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Mineralogy of glaciomarine sediments from the Prydz Bay–Kerguelen region: relation to modern depositional environments

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Abstract: Surface mineralogical compositions and their association to modern processes are well known from the east Atlantic and south-west Indian sectors of the Southern Ocean, but data from the interface of these areas - the Prydz Bay–Kerguelen region - is still missing. The objective of our study was to provide mineralogical data of reference samples from this region and to relate these mineralogical assemblages to hinterland geology, weathering, transport and depositional processes. Clay mineral assemblages were analysed by means of X-ray diffraction technique. Heavy mineral assemblages were determined by counting of gravity-separated grains under a polarizing microscope. Results show that by use of clay mineral assemblages four mineralogical provinces can be subdivided: i) continental shelf, ii) continental slope, iii) deep sea, iv) Kerguelen Plateau. Heavy mineral assemblages in the fine sand fraction are relatively uniform except for samples taken from the East Antarctic shelf. Our findings show that mineralogical studies on sediment cores from the study area have the potential to provide insights into past shifts in ice-supported transport and activity and provenance of different water masses (e.g. Antarctic slope current and deep western boundary current) in the Prydz Bay–Kerguelen region.

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Introduction

The Prydz Bay–Kerguelen area is one of the key regions in the Antarctic because it contains the world's largest outlet glacier and three major areas of bottom water production associated with sea ice formation. Total annual ice production in the most important area, the Cape Darnley polynya, equals about half of the production rate of ice of the Ross Ice Shelf polynya and is comparable to that of Mertz Glacier polynya (Tamura *et al.* 2008).

In the recent past, research in the study area focused on oceanographic questions. Extensive oceanographic studies have been undertaken to infer the sources and flow routes of surface, deep and bottom waters (Smith *et al.* 1984, Vaz & Lennon 1996, Bindoff *et al.* 2000, McCartney & Donohue 2007, Roquet *et al.* 2009). Mineralogical surveys of modern sediments, however, are rare (Von der Borch & Oliver 1967). Neither has the modern lateral distribution of mineralogical components on the sea floor been mapped nor the significance of different processes affecting these distributions been assessed. Consequently, the influence of modern transport and depositional processes on the composition of sediments in this region is poorly understood.

For palaeoenvironmental research, however, knowledge of present-day processes and their fingerprints in modern sediments is indispensable. In the Prydz Bay–Kerguelen region it is of major interest for the reconstruction of bottom water activity and ice sheet dynamics, how sediments in different areas are affected by the flow of Circumpolar Deep Water (CDW), Antarctic Bottom Water (AABW), the Antarctic slope current (ASC) or input of ice-rafted material from the Lambert Glacier drainage basin and down-slope transport.

Investigations of surface sediments, that place clay mineral distributions in a modern oceanographical and sedimentological context, are available from the South Atlantic covering the area of 70°W–40°E and 10°N–80°S (Petschick *et al.* 1996, Diekmann *et al.* 2003). The authors concluded that most of the clay minerals are of terrigenous origin and relate marine clay mineral assemblages to five main source regions. Input of the material is driven by a complex interaction of ocean currents, river, wind and ice activity, as well as turbidity and contour currents.

