of clay mineral assemblages in the glacial diamictons of cores GC359 and GC360 could be explained by subglacial erosion of old smectite- and kaolinite-enriched sedimentary strata cropping out within that basin (Fig. 15a). The palaeo-ice stream flowing through Ronne Entrance may have deposited detritus derived from these sediments in the subglacial soft till at site GC360, whereas the trunk of the ice stream flowing along the SW-tip of Alexander Island may have by-passed the basin and deposited (undiluted) glaciogenic debris sourced from the Antarctic Peninsula at site GC359. This interpretation were consistent with observations of Dyke & Prest (1987) and Dyke & Morris (1988), who reported relatively narrow and locally restricted dispersal trains of subglacial sediments from the Laurentide Ice Sheet.

The geographical heterogeneity of the clay mineral composition of the muddy diamictons and gravelly sandy muds of Group B/Group C and the acoustic sub-bottom and seismic profiles from the shelf demonstrate that these glacial deposits are derived from older sediments of different ages, including older tills. The variability of the clay mineral assemblages even within a particular group indicates a heterogeneous clay mineral composition of underlying source sediments. This heterogeneity suggests that during past glacial periods the ice stream flowing through Belgica Trough did not always drain the same source area in the West Antarctic hinterland. The main catchment area of the ice stream may have changed geographically either within a single (i.e. the last) glacial period or from one glacial period to another. The heterogeneity of the clay mineral composition of the sub- and proglacial deposits in our cores reflects this variability.

4.3.1.4. Continental slope (Group D)

The GDFs of Group D have a clay mineral composition intermediate between that of glacial diamictons in Group B and Group C, documenting that the GDFs consist of redeposited till material derived from the adjacent shelf. This finding corroborates previous interpretations that the palaeo-ice stream in Belgica Trough advanced to the shelf break during the last glacial period (Ó Cofaigh et al., 2005a; Dowdeswell et al., 2008). On the basis of clay mineral analyses on one core from the shelf (PS2533-2) and two cores from the slope (PS2538-2, PS2540-3), Hillenbrand et al. (2005) had attributed the enhanced smectite concentration in the GDFs to a high subglacial supply of detritus from Ronne Entrance. This could be explained by a switching in the flow direction of the Belgica palaeo-ice stream, similar to what has been observed on the mid-Norwegian glaciated margin (Dowdeswell et al., 2006b). However, our much larger clay mineral data set presented here implies that the smectite enrichment in the GDFs on the slope is caused by a high delivery of till material containing detritus reworked from old sedimentary strata. Only the clay mineral assemblage in the GDF of core GC381 east of the Belgica TMF shows some similarity to that in the subglacial soft till of core GC359 (Figs. 4, 5). This relationship suggests that subglacial detritus supplied from eastern Ronne Entrance influenced debris flow sedimentation at site GC381.

4.3.2. Assemblages in the transitional facies

4.3.2.1. Continental shelf (Groups A, B, C)

The clay mineral composition of the structureless to laminated sandy muds deposited subsequent to grounding line retreat from the shelf changes from an assemblage similar to that in the sub- and proglacial sediments to an assemblage resembling that in the sediments deposited under seasonally open-water conditions (Figs. 3a-h, 6, 8, Supplementary Figure). In comparison to the glacial assemblages, the deglacial assemblages of Groups A, B and C show more overlap (Fig. 7). Group A is still slightly enriched in chlorite, Group B is still slightly enriched in illite, and Group C is still slightly enriched in smectite (Fig. 7). When the grounding line was located proximal to a core site on the shelf, the lithogenic detritus deposited at the site had the same clay mineralogical fingerprint as the subglacial debris. During deglaciation the grounding line retreated further away from the core site, and as a consequence additional lithogenic detritus from a wider source area was supplied to the site by ocean currents (Fig. 10). At most core sites on the southern Bellingshausen Sea shelf (e.g. GC366, GC359, PS2533-2, PS2542-2, GC374) the clay mineral composition changed gradually. However, at some sites (e.g. GC357, GC360, GC371) a clay mineral assemblage different from the glacial or seasonally open-marine assemblage was deposited during the transition, which probably results from a time-transgressive deglaciation of the source areas for detritus supplied by the ocean currents.

We demonstrate the consequences of a possible time-transgressive deglaciation on cores GC360 and GC359 from Ronne Entrance, where the depositional conditions during deglaciation were apparently complex. As soon as the grounding line had retreated to the south of the deep inner shelf basin, which we consider as a possible source for smectite-enriched detritus, delivery of this detritus to site GC360 dropped sharply, and supply of chlorite- and illite-rich detritus derived from the Antarctic Peninsula hinterland increased (Fig. 15b). In contrast, the sediments deposited at site GC359 during the deglaciation show a decrease of clay mineral detritus sourced from the Antarctic Peninsula and an increase of smectite, which we attribute to the onset of delivery of smectite-enriched volcanic detritus from Alexander Island. This can be explained by grounding line retreat to the present-day northern coastline of Beethoven Peninsula.

4.3.2.2. Continental slope (Group D)

Similar to the glacial situation, the clay mineral assemblages in the deglaciation sediments of Group D represent a mixture between Group B and C (Fig. 7). On the western Belgica TMF the sandy mud unit marking the transition from GDF deposition to open-marine sedimentation exhibits an initial increase in smectite contents (up to 52% in core GC378) followed by a decrease to smectite concentrations more typical of the post-glacial sediments (Fig. 3i-k, Supplementary Figure). On the shelf, similarly high smectite concentrations were only observed in the glacial diamicton of core GC372 located in the second-order trough. Therefore, we speculate that at the end of the last glacial period, when the grounding line had already retreated from the shelf break, primarily detritus eroded from old smectite-rich sediments in the the second-order trough was delivered to the western Belgica TMF. There are two possible explanations for a more important role played by the second-order trough for deposition on the TMF during the last deglaciation. First, proglacial and/or subglacial meltwater outbursts may have occurred during the deglaciation. These meltwater outbursts may have carved the second-order trough into the outer shelf, thereby delivering vast amounts of eroded, old sediments to the Belgica TMF. Second, the grounding line may have remained longer at the shelf break in the second-order trough than in the main Belgica Trough. The latter scenario may imply that ice-sheet retreat in Antarctica at the last deglaciation was mainly initiated by a decrease in ice accumulation or increase in ice-sheet melting rather than sea-level rise. This finding were in conflict with several Antarctic ice-sheet models, which concluded that ice-sheet retreat at the last termination was triggered by global sea-level rise in response to melting of Northern Hemisphere ice sheets (e.g. Huybrechts, 2002), but would support a new WAIS model, which highlights the importance of oceanic sub-ice melting for WAIS retreat (Pollard & DeConto, 2009).

4.3.3. Assemblages in the post-glacial facies

The clay mineral assemblages of the post-glacial, seasonally open-marine sediments within Groups A, B, C and D vary less than in the sediments deposited during the last glacial period and deglaciation (Fig. 9). Moreover, the differences in clay mineral composition between the different groups are less pronounced (Fig. 9). These changes demonstrate stronger mixing of detritus, which is derived from the various source regions along the West Antarctic coast and transported to the core sites by tidal and wind driven currents and icebergs (Fig. 10).

Nevertheless, the post-glacial sediments of core GC372 and Group B, which comprises the cores on the shelf west of the Belgica Trough axis, are characterised by a clay mineral assemblage enriched in illite supplied from Eltanin Bay, whereas the sediments in most cores of Group C, which comprises the sites on the shelf east of the Belgica Trough axis, exhibit higher contents of smectite delivered from Ronne Entrance (Fig. 9). The smectite contents at both sites GC359 and GC360 are higher in the seasonally open-marine sediments than in the sediments deposited during the last deglaciation (Figs. 6, 8). This smectite increase points to a higher supply of detritus from Beethoven Peninsula and/or less dilution with glaciogenic debris from the Antarctic Peninsula mainland during the present interglacial period (Fig. 15c).

5. Conclusions

- The typical lithological succession of sediment cores collected from the shelf and slope in the southern Bellingshausen Sea comprises three units (from base to top): massive lithogenic diamictons and gravelly sandy muds, structureless to laminated/stratified glaciomarine gravel-bearing sandy muds/muddy sands, and bioturbated diatom-/foraminifera-bearing muds. These lithological units can be attributed to facies types deposited during the last glacial period, the last deglaciation and the present interglacial period. The clay mineral composition of the facies types reflects the different environmental settings.

- The thinness of the deglacial and seasonally open-marine sediments in combination with the relation between the clay mineral composition of the glacial diamictons on the shelf and the GDFs on the slope corroborate that a grounded ice stream advanced through Belgica Trough to the shelf break during the last glacial period. The Belgica Trough palaeo-ice stream transported detritus eroded in the West Antarctic hinterland through Eltanin Bay and Ronne Entrance across the shelf and deposited this material as a soft till at its base and as GDFs on the Belgica TMF.
- The clay mineral assemblages in the soft tills on the shelf form relatively short subglacial dispersal trains (less than 100 km). Clay mineralogical, acoustic sub-bottom and seismic data indicate that at some locations the palaeo-ice stream probably reworked old sedimentary strata and tills derived from these sediments while advancing across the shelf and mixed this debris into its deformable bed together with the debris from the West Antarctic hinterland. The recycling of older sediments would explain the relatively short ranges of the clay mineralogical dispersal trains and suggest that, at least at a local scale, the Belgica Trough palaeo-ice stream replenished its till bed by eroding underlying sedimentary strata.
- High smectite contents observed in the GDFs on the slope during the last

glacial period are likely to result from recycling of old shelf sediments and not from a higher supply of smectite enriched volcanogenic debris from Alexander Island as previously thought.

- Clay mineral assemblages together with acoustic sub-bottom and seismic profiles from the shelf suggest that the recovered soft glacial diamictons and gravelly deposits were eroded from older sedimentary strata deposited during different glacial and interglacial periods or during different phases of the last glacial period. This finding demonstrates that till layers on the Antarctic shelf should not be assigned to the last glacial maximum, if no independent age control is available. However, if it can be shown that subglacial bedforms associated with a glacial unconformity formed during the last glacial cycle, this result does not affect reconstructions of ice-sheet extent during the last glacial period.
- The clay mineral assemblages in the recovered soft tills on the outer shelf are assumed to reflect those in underlying till bodies. The clay mineralogical heterogeneity of the tills suggests that the ice stream drained different source areas in the West Antarctic hinterland and on the southern Bellingshausen Sea shelf during different glacial periods/different phases of the last glacial period.

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7. References

Anderson, J.B., 1999. Antarctic Marine Geology. Cambridge University Press, Cambridge, UK. 289 pp.

Biscaye, P.E., 1964. Distinction between kaolinite and chlorite in recent sediments by X-ray diffraction. American Mineralogist 49, 1281-1289.

Biscaye, P.E., 1965. Mineralogy and sedimentation of recent deep-sea clays in the Atlantic Ocean and adjacent seas and oceans. Geological Society of America Bulletin 76, 803-832.

Brindley, G.W., Brown, G. (Eds.), 1980. Crystal Structures of Clay Minerals and their X-ray Identification. Mineralogical Society of London Monogrographs 5, London, 495 pp.

Clark, P.U., 1987. Subglacial sediment dispersal and till composition. Journal of Geology 95, 527-541.

Diekmann, B., Kuhn, G., 1997. Terrigene Partikeltransporte als Abbild spätquartärer Tiefen- und Bodenwasserzirkulation im Südatlantik und angrenzendem Südpolarmeer. Zeitschrift der Deutschen Geologischen Gesellschaft 148, 405-429.

Domack, E.W., Jacobson, E.A., Shipp, S.S., Anderson, J.B., 1999. Late Pleistocene–Holocene retreat of the West Antarctic Ice-Sheet system in the

Ross Sea: Part 2. Sedimentologic and stratigraphic signature. Geological Society of America Bulletin 111, 1517-1536.

Dowdeswell, J.A., Ó Cofaigh, C., Pudsey, C.J., 2004a. Continental slope morphology and sedimentary processes at the mouth of an Antarctic palaeo-ice stream. Marine Geology 204, 203-214.

Dowdeswell, J.A., Ó Cofaigh, C., Pudsey, C.J., 2004b. Thickness and extent of the subglacial till layer beneath an Antarctic paleo-ice stream. Geology 32, 13-16.

Dowdeswell, J.A., Evans, J., Ó Cofaigh, C., Anderson, J.B., 2006a. Morphology and sedimentary processes on the continental slope off Pine Island Bay, Amundsen Sea, West Antarctica. Geological Society of America Bulletin 118, 606-619.