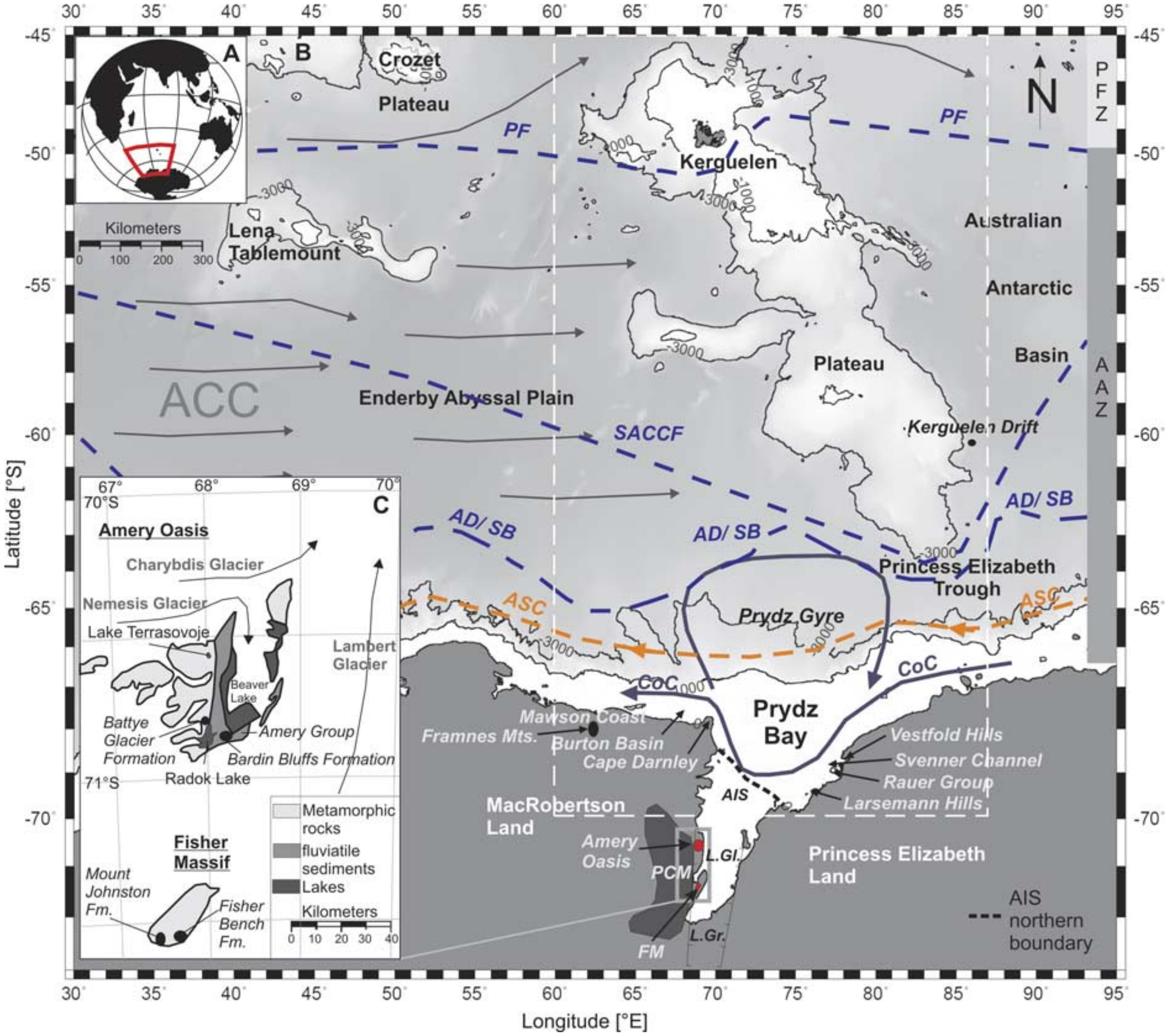

Fig. 1. Topographic and oceanographic features in the Prydz Bay–Kerguelen region (white box) and surrounding areas. **a.** Location of the investigation area. **b.** AIS = Amery Ice Shelf, FM = Fisher Massif, L.Gl. = Lambert Glacier, L.Gr. = Lambert Graben, PCM = Prince Charles Mountains, ACC = Antarctic Circumpolar Current, CoC = Antarctic coastal current, ASC = Antarctic slope current (McCartney & Donahue 2007), AAZ = Antarctic zone, AD = Antarctic Divergence (Roquet *et al*. 2009), PF = Polar Front, PFZ = Polar Front Zone, SACCF = southern ACC Front, SB = southern boundary of the ACC (Orsi *et al*. 1995), Prydz Gyre adopted from Smith *et al*. (1984). Map scale at 65°S. **c.** Enlarged picture of Amery Oasis and Fisher Massif with Pagodroma Group (black dots = Battye Glacier Fm., Bardin Bluffs Fm., Mount Johnston Fm., and Fisher bench Fm.) and Amery Group indicated (modified after Ehrmann *et al*. 2003).

Furthermore, Petschick *et al*. (1996) pointed out that clay mineral assemblages of deep sea sediments are not derived from a single source area nor along a single transport path, which complicates the connection of mineralogical compositions to certain provenances. Other investigations west of the study area have been accomplished by Moriarty (1977) who compiled clay mineral maps of south-east Indian Ocean sediments between 100–170°E and 20–70°S. Regarding the clay mineral signature of ice-transported material he underlined the importance of sediments deposited prior to Antarctic glaciation, which are now partly hidden underneath the ice. Fluvial pre-icecap sediments were also found in the Beaver Lake area, Prince Charles Mountains (Webb & Fielding 1993, Whitehead *et al*. 2006) and are possibly more widespread than currently known. Kaolin-rich and smectite-rich sediments of the Pagodroma Group deposited in a fjordal marine environment (Hambrey & McKelvey 2000) provide excellent mineralogical tracers (Ehrmann *et al*. 2003).

Further mineralogical information on marine sediments within the Prydz Bay–Kerguelen region was provided by several palaeoenvironmental studies focussing on past variations of the Lambert Glacier drainage system (Ehrmann *et al*. 1991, Cooper & O'Brien 2004, Junttila *et al*. 2005) and on palaeoceanography (Ehrmann *et al*. 1992, Cooper &

O'Brien 2004). In these studies, conclusions were drawn on provenance shifts using clay minerals and subordinate heavy minerals. An overview, however, on modern processes and related mineralogical signatures is still missing.

In this paper, we provide a set of reference data for clay mineral and heavy mineral assemblages in the Prydz Bay–Kerguelen region. Ocean currents are used to aid the interpretation of clay mineral trends. Heavy mineral assemblages are tested for suitability to reflect differences in the geologic background between the relevant drainage areas. In this regard, samples taken from pre-Holocene deposits play a major role as they probably reflect the direct influence from the hinterland. Mineralogical proxies are examined as tracers of late Quaternary shifts in the glaciomarine environment and provenances in response to climate changes.

Regional setting

The Prydz Bay–Kerguelen region (Fig. 1) is situated between 50–69°S and 65–85°E and includes four main topographic features:

i) Lambert Glacier (Fig. 1), approximately 400 km long, is the world's largest outlet glacier. It drains about 16% of the East Antarctic Ice Sheet (EAIS) (Fricker *et al.* 2000) and is predominantly responsible for the supply of terrigenous sediments to Prydz Bay and adjacent areas.

ii) Prydz Bay represents the largest shelf sea on the East Antarctic margin, though smaller than the Weddell Sea or Ross Sea. The shelf region is covered by seasonal sea ice and is bounded to the east by Princess Elizabeth Land and to the west by Mac. Robertson Land (Fig. 1). Continental shelf width varies between 70 and 250 km. Water depths in general increase from 200 m near the shelf edge to 1600 m farther inland due to over-deepening through advances of the Lambert Glacier (Federov *et al.* 1982, Harris *et al.* 1997). Glacial incisions and rift basins have water depths of up to 1000 m (locally).

iii) The Kerguelen Plateau, which is a NW–SE trending, 2500 km long submarine barrier reaching widths of up to 600 km (Fig. 1). It rises to 4 km above that sea floor, but rises above sea level only in the area of Iles Kerguelen and Heard Island.

iv) Enderby abyssal plain (Fig. 1), which comprises water depths between 4000 and 5000 m. Sedimentation to a large part takes place by turbidity currents and by pelagic rain of biosilicous remains (Goodell 1973, Kuvaas & Leitchenkov 1992).