Dowdeswell, J.A., Ottesen, D., Rise, L., 2006b. Flow-switching and large-scale deposition by ice streams draining former ice sheets. Geology 34, 313-316.

Dowdeswell, J.A., Ottesen, D., Rise, L., Craig, J., 2007. Identification and preservation of landforms diagnostic of past ice-sheet activity on continental shelves from three-dimensional seismic evidence. Geology 35, 359-362.

Dowdeswell, J.A., Ó Cofaigh, C., Noormets, R., Larter, R.D., Hillenbrand, C.-D., Benetti, S., Evans, J., Pudsey, C.J., 2008. A major trough-mouth fan on the continental margin of the Bellingshausen Sea, West Antarctica: The Belgica Fan. Marine Geology 252, 129-140.

Dyke, A.S., Prest, V.K., 1987. Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. Géographie Physique et Quaternaire 41, 237-263.

Dyke, A.S., Morris, T.F., 1988. Canadian landform examples: drumlin fields, dispersal trains, and ice streams in Arctic Canada. The Canadian Geographer 32, 86-90.

Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., Veillette, J.J., 2002. The Laurentide and Innuitian ice sheets during the Last Glacial Maximum. Quaternary Science Reviews 21, 9-31.

Ehrmann, W., Melles, M., Kuhn, G., Grobe, H., 1992. Significance of clay mineral assemblages in the Antarctic Ocean. Marine Geology 107, 249-273.

Evans, J., Pudsey, C.J., 2002. Sedimentation associated with Antarctic Peninsula ice shelves: implications for paleoenvironmental reconstructions of glacimarine sediments. Journal of the Geological Society 159, 233-237.

Evans, J., Pudsey, C.J., Ó Cofaigh, C., Morris, P.W., Domack, E.W., 2005. Late Quaternary glacial history, dynamics and sedimentation of the eastern margin of the Antarctic Peninsula Ice Sheet. Quaternary Science Reviews 24, 741–774.

Evans, J., Dowdeswell, J.A., Ó Cofaigh, C., Benham, T.J., Anderson, J.B., 2006. Extent and dynamics of the West Antarctic Ice Sheet on the outer continental shelf of Pine Island Bay during the last glaciation. Marine Geology 230, 53-72.

Heroy, D.C., Anderson, J.B., 2005. Ice-sheet extent of the Antarctica Peninsula region during the Last Glacial Maximum (LGM) - Insights from glacial geomorphology. Geological Society of America Bulletin 117, 1497-1512.

Hillenbrand, C.-D., Ehrmann, W., 2002. Distribution of clay minerals in drift sediments on the continental rise west of the Antarctic Peninsula, ODP Leg

178, Sites 1095 and 1096. In: Barker, P.F., Camerlenghi, A., Acton, G.D., Ramsay, A.T.S. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 178. Ocean Drilling Program, Texas A&M University, College Station, pp. 1-29. CD-ROM.

Hillenbrand, C.-D., Ehrmann, W., 2003. Palaeoenvironmental implications from Tertiary sediments of Kainan Maru Seamount and northern Gunnerus Ridge. Antarctic Science 15, 522-536.

Hillenbrand, C.-D., Grobe, H., Diekmann, B., Kuhn, G., Fütterer, D., 2003. Distribution of clay minerals and proxies for productivity in surface sediments of the Bellingshausen and Amundsen seas (West Antarctica) - Relation to modern environmental conditions. Marine Geology 193, 253-271.

Hillenbrand, C.-D., Baesler, A., Grobe, H., 2005. The sedimentary record of the last glaciation in the western Bellingshausen Sea (West Antarctica): implications for the interpretation of diamictons in a polar-marine setting. Marine Geology 216, 191-204.

Hillenbrand, C.-D., Moreton, S.G., Caburlotto, A., Pudsey, C.J., Lucchi, R.G., Smellie, J.L., Benetti, S., Grobe, H., Hunt, J.B., Larter, R.D., 2008. Volcanic time-markers for marine isotopic stages 6 and 5 in Southern Ocean sediments and Antarctic ice cores: implications for tephra correlations between palaeoclimatic records. Quaternary Science Reviews 27, 518-540, doi:10.1016/j.quascirev.2007.11.009

Hole, M.J., Smellie, J.L., Mariner, G.F., 1991. Geochemistry and tectonic setting of alkali-basalts from Alexander Island. In: Thomson, M.R.A., Crame, J.A., Thomson, J.W. (Eds.), Geological evolution of Antarctica, Cambridge University Press, Cambridge, pp. 521-526.

Huybrechts, P., 2002. Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles. Quaternary Science Reviews 22, 203-231.

Klassen, R.A., 2001. A Quaternary geological perspective on geochemical exploration in glaciated terrain. In: McClenaghan, M.B., Bobrowsky, P.T., Hall, G.E.M., Cook, S.J. (Eds.), Drift Exploration in glaciated Terrain, Geological Society, London, Special Publications 185, 1-17, The Geological Society of London.

Kurtz, D.D., Anderson, J.B., 1979. Recognition and sedimentologic description of recent debris flow deposits from the Ross and Weddell seas, Antarctica. Journal of Sedimentary Petrology 49, 1159-1170.

Licht, K.J., Jennings, A.E., Andrews, J.T., Williams, K.M., 1996. Chronology of late Wisconsin ice retreat from the western Ross Sea, Antarctica. Geology 24, 223-226.

Licht, K.J., Dunbar, N.W., Andrews, J.T., Jennings, A.E., 1999. Distinguishing subglacial till and glacial marine diamictons in the western Ross Sea, Antarctica: implications for a Last Glacial Maximum grounding line. Geological Society of America Bulletin 111, 91-103.

Lowe, A.L., Anderson, J.B., 2002. Late Quaternary retreat of the West Antarctic Ice Sheet in Pine Island Bay, Antarctica. Quaternary Science Reviews 21, 1879-1897.

Miller, H., Grobe, H. (Eds.), 1996. Die Expedition Antarktis-XI/3 mit FS "Polarstern" 1994. Reports on Polar Research 188, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, 115 pp.

Noormets, R., Dowdeswell, J.A., Larter, R.D., Ó Cofaigh, C., Evans, J., 2009. Morphology of the upper continental slope in the Bellingshausen and Amundsen Seas – Implications for sedimentary processes at the shelf edge of West Antarctica. Marine Geology 258, 100-114.

Ó Cofaigh, C., Larter, R.D., Dowdeswell, J.A., Hillenbrand, C.-D., Pudsey, C.J., Evans, J., Morris, P., 2005a. Flow of the West Antarctic Ice Sheet on the continental margin of the Bellingshausen Sea at the Last Glacial Maximum. Journal of Geophysical Research 110, B11103, doi:10.1029/2005JB003619.

Ó Cofaigh, C., Dowdeswell, J.A., Allen, C.S., Hiemstra, J., Pudsey, C.J., Evans, J., Evans, D.J.A., 2005b. Flow dynamics and till genesis associated with a marine-based Antarctic palaeo-ice stream. Quaternary Science Reviews 24, 709-740.

Ó Cofaigh, C., Evans, J., Dowdeswell, J.A., Larter, R.D., 2007. Till characteristics, genesis and transport beneath Antarctic paleo-ice streams. Journal of Geophysical Research 112, F03006, doi:10.1029/2006JF000606.

Petschick, R., Kuhn, G., Gingele, F.X., 1996. Clay mineral distribution in surface sediments of the South Atlantic: sources, transport, and relation to oceanography. Marine Geology 130, 203-229.

Pollard, D., DeConto, R.M., 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. Nature 458, 329-333.

Robert, C., Maillot, H., 1990. Palaeoenvironments in the Weddell Sea area and Antarctic climates, as deduced from clay mineral associations and geochemical data, ODP Leg 113. In: Barker, P.F., Kennett, J.P., et al. (Eds.) Proceedings of the Ocean Drilling Program, Scientific Results 113, College Station, Texas, U.S.A., pp. 51–66.

Smellie, J.L., 1999. Lithostratigraphy of Miocene-Recent, alkaline volcanic fields in the Antarctic Peninsula and eastern Ellsworth Land. Antarctic Science 11, 362-378.

Vennum, W.R., Nejedly, J.W., 1990. Clay mineralogy of soils developed on weathered igneous rocks, West Antarctica. New Zealand Journal of Geology and Geophysics 33, 579-584.

Wellner, J.S., Lowe, A.L., Shipp, S.S., Anderson, J.B., 2001. Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate: implications for ice behavior. Journal of Glaciology 47, 397-411.

Wright, R., Anderson, J.B., 1982. The importance of sediment gravity flow to sediment transport and sorting in a glacial marine environment: eastern Weddell Sea. Geological Society of America Bulletin 93, 951-963.

8. Figure captions

Figure 1: Map of the southern Bellingshausen Sea with locations of sediment cores and surface sediment samples (note: only identifications of gravity core sites are given, for a summary of all locations see Supplementary Table). Grounded ice-flow directions according to Ó Cofaigh et al. (2005a).

Figure 2: Clay mineral composition of seabed surface sediments in the study area (for sample locations see Supplementary Table).

Figure 3: Lithology, shear strength, clay mineral content and facies types of cores GC366 (Fig. 3a), GC360 (Fig. 3b), GC359 (Fig. 3c), GC357 (Fig. 3d), PS2533-2 (Fig. 3e), GC371 (Fig. 3f), PS2542-2 (Fig. 3g), GC374 (Fig. 3h), PS2538-2 (Fig. 3i), GC380 (Fig. 3j) and GC381 (Fig. 3k) (see also Supplementary Figure).

Figure 4: Average clay mineral composition of sediments in the lower lithological unit of the studied cores.

Figure 5: Ternary diagrams showing the average clay mineral composition of sediments in the lower lithological unit of the studied cores. End members are the average clay mineral composition of surface sediment samples from Ronne Entrance and Eltanin Bay (Fig. 2). Group A comprises site GC359, where grounded ice did not flow into Belgica Trough (cf. Fig. 1), Group B comprises core sites on the shelf west of the Belgica Trough main axis, Group C comprises sites on the shelf east of the trough axis, and Group D comprises sites from the continental slope.

Figure 6: Average clay mineral composition of sediments in the middle lithological unit of the studied cores.

Figure 7: Ternary diagrams showing the average clay mineral composition of the sediments in the middle lithological unit of the studied cores. End members and groups as in Figure 5.

Figure 8: Average clay mineral composition of sediments in the upper lithological unit of the studied cores.

Figure 9: Ternary diagrams showing the average clay mineral composition of the sediments in the upper lithological unit of the studied cores. End members and groups as in Figure 5.

Figure 10: Conceptual model for the deposition of the facies types and their associated clay mineral assemblages on the southern Bellingshausen Sea shelf since the last glacial maximum (facies model modified from Domack et al., 1999). This model applies only to core sites from Group B, which were affected by ice draining through Eltanin Bay. In a model for core sites from Group C, which were affected by ice draining through Ronne Entrance, smectite- and illite-rich clay would have to be exchanged.

Figure 11: Conceptual model for the subglacial erosion of old, smectite-bearing sediments on the southern Bellingshausen Sea shelf and the deposition of subglacial sediments during the last glacial period. This model explains, for example, the differences in clay mineral composition of the glacial diamictons recovered at sites PS2533-2 and GC372 (see Fig. 12).

Figure 12: Ternary diagram showing the clay mineral composition of all samples taken from the glacial diamictons in cores PS2533-2 and GC374 collected

from the middle and outer shelf in Belgica Trough and cores GC372 and PS2542-2 recovered from the second-order trough that is incised into Belgica Trough on the outer shelf (site numbers in the key in the upper right are orientated according to their approximate relative location, see Fig. 1). End members and groups as in Figure 5.

Figure 13: Single-channel seismic profile[1] crossing the western flank of Belgica Trough on the outer shelf, including the small second-order trough incised into the main trough (for location of profile see Fig. 1). Downlap and onlap relationships between near-seabed sedimentary units indicate their diachronous deposition. Bubble pulse reflections are also indicated.

[Footnote 1: The seismic source was a single 4.9 litre airgun towed at a water depth of 4m. The interaction of the initial pulse from the airgun with the "ghost" reflection from the sea surface gives a characteristic peak-trough-peak signature, which is reflected from the seafloor and masks other reflections for ca. 35 ms. The data is also affected by bubble pulse reverberations with a period of ca. 135 ms, which have been partially suppressed by predictive convolution.]