Oceanography, icebergs and sea ice

Surface circulation (Fig. 1) in the Prydz Bay–Kerguelen region is related to the prevailing wind systems. Near to the continent the Antarctic coastal current (CoC, Vaz & Lennon 1996) and the Antarctic continental slope (or Polar) current (ASC, Bindoff *et al.* 2000) are forced by the polar easterlies and move to the west (Fig. 1). At approximately 64°N the Antarctic Divergence (AD) delineates the boundary of the eastward-flowing strong band of the Antarctic Circumpolar Current (ACC) driven by strong westerly winds (Fig. 1). The opposing surface current directions generate a cyclonic gyre in Prydz Bay (Fig. 1) with cold water inflow from the east, and outflow along the western side of the embayment (Smith *et al.* 1984). Circulation in the embayment is also enhanced by intense polynya activity that leads to bottom water formation (Tamura *et al.* 2008) favouring down-slope currents beyond the shelf edge. Sedimentation on the continental slope is controlled by the interaction of down-slope density (e.g. turbidity) currents and along-slope (contour) currents (Kuvaas & Leitchenkov 1992), for example the ASC.

The most prominent oceanographic feature in the study area is the ACC (Fig. 1). It extends from the sea surface to depths of 2000–4000 m and can be as wide as 2000 km. Most of the deep and bottom water masses of the ACC consist of CDW that represents a mixture of water masses from the Atlantic, the Antarctic, the Indian and Pacific Oceans. Several oceanic fronts (e.g. Orsi *et al.* 1995) identified as narrow regions of sharp horizontal density gradients and by increasing nutrients levels subdivide the ACC from north to south into sub-Antarctic zone (SAZ), Polar Frontal zone (PFZ) and Antarctic zone (AAZ, Fig. 1).

A comprehensive overview of sea ice concentration and sea ice motion is provided by Schmitt *et al.* (2004). The speed and direction of ice drift is dependent on the winds and surface currents. In Prydz Bay, ice follows the Antarctic coastal current to the west and is deflected to the north by southerly winds. North of the AD, ice then diverges to the east. During winter, annual sea ice extends north of 60°S, whereas multi-year sea ice is mainly restricted to coastal areas.

Geology

Prydz Bay and Lambert Graben (Fig. 1) are incised in the East Antarctic shield, which is built up of Archean, Proterozoic and Cambrian metamorphic rocks and intrusives. East Antarctica once formed a central part of the Gondwana supercontinent (Tingey 1991).

South of Prydz Bay the Lambert Graben extents 700 km inland. It represents the failed arm of a triple junction associated with breakup of India and Antarctica/Australia during early Cretaceous times, at approximately 130 Ma. During the Permian and Mesozoic, sequences up to 5 km thick of continental deposits comprising sandstones, shales, coal and conglomerates of alluvial and glacial origin accumulated on the mostly Proterozoic basement (Cooper *et al.* 1991, Tingey 1991). In the Prince Charles Mountains around Beaver Lake (Fig. 1) these deposits constitute the

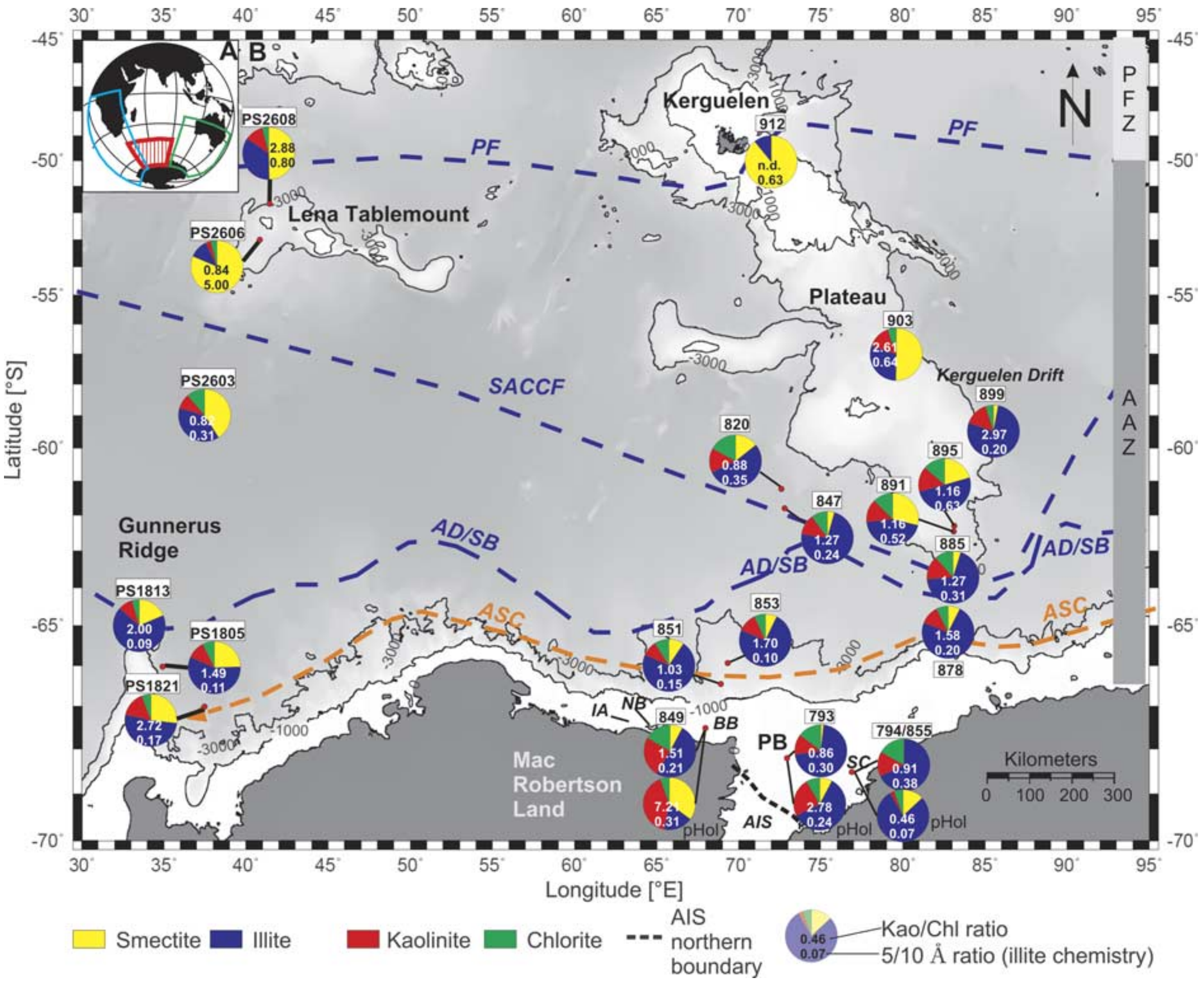

Fig. 2. Clay mineral assemblages of sea-bed surface sediments in the Prydz Bay–Kerguelen region and of pre-Holocene deposits (pHol) on the East Antarctic shelf. **a.** Location of the investigation area (red, vertical lines) and areas of previous clay mineral studies of sea surface sediments indicated (green polygon = Moriarty 1977, blue polygon = Petschick *et al*. 1996). **b**. Surface samples PS1805 to PS2608 published by Diekmann *et al*. (2003). AIS = Amery Ice Shelf, BB = Burton basin, IA = Iceberg alley, NB = Nielsen basin, PB = Prydz Bay, SC = Svenner Channel. AAZ = Antarctic zone, AD = Antarctic Divergence, ASC = Antarctic slope current, PF = Polar Front, PFZ = Polar Front Zone, SACCF = southern ACC Front, n.d. = not determined. Map scale at 65°S.

Amery Group (Fig. 1; Tingey 1991, Webb & Fielding 1993). Since the Paleocene these sediments have been re-deposited several times (Whitehead *et al*. 2006) forming the sediment sequences of the Pagodroma Group (Fig. 1; Hambrey & McKelvey 2000).

The largest outcrop of bedrock is located on the western flank of the Lambert Graben (Fig. 1), where the Prince Charles Mountains (PCM) form the best-exposed cross section through the East Antarctic shield. The mountains consist of isolated nunataks and steep-sided, flat-topped massifs that stand up to 1000 m above the surrounding ice sheet (Tingey 1991). They are composed of Precambrian metamorphic rocks grading from granulite-facies gneisses with intrusions of charnockite plutons, pegmatite veins and alkaline dykes in the northern province of the bedrock outcrop to amphibolite-facies and greenschist-facies gneisses in the southern province (Tingey 1991).