Figure 14: TOPAS acoustic sub-bottom profile[2] from near site GC357 (for location of profile see Fig. 1). A flat sub-bottom reflector (white arrows) that probably corresponds to a glacial unconformity truncates seaward dipping sub-seafloor reflectors and crops out locally at the modern seafloor. The dipping reflectors are interpreted as eroded, old sedimentary strata.

[Footnote 2: Vertical noise stripes on the profile are reverberations caused by contact between the ship's hull and sea ice.]

Figure 15: Inferred ice-flow directions (arrows) and clay mineralogical provenance of subglacial debris supplied to sites GC359 and GC360 during the last glacial period (Fig. 15a), the deglaciation (Fig. 15b) and the present interglacial period (Fig. 15c). The grey shaded area indicates the spatial distribution of grounded ice (schematically), the bold broken line marks the position of the grounding line (schematically). The hatched area on Beethoven Peninsula highlights the occurrence of Cenozoic volcanic rocks as a smectite source. The hatched area in Ronne Entrance indicates the inferred position of smectite-rich sedimentary strata in a deep shelf basin.

9. Supplementary table and figures

Supplementary Table: Locations of the studied gravity cores (GC) and undisturbed surface sediment samples that were collected with a box corer (BC), giant box corer (GBC) and multiple corer (MC), respectively.

Supplementary Figure: Lithology, shear strength, clay mineral content and facies types of the studied sediment cores that have not been presented in Fig. 3.

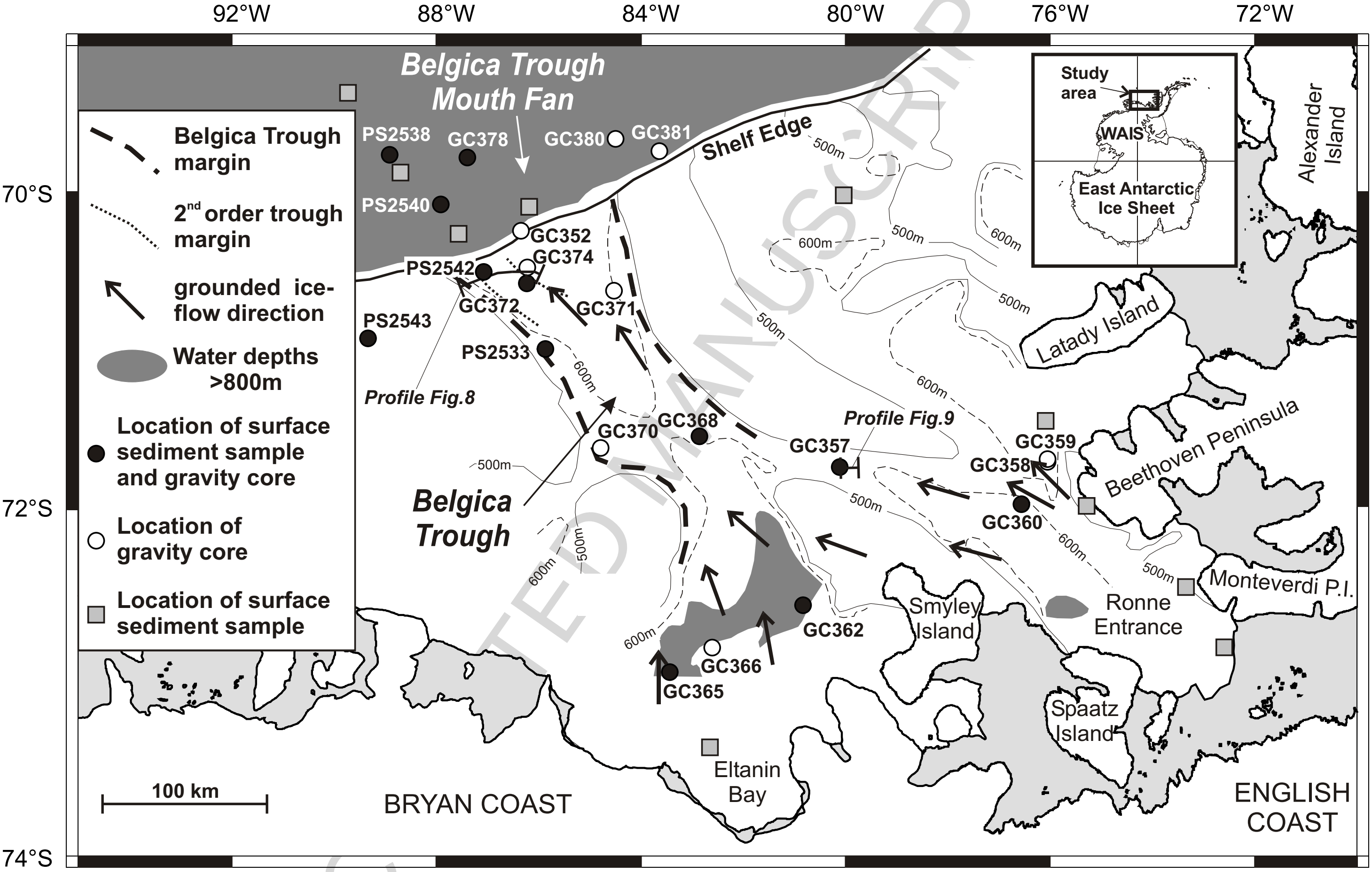


Fig.1 Hillenbrand et al.

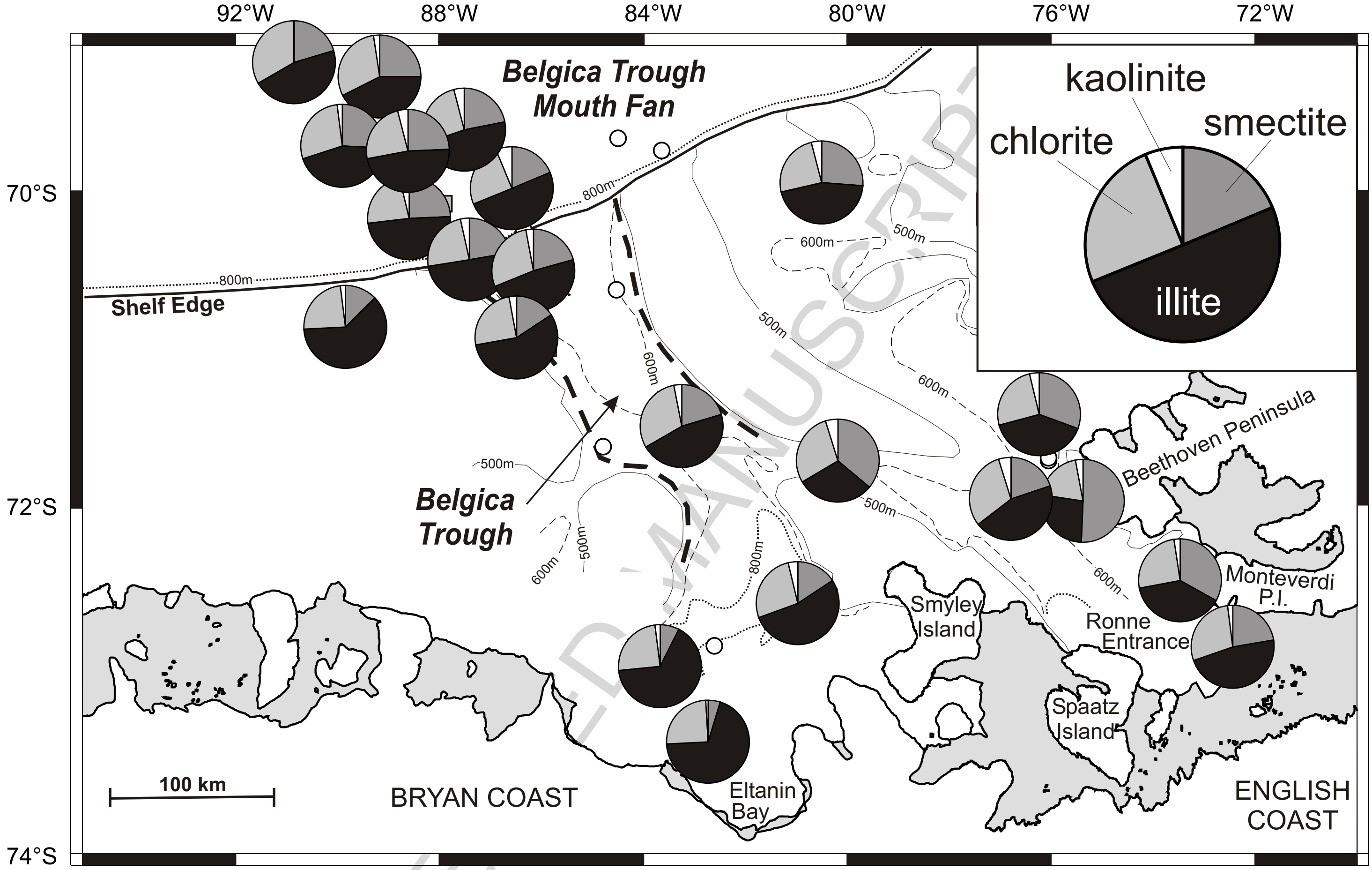


Fig.2 Hillenbrand et al.