Along the eastern side of Prydz Bay, in the Larsemann Hills, Vestfold Hills and Rauer Islands (Fig. 1), several rock outcrops give insights into the petrography of the high-grade Archean and Proterozoic metamorphic rocks. Larsemann Hills consists of garnet-bearing gneiss with subordinate blue cordierite (Tingey 1991, Thost *et al*. 1998). To the north, there is a scattering of smaller outcrops of Cambrian granites and Proterozoic gneisses. The Rauer Group, situated 100 km north-east of the Larsemann Hills (Fig. 1) comprises granulite-facies tonalitic orthogneisses with intrusions of mafic to ultramafic dykes (Tingey 1991). Subsidiary paragneisses, marbles and skarn rocks can be found. Following to the north-east Vestfold Hills offer the third large outcrop of bedrock off Princess

Table I. Overview of sample sites and devices used for retrieval of surface samples and pre-Holocene samples.

Site	Device	Latitude (°S)	Longitude (°E)	Water depth (m)
PS69/793-1	multicorer	-68.01	72.89	-703
PS69/793-2	gravity corer (Kiel type)	-68.01	72.89	-673
PS69/794-2	multicorer	-68.72	76.68	c. -850
PS69/820-2	multicorer	-60.95	72.72	-4161
PS69/847-1	multicorer	-61.85	72.73	-4104
PS69/849-1	multicorer	-67.58	68.13	-553
PS69/849-2	gravity corer (Kiel type)	-67.58	68.12	-559
PS69/851-2	multicorer	-66.37	69.01	-2036
PS69/853-2	multicorer	-66.00	69.22	-2365
PS69/855-1	piston corer (BGR type)	-68.70	76.72	-848
PS69/878-4	giant box corer	-65.34	82.66	-3093
PS69/885-1	giant box corer	-63.84	82.87	-3702
PS69/891-5	giant box corer	-62.66	82.84	-2290
PS69/895-1	multicorer	-61.70	82.83	-2352
PS69/899-1	multicorer	-59.62	85.67	-4126
PS69/903-1	multicorer	-57.23	79.38	-1713
PS69/907-3	multicorer	-55.00	73.33	-2251
PS69/912-5	multicorer	-50.31	71.57	-565

Elizabeth Land (Fig. 1). The rock suite comprises Archean granulite facies gneisses intersected by several mafic dyke swarms with an interlayering of metavolcanics, pyroxenites, metagabbros, felsic orthogneisses and paragneisses (Tingey 1991, Thost *et al*. 1998).

West of Prydz Bay, on Mac. Robertson Land (Fig. 1), bedrock is exposed along Mawson Coast (Fig. 1). Rocks mainly consist of high-grade granulite-facies gneisses intruded by large charnockite plutons (Tingey 1991). South of Mawson Station, bedrock of the Framnes Mountains (Fig. 1) crops out over an area of about 2000 km^2 comprising a variety of hypersthene-bearing felsic intrusives, granodiorites and tonalities (Tingey 1991).

Material and methods

Twelve undisturbed sea-bottom surface samples were taken during RV *Polarstern* cruise ANT-XXIII/9 by use of giant-box corer and multicorer (Fig. 2). Additionally, three sediment samples from piston cores and gravity cores retrieved from the continental shelf were investigated for clay mineral and heavy mineral distributions (Table I). Samples obtained from sediment cores were taken from terrigenous sediment units directly underlying diatom oozes. They are thus tentatively assigned to the Last Glacial period. The advantage of mineral distributions gathered from these glacial environments is that they directly display the composition of material derived from the hinterland (Ehrmann *et al*. 1992, Diekmann & Kuhn 1999). In this paper, however, we use the term 'pre-Holocene' to refer to these samples. In addition one should note that because of different accumulation rates in the different environments the term 'modern' for surface samples is not to be taken in its strict sense.