Fig.3a

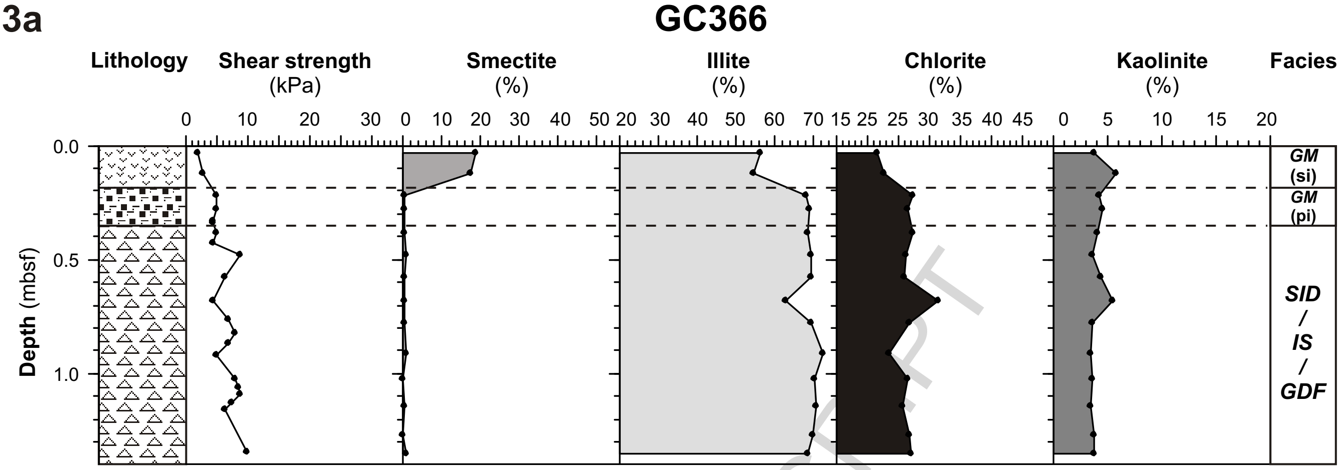


Fig.3b

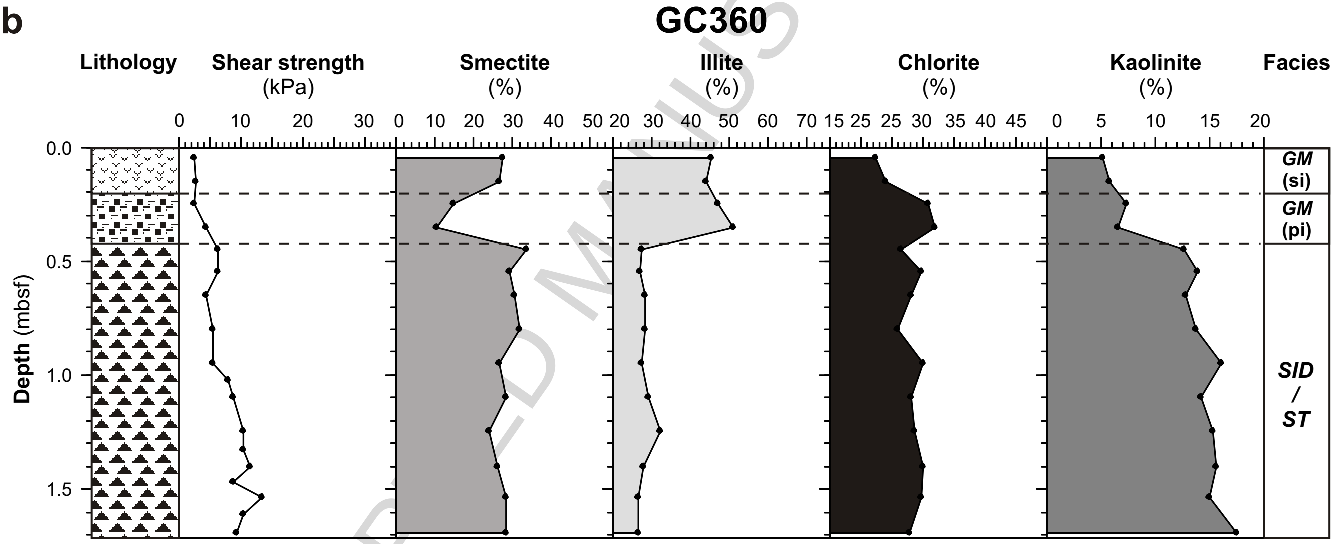


Fig.3c

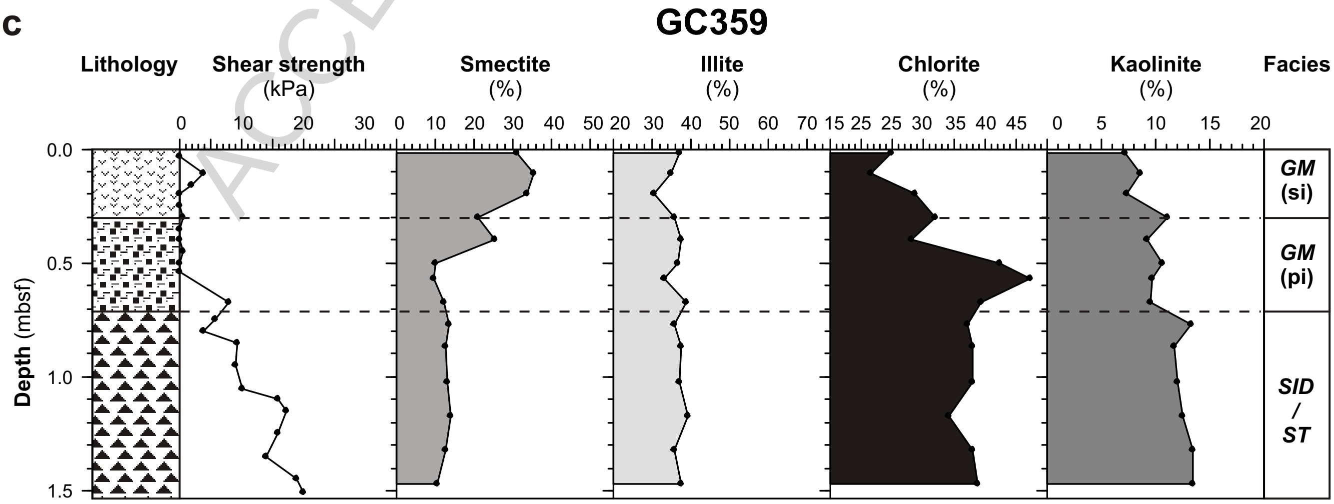


Fig.3d

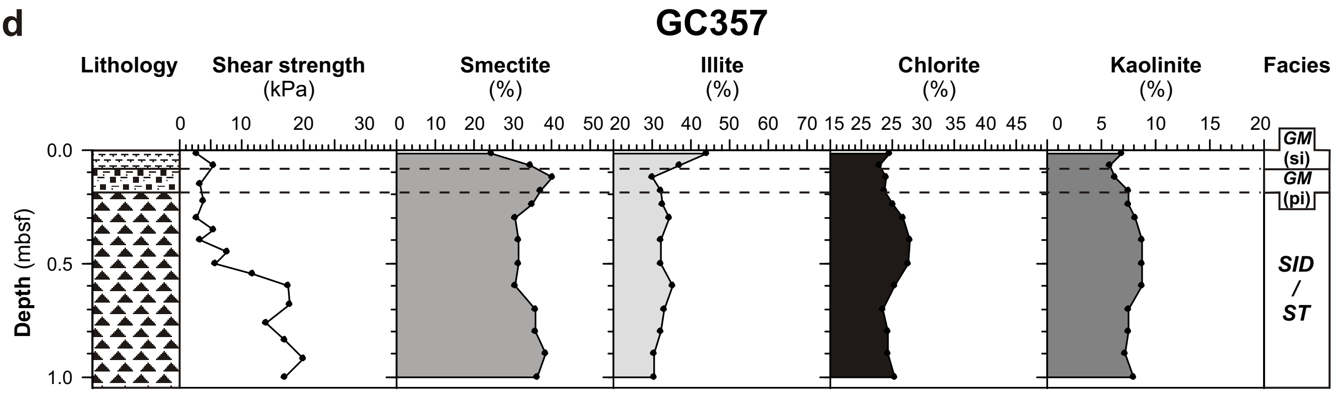


Fig.3e

PS2533-2

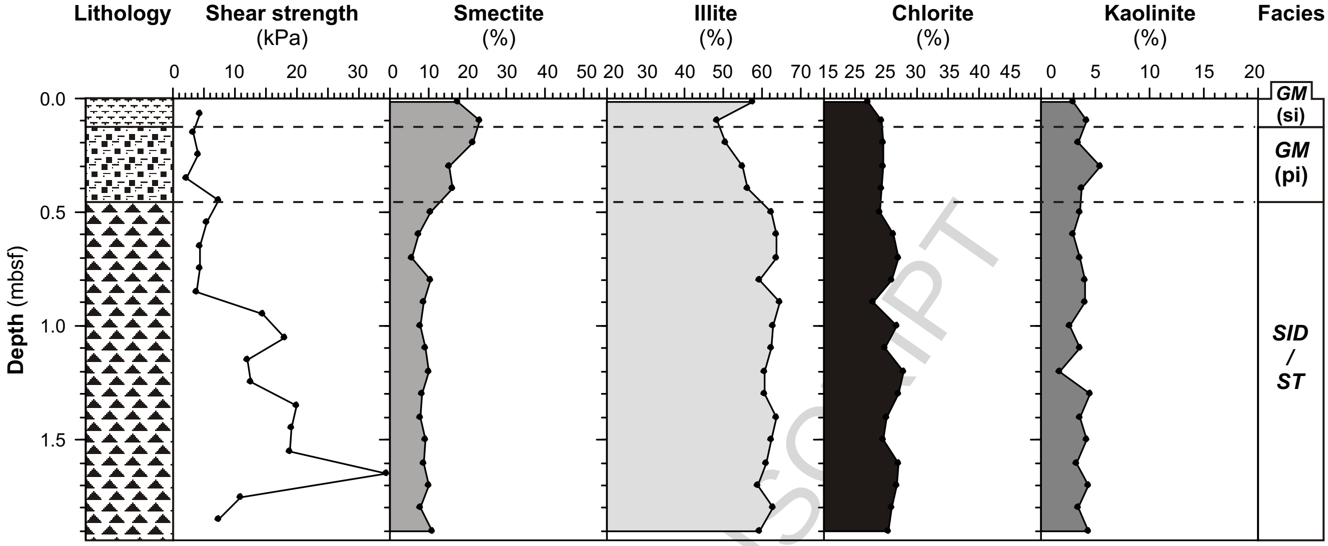


Fig.3f

GC371

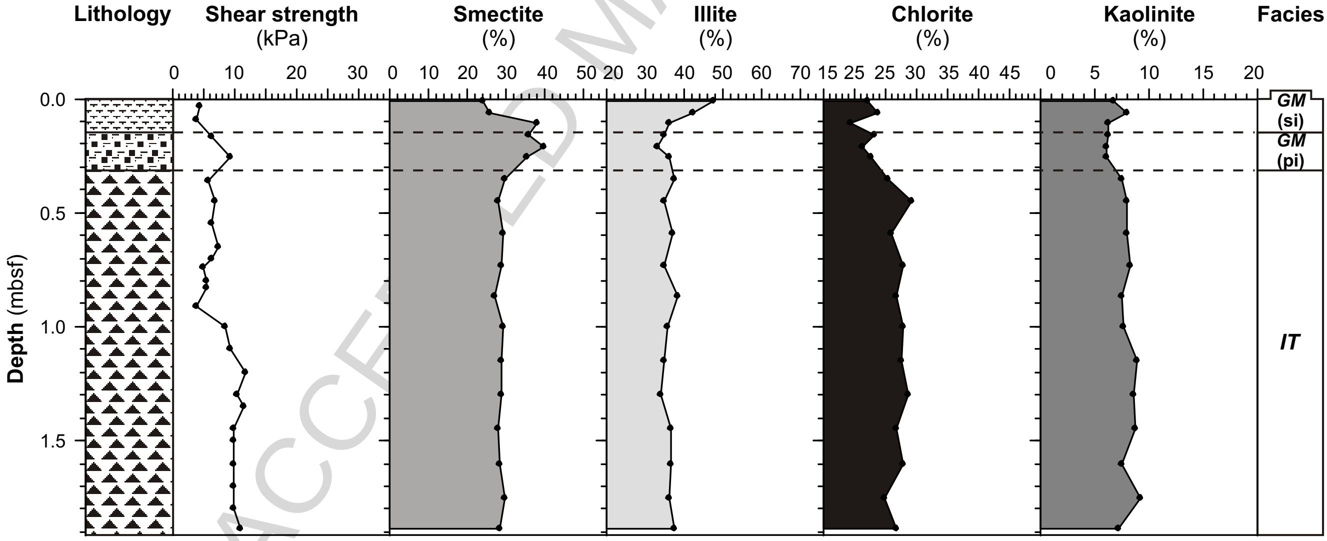


Fig.3g

PS2542-2

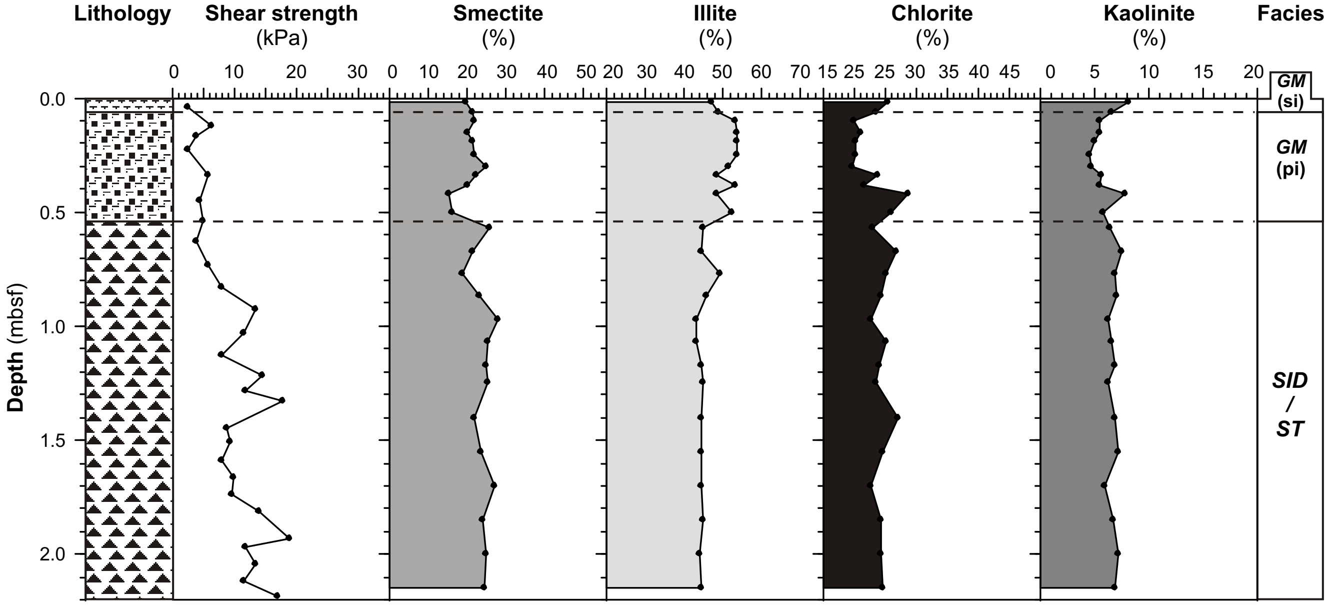


Fig.3h

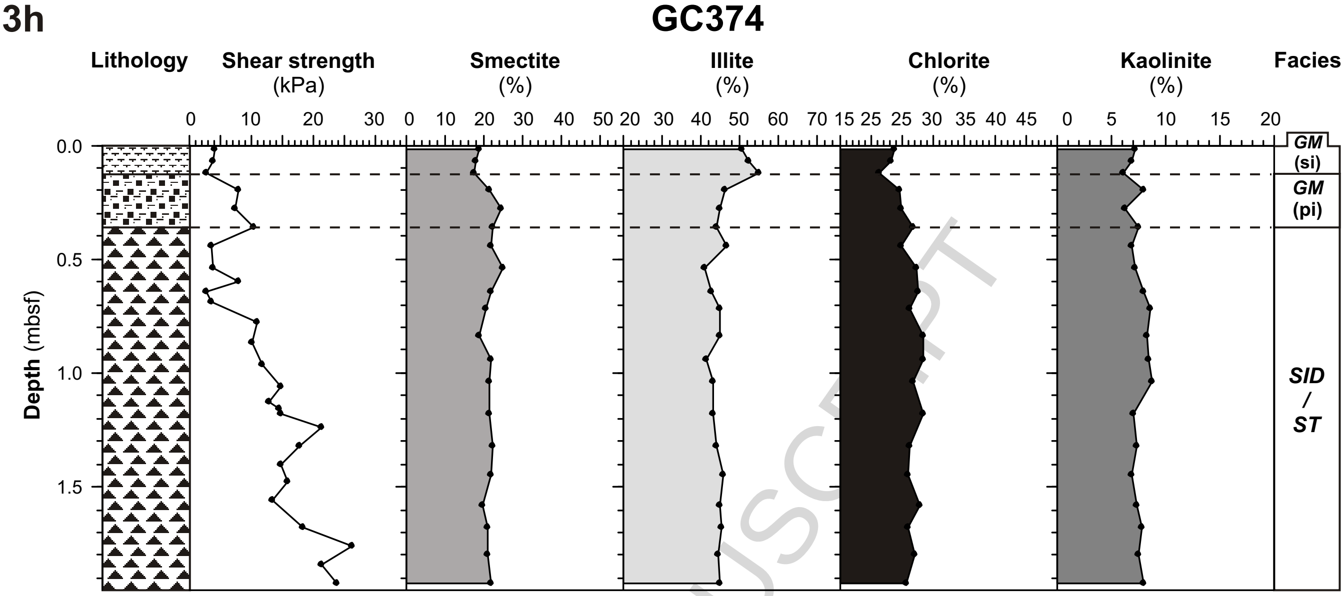

GC374
Lithology
Shear strength (kPa)
Smectite (%)
Illite (%)
Chlorite (%)
Kaolinite (%)
Facies
Depth (mbsf)
GM (si)
GM (pi)
SID / ST

Fig.3i

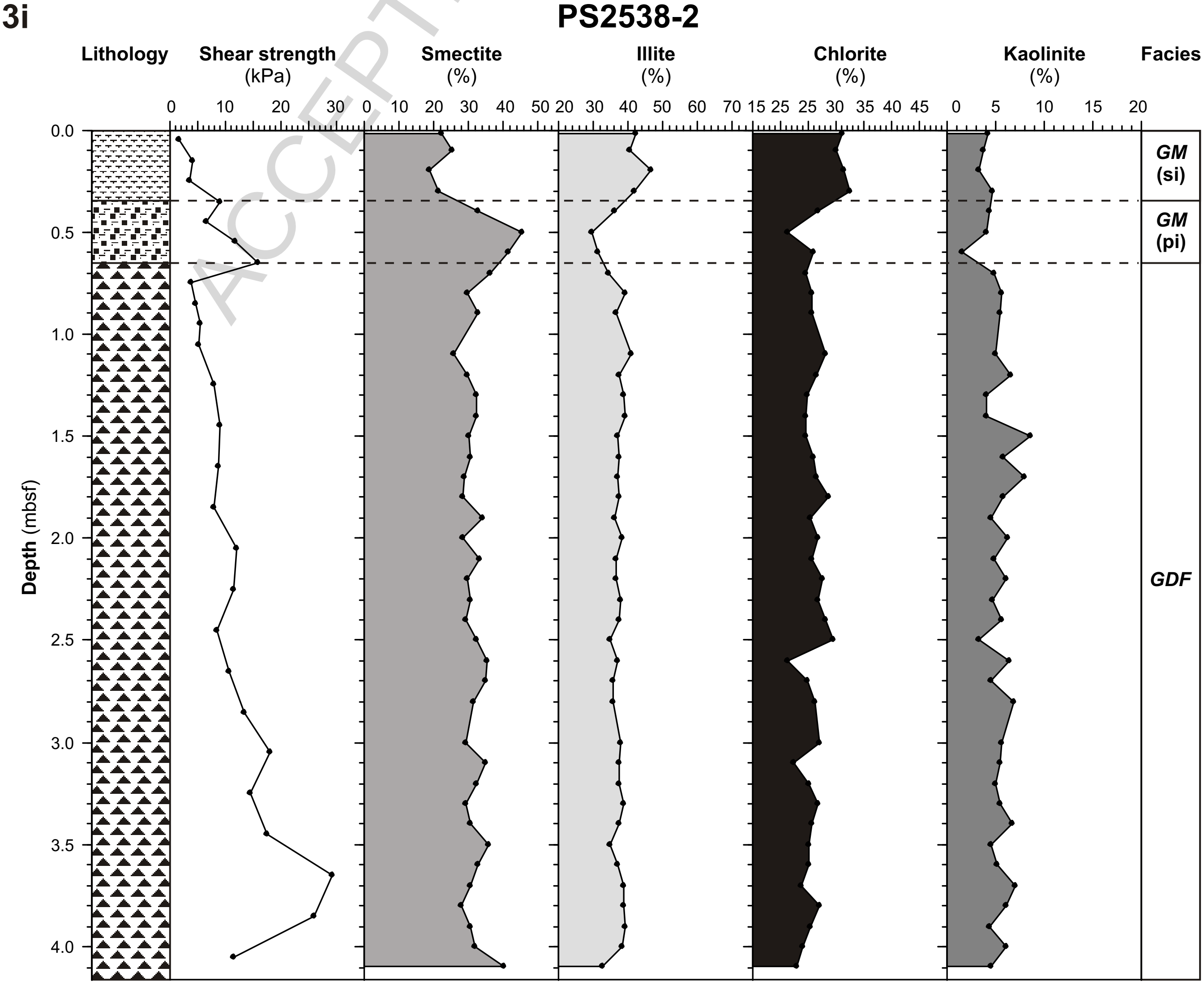

PS2538-2
Lithology
Shear strength (kPa)
Smectite (%)
Illite (%)
Chlorite (%)
Kaolinite (%)
Facies
Depth (mbsf)
GM (si)
GM (pi)
GDF

Fig.3j

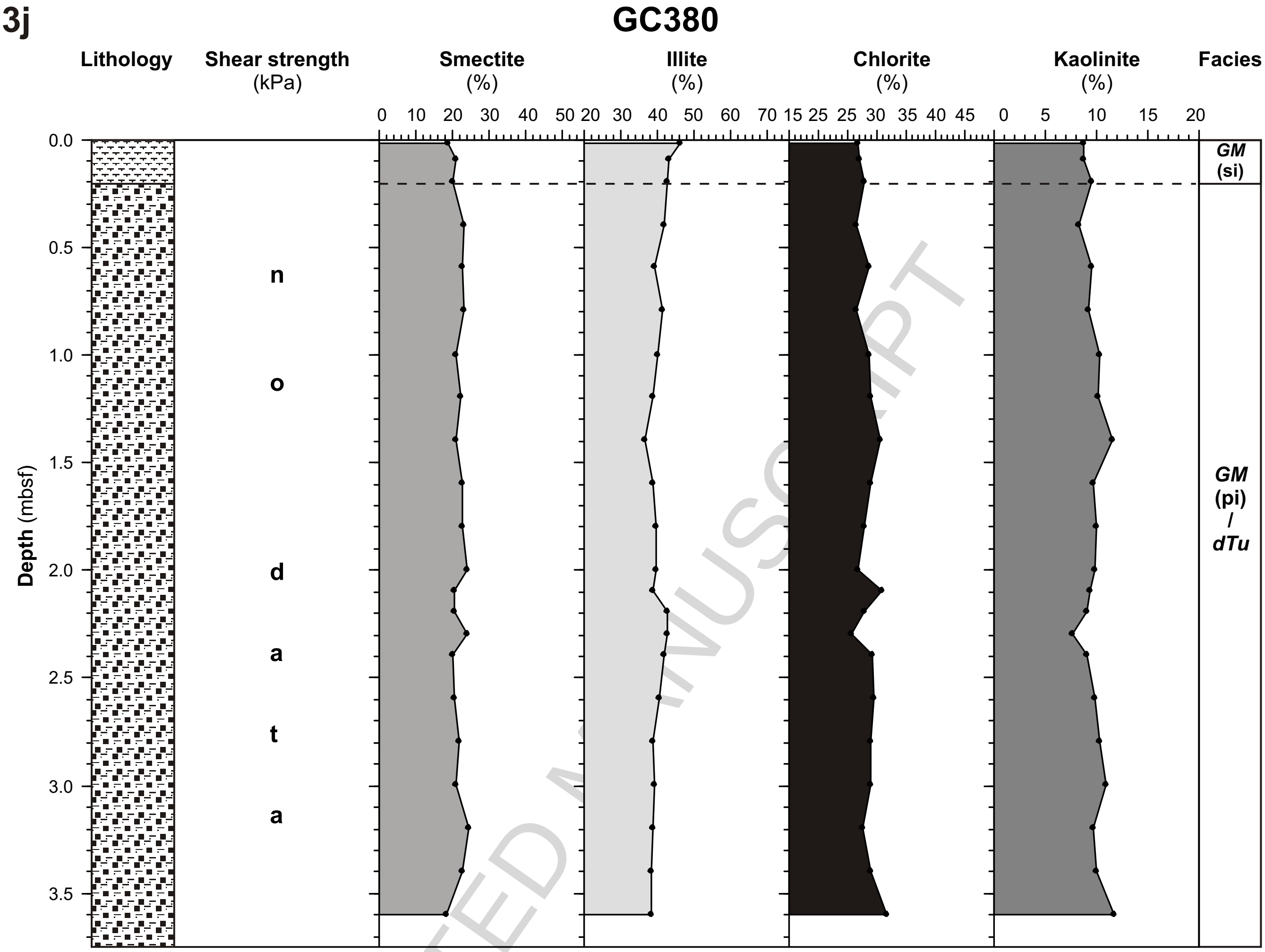
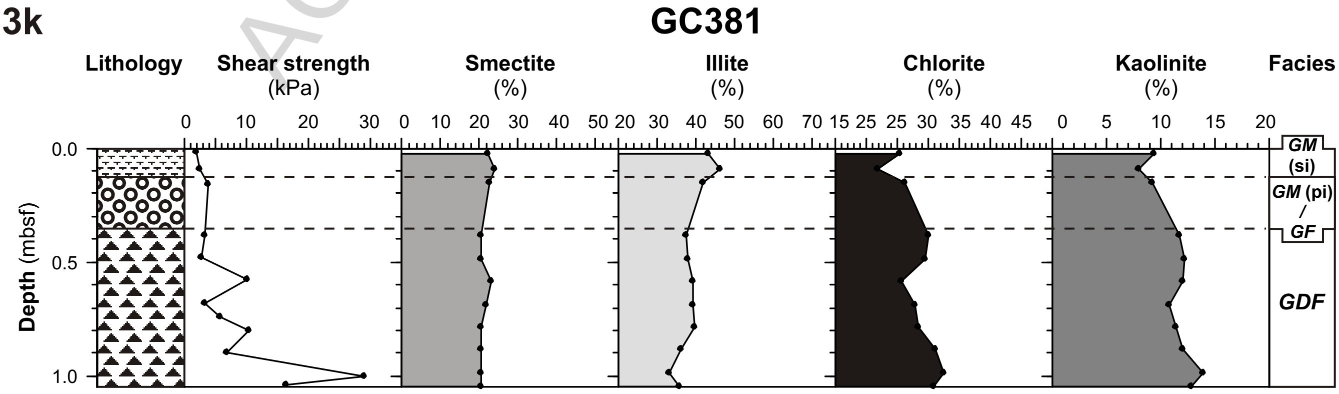