From each site, one 1 cm slice from the upper sediment was used for clay mineralogy. A second sample from each site with a thickness of 5 cm was used for heavy mineral determination. Both samples were treated with 10% hydrogen peroxide for disaggregation and elimination of organic matter until chemical reaction ceased. Sample one, assigned to clay mineral analysis, was wet-sieved through 63 μm and 2000 μm meshes to isolate the fines from the sand fraction and gravel fraction. Silt and clay were separated by Stokes Law using Atterberg settling tubes (Müller 1967).

Some sediment samples included high concentrations of biogenic opal with potential to bias the determination and quantification of clay minerals (Petschick *et al*. 1996). Therefore biogenic opal was dissolved by heating the material of the clay fraction at 85°C in a 1.5 M sodium hydroxide solution for two hours. After smear slides were inspected to verify that all biogenic opal had been removed, the suspension was washed to pH of 7–8 by centrifuging with demineralized water and dried at 50°C. Preferentially oriented clay-mounts were produced following the method and precisions explained in detail elsewhere (Ehrmann *et al*. 1992, Petschick *et al*. 1996). Clay mineralogy was determined semiquantitatively by X-ray diffraction measurements conducted on a Philips PW1820 diffractometer system (CoK-alpha radiation at 1600 W, 40 kV, 40 mA). Mineral proportions of the main clay mineral groups smectite, illite, kaolinite and chlorite were determined with the help of MacDiff 4.2.5 program (http://www.geologie.uni-frankfurt.de/Staff/Homepages/Petschick/Classicsoftware.html, accessed 11 August 2010) from weighted peak areas recorded in the X-ray diffractograms. For simplification, the terms smectite, kaolinite, illite and chlorite are here used as a general expression for the relevant mineral groups. The distribution of clay minerals was calculated using empirically estimated weighting factors (Biscaye 1965). The 5/10 Å ratio gives evidence on the illite octahedral composition. According to Esquevin

Table II. Mineralogical composition of the clay fraction determined from sea bed surface sediments and pre-Holocene sediment samples (with core depth in centimetres in brackets) from the Prydz Bay–Kerguelen region.

Position	Sm %	Ill %	Kao %	Chl %	K/C	5/10 Å	Ill 10 Å IB	Sm 17 Å IB	Q/Fsp	KFsp/ Plag	Px/Q	Hb/Q	Province
Surface samples													
793-1	1.7	71.0	12.6	14.7	0.9	0.3	0.5	-	1.7	0.2	0.1	0.07	shelf
794-2	0.3	67.6	15.3	16.8	0.9	0.4	0.5	-	1.6	0.2	0.1	0.09	shelf
820-2	14.4	53.6	15.0	17.0	0.9	0.3	0.4	1.0	1.9	0.3	0.1	0.05	deep sea
847-1	4.4	72.7	12.9	10.1	1.3	0.2	0.7	1.1	1.5	0.3	0.1	0.07	deep sea
849-1	7.8	50.7	24.9	16.5	1.5	0.2	0.4	0.9	2.2	0.5	0.1	0.02	shelf
851-1	9.4	72.2	9.3	9.1	1.0	0.1	0.6	0.9	1.6	0.3	0.1	0.05	slope
853-1	7.1	74.1	11.9	7.0	1.7	0.1	0.6	1.4	1.6	0.3	0.1	0.07	slope
878-4	7.4	73.6	11.7	7.4	1.6	0.2	0.6	1.4	2.0	0.4	0.0	0.05	slope
885-1	4.9	68.9	14.7	11.6	1.3	0.3	0.7	-	1.7	0.3	0.1	0.06	deep sea
891-5	28.7	44.7	14.3	12.3	1.2	0.5	0.4	1.1	2.8	0.3	0.1	0.03	Kerguelen
895-1	20.5	50.3	15.6	13.5	1.2	0.6	0.5	1.2	2.4	0.2	0.1	0.04	Kerguelen
899-2	2.9	77.2	14.9	5.0	3.0	0.2	0.8	0.8	1.6	0.3	0.1	0.09	deep sea
903-1	50.3	30.0	14.3	5.5	2.6	0.6	0.3	0.9	2.3	0.3	0.1	0.05	Kerguelen
912-5	89.1	10.7	0.2	0.0	n.d.	0.6	0.1	1.0	0.1	1.5	2.3	0.23	Kerguelen
Pre-Holocene samples													
849-2 (370)	35.1	18.0	41.2	5.7	7.2	0.3	0.5	1.2	2.3	1.1	0.1	0.02	shelf
793-2 (96)	7.7	60.0	23.8	8.5	2.8	0.2	0.4	1.0	1.9	0.3	-	0.06	shelf
855-1 (1528)	13.1	78.7	2.6	5.6	0.5	0.1	0.5	0.8	1.2	0.2	0.1	0.14	shelf