Fig.3k



Key: diatom-bearing to diatomaceous mud; foraminifera-bearing to foraminiferal mud; sandy mud to muddy sand; sandy gravel; gravelly sandy mud; muddy diamicton

GM: glaciomarine sediment
si: seasonal sea-ice cover
pi: permanent sea-ice cover/ distal ice-shelf cover

IS: iceberg-rafted sediment
IT: iceberg turbate
SID: proximal sub-ice shelf diamicton

ST: soft till
GDF: glaciogenic debris flow
GF: grain-flow deposit
dTu: distal turbidite

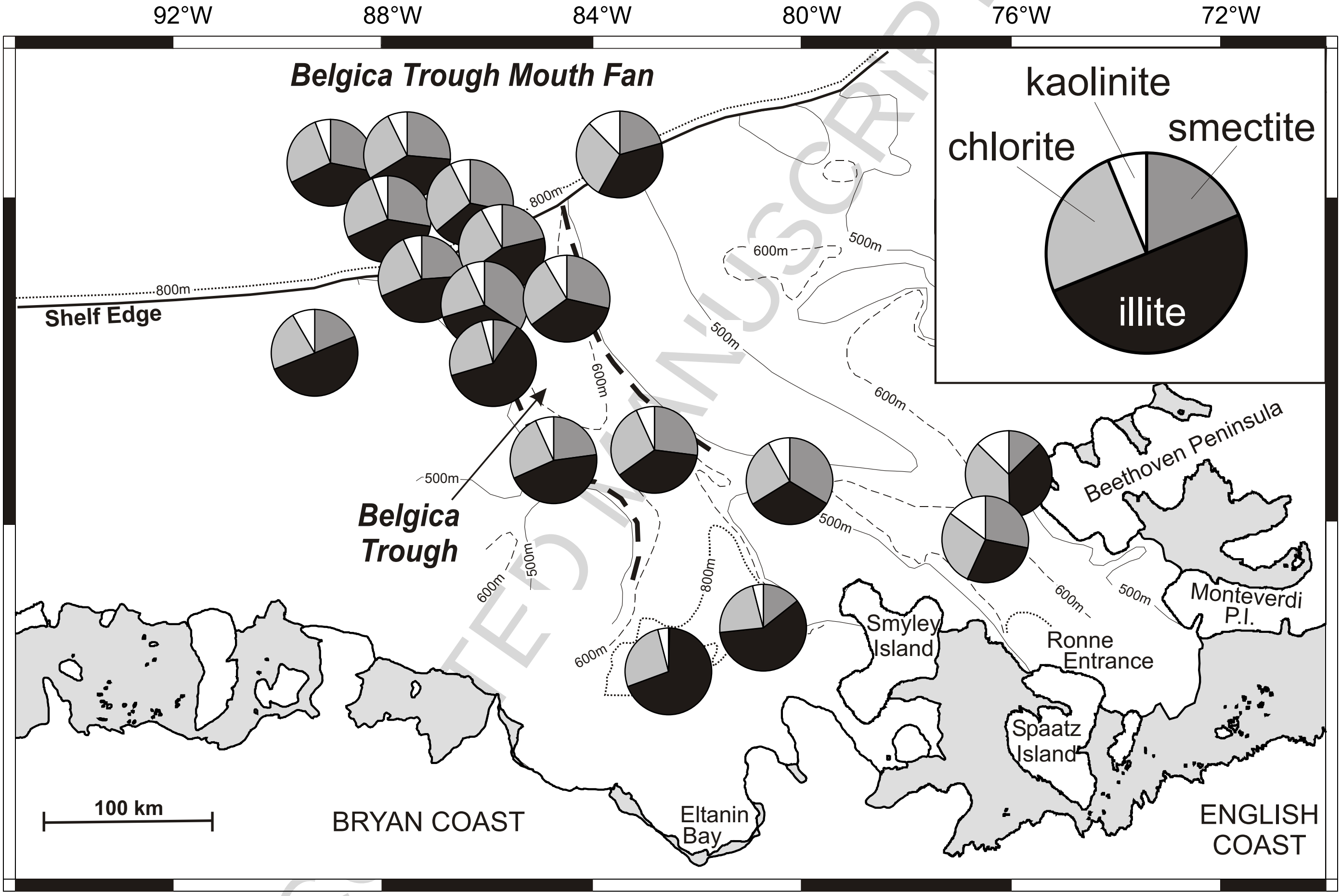


Fig.4 Hillenbrand et al.

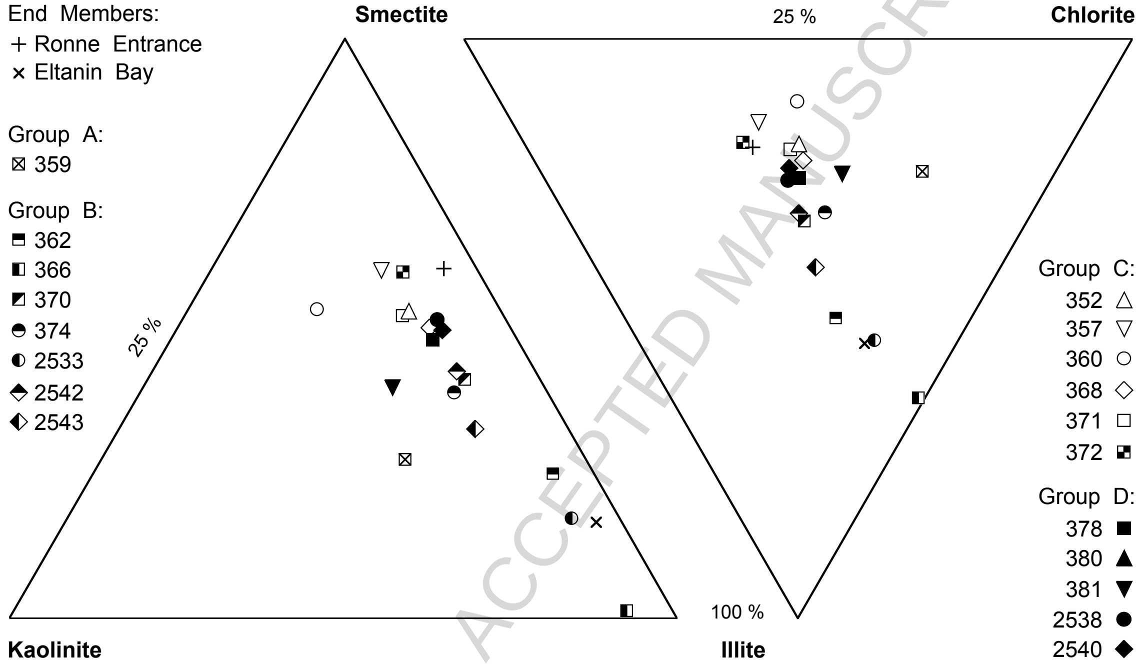


Fig. 5 Hillenbrand et al.

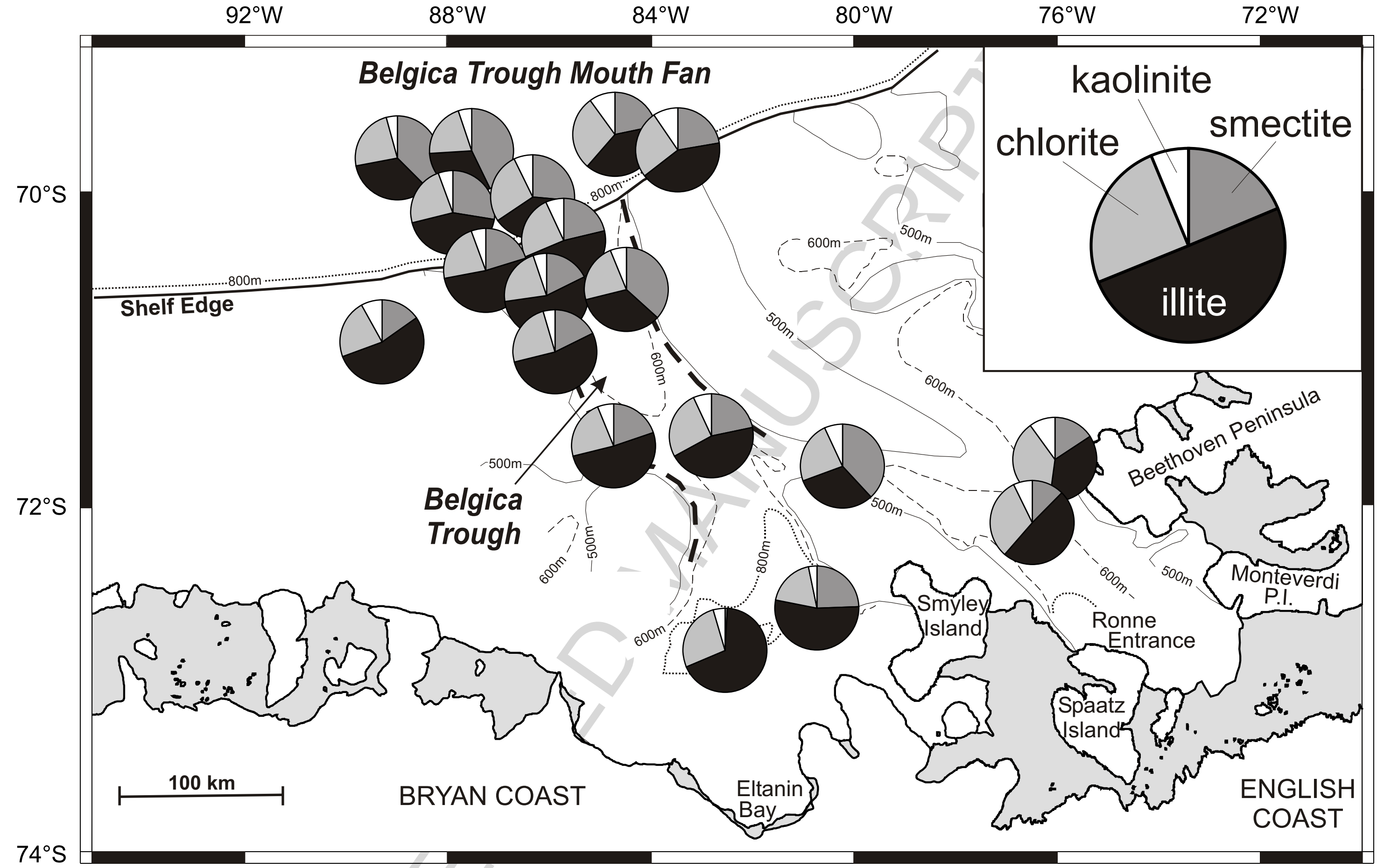


Fig.6 Hillenbrand et al.

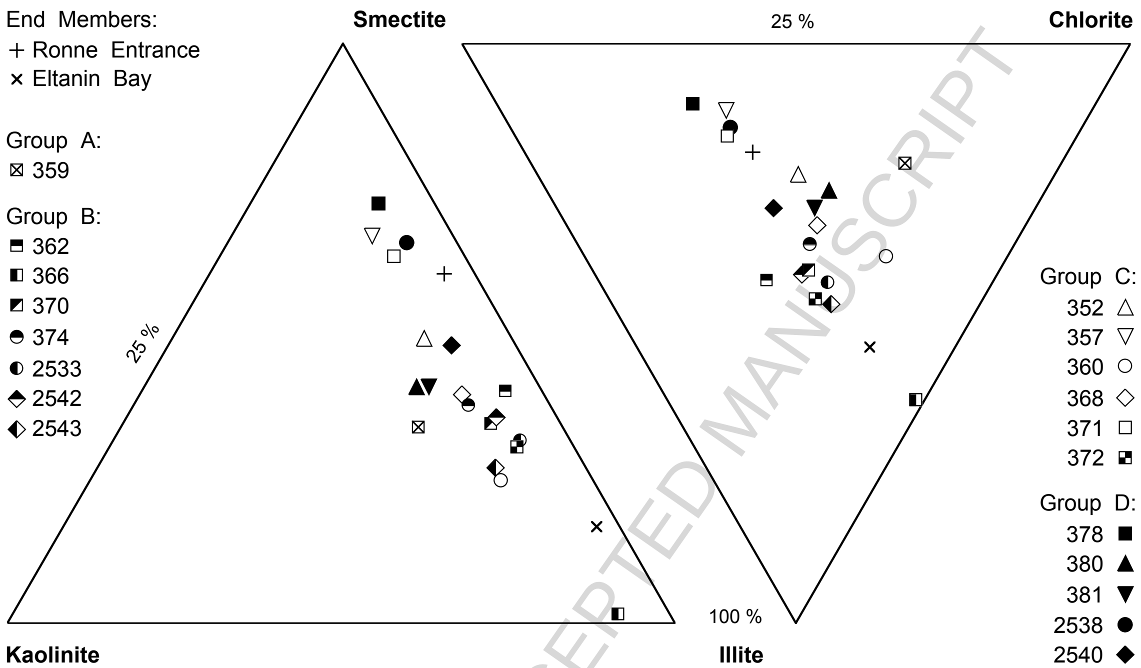


Fig. 7 Hillenbrand et al.

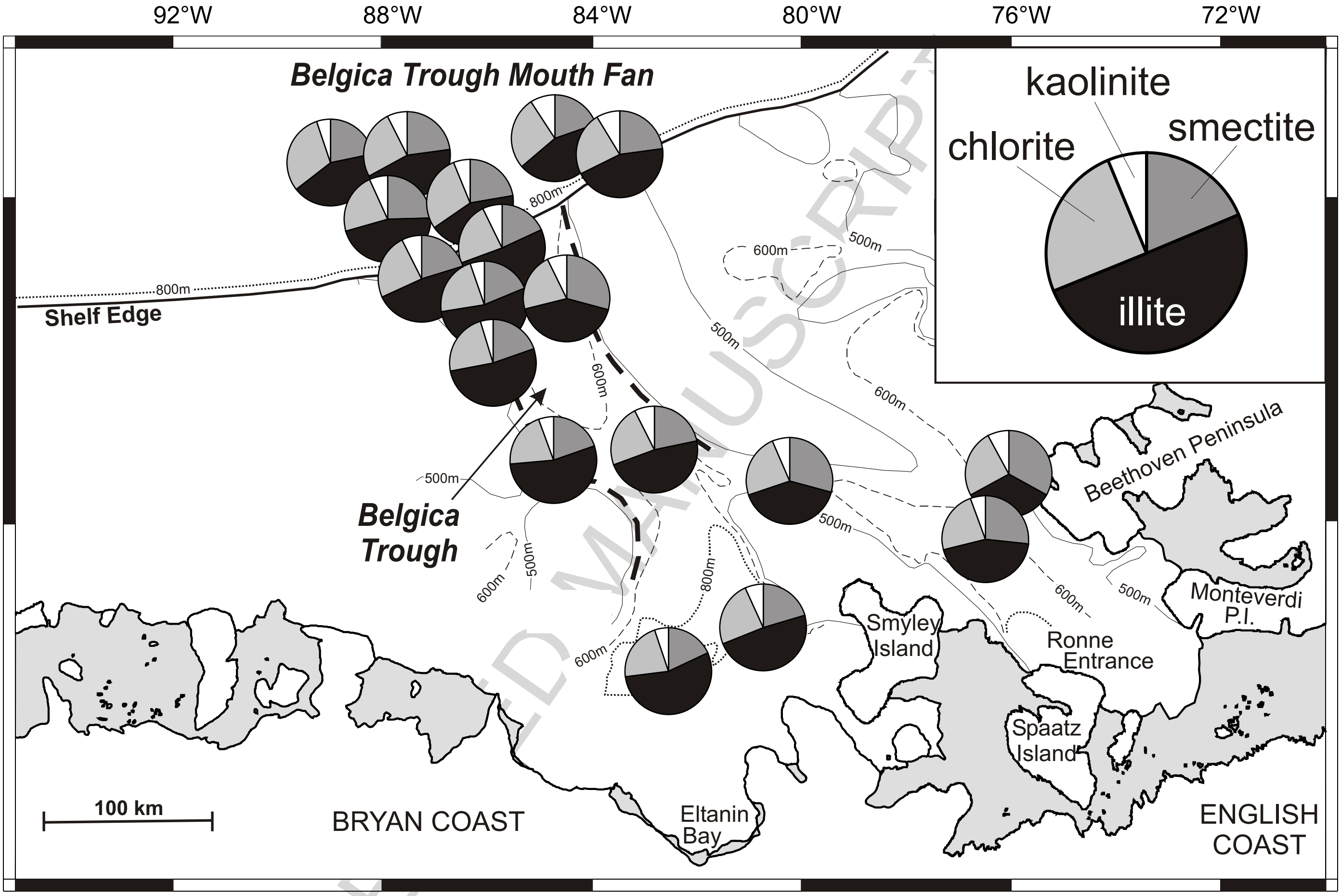


Fig.8 Hillenbrand et al.

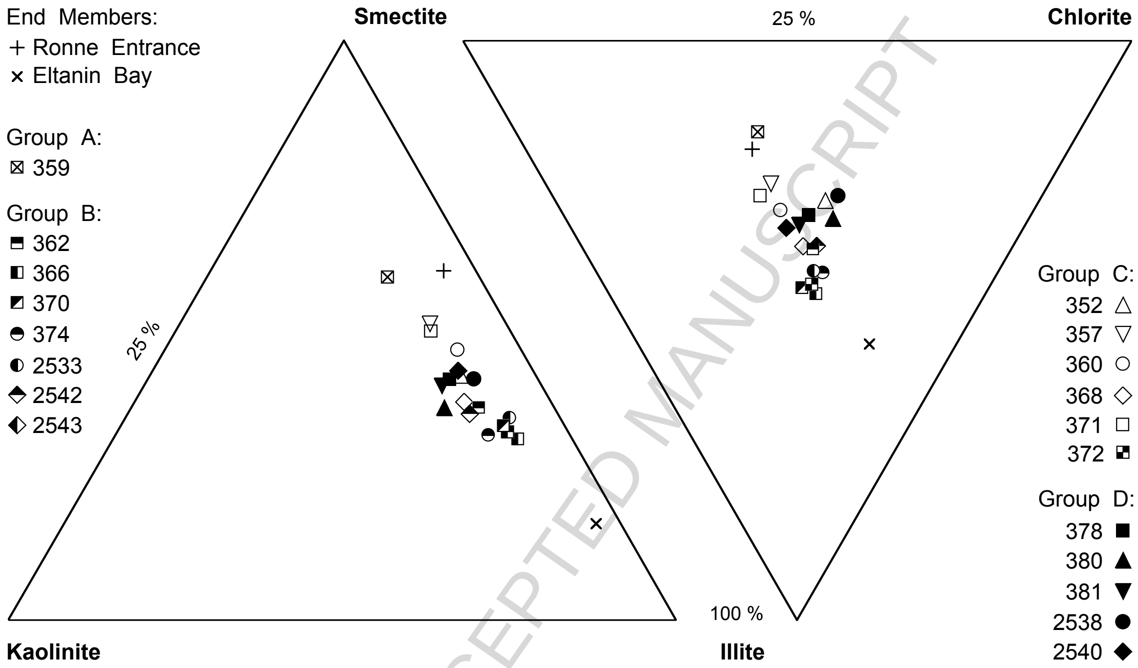


Fig. 9 Hillenbrand et al.

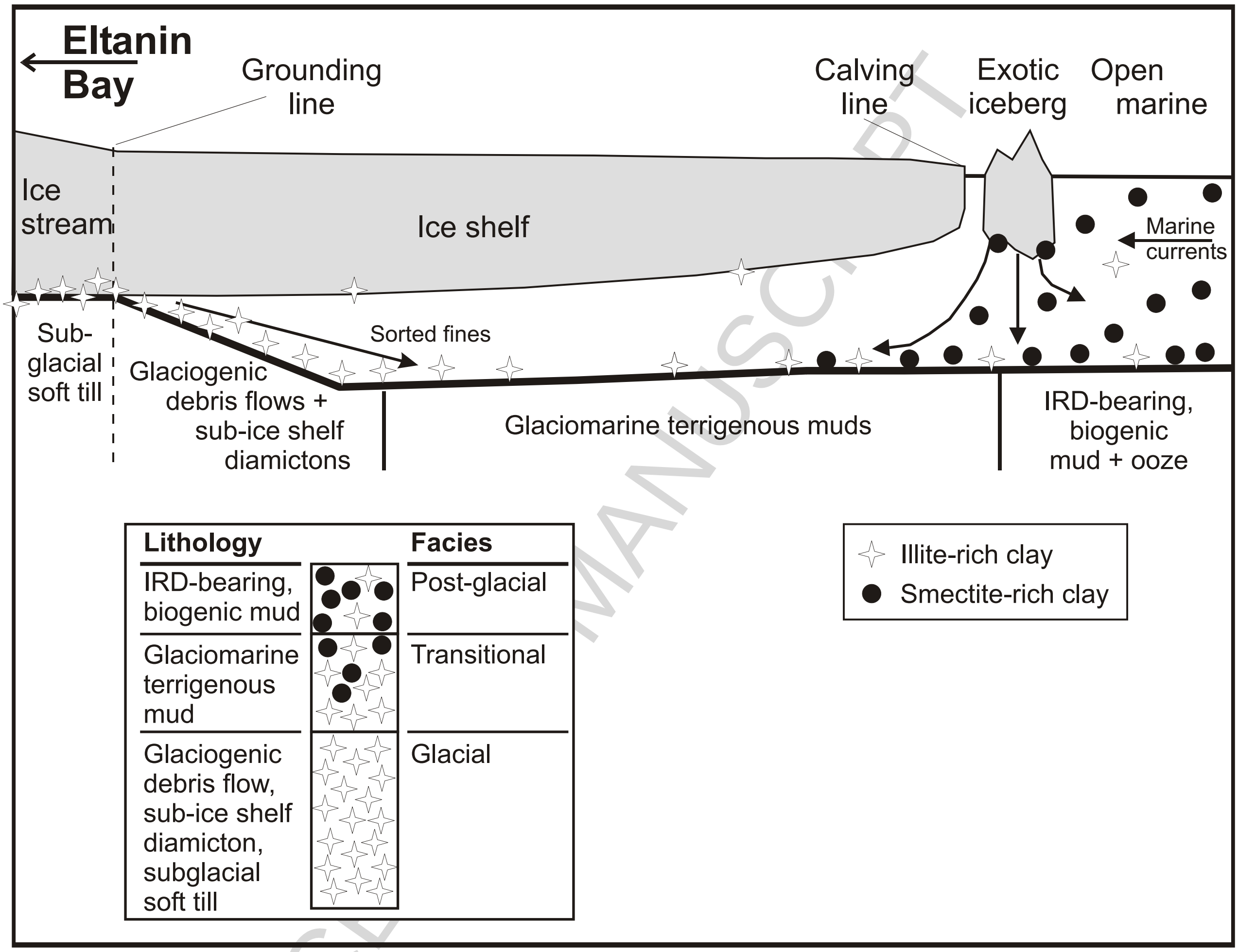


Fig.10 Hillenbrand et al.

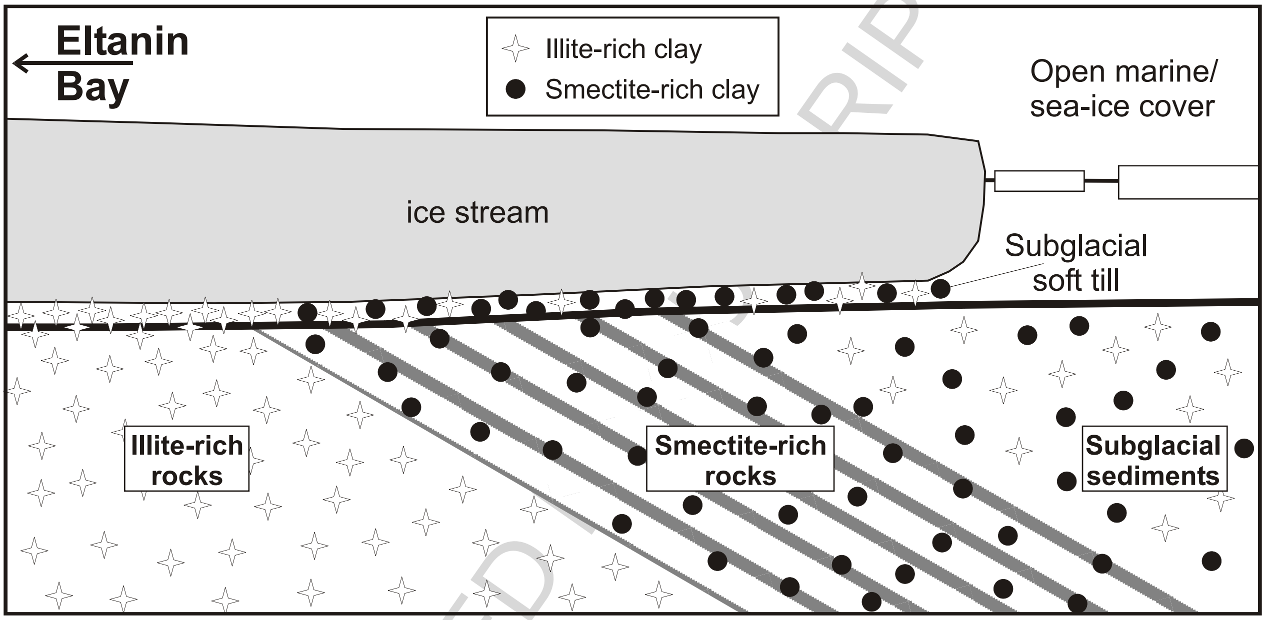


Fig.11 Hillenbrand et al.

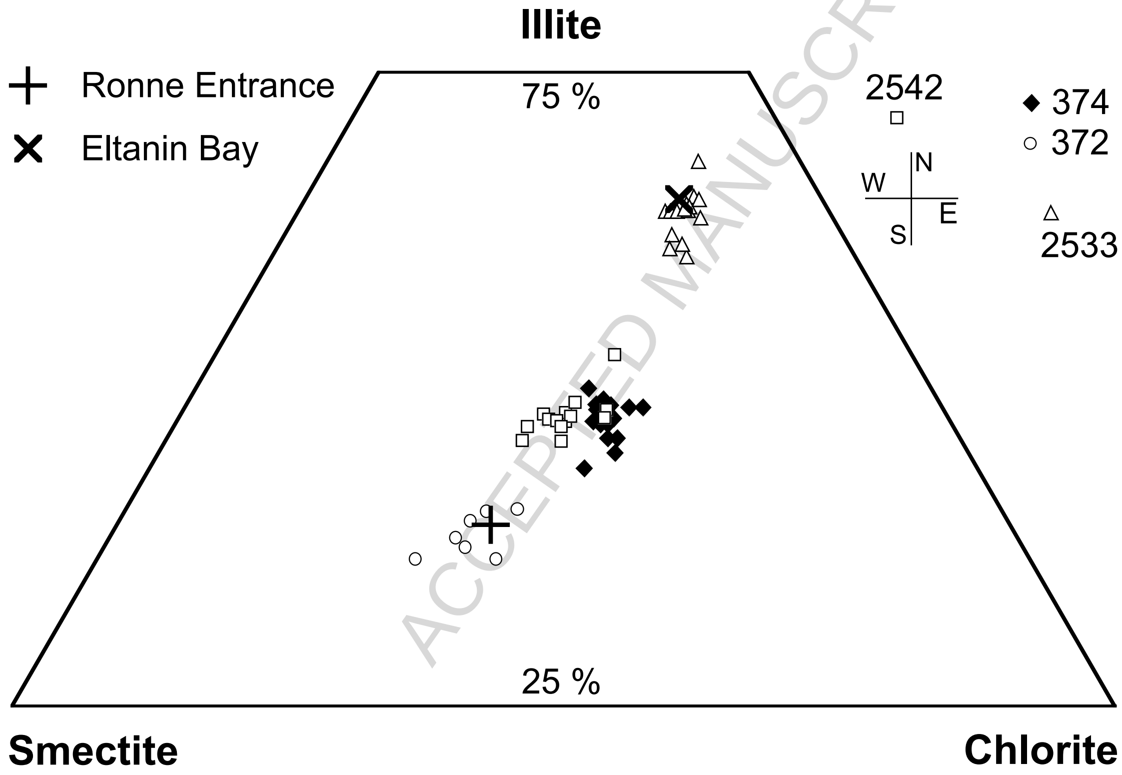


Fig. 12 Hillenbrand et al.

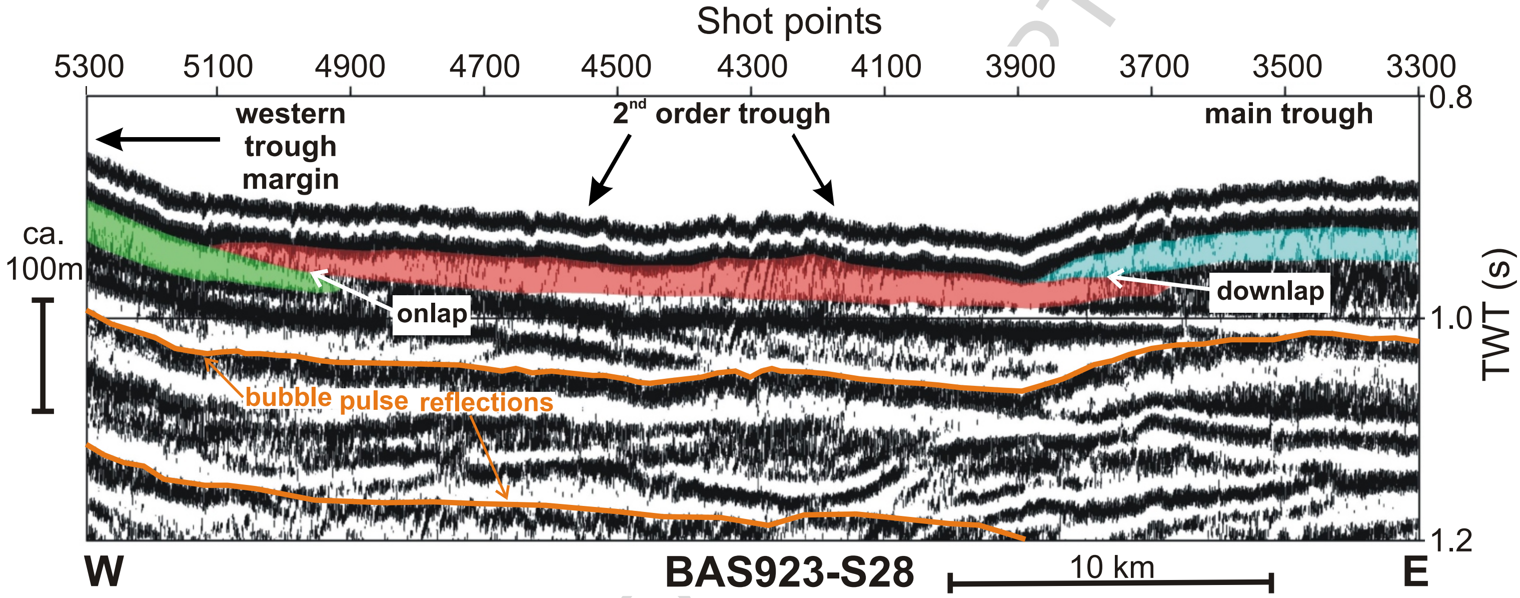


Fig.13 Hillenbrand et al.

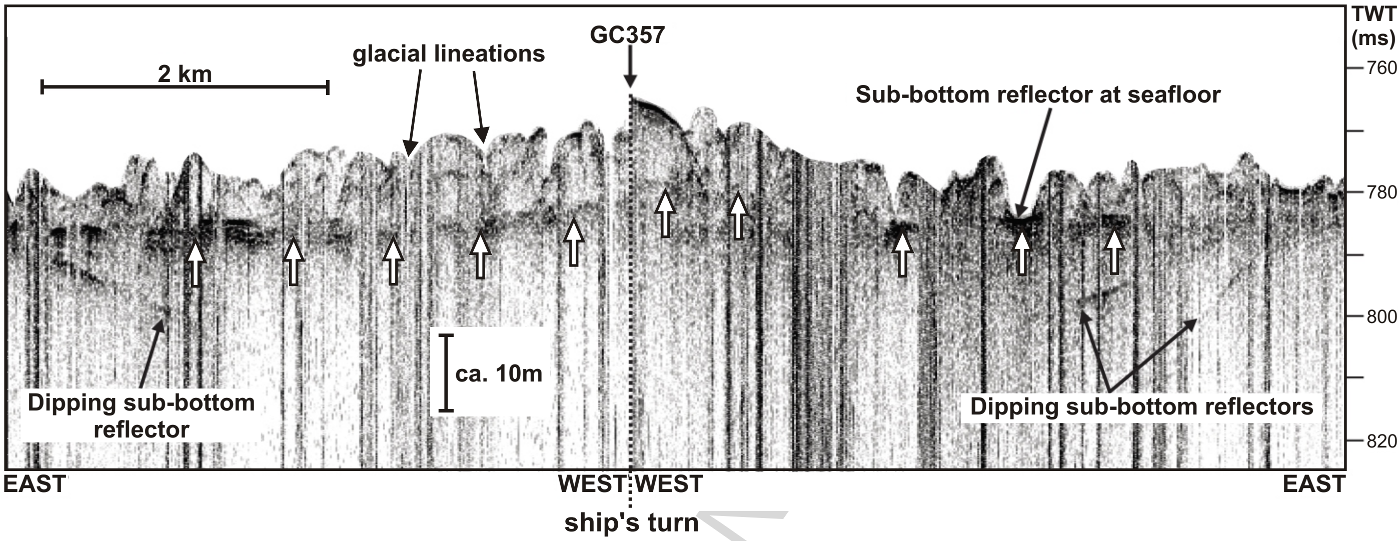


Fig.14 Hillenbrand et al.

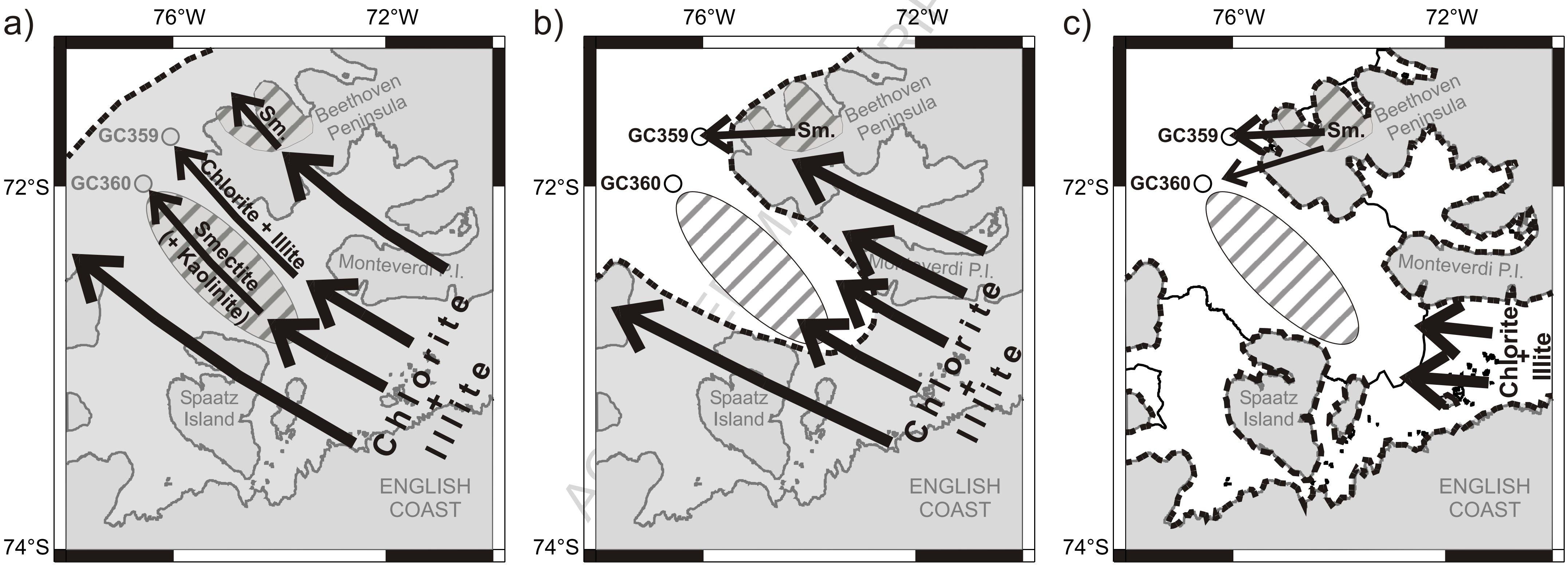


Fig.15 Hillenbrand et al.