Sm = smectite, Ill = illite, Kao = kaolinite, Chl = chlorite, K/C = kaolinite/chlorite ratio, IB = Integral breadth used as crystallinity index, 5/10 Å = illite chemistry, Q/Fsp = quartz/feldspar ratio, KFsp/Plag = K-feldspar/plagioclase ratio, Px/Q = pyroxene/quartz ratio, Hb/Q = hornblende/quartz ratio. The assignment of each sample to a certain mineralogic province is shown; shelf = 'continental shelf province', slope = 'continental slope province', deep sea = 'deep sea province', Kerguelen = 'Kerguelen Plateau province'.

(1969) low 5/10 Å values (< 0.15) are characteristic of Fe, Mg-rich (biotitic) illites. Substitution of Mg and Fe by Al increases the ratio with values exceeding 0.4 corresponding to a muscovitic composition.

For analysis of the 'crystallinity' of smectite and illite, the integral breadth of the glycolated 17 Å-smectite and 10 Å-illite peaks were measured (Petschick *et al*. 1996). Crystallinity usually provides a qualitative index for lattice order and crystallite size but it can also be used as a tracer for source regions and transport path of young sediments (Petschick *et al*. 1996).

Subsidiary to the clay mineral assemblages, the occurrence of other minerals in the clay mineral fraction like quartz, plagioclase, K-feldspar, hornblende and pyroxene was determined. These minerals can provide adjuvant information on the provenance of the material and reveal information on weathering, transport and deposition mechanisms of sediment material.

Heavy mineral analysis

In sediment sample two the 63–125 μm fine sand fraction was isolated from the rest of the sand fraction by wet sieving. Approximately 2.7 g of fine sand was dispersed in 10 ml of sodium-metatungstate solution (density 2.86–2.89 g cm^{-3}) in centrifuge tubes. The heavy mineral fraction was separated from the light minerals by centrifuging (20 min at 3000 rpm), subsequent freezing in liquid nitrogen and staged melting. The heavy minerals were mounted on glass slides using Meltmount (refraction index = 1.68). A minimum of 300 translucent grains were counted along traverses under a polarizing microscope. Gale & Hoare (1991) recommend counting a minimum of about 300 grains to determine the broad distribution of species in a sample. Improvement in the precision is very small with counts greater than 500 grains.

The results are presented as grain percentages in the heavy mineral fraction, corrected for opaque and weathered grains. Additionally the ratio of opaque to translucent grains and the ratio of altered to translucent grains were calculated. All specifications of sample locations and data can be extracted from the information system 'Pangaea' (http://www.pangaea.de/PHP/CruiseReports.php?b=Polarstern; PS69 (Prydz Bay)).

Results

Clay mineral assemblages

Clay mineral assemblages in the twelve studied samples show distinct regional variations in the study area (Fig. 2, Table II). South of 57°S, illite is the dominant clay mineral with values ranging between 10% on the northern Kerguelen Plateau and 77% on the Kerguelen drift and in the Svenner Channel situated on Prydz Bay shelf (Fig. 2). It is followed by smectite, making up to 89% of the clay mineral assemblage at site PS69/912 (PS = Polarstern) on the northernmost Kerguelen site. However, south of 58°S smectite does not exceed 30%. Kaolinite occurs with about 10–15%, except for the continental shelf, where it can reach concentrations of 24% in surface samples and up to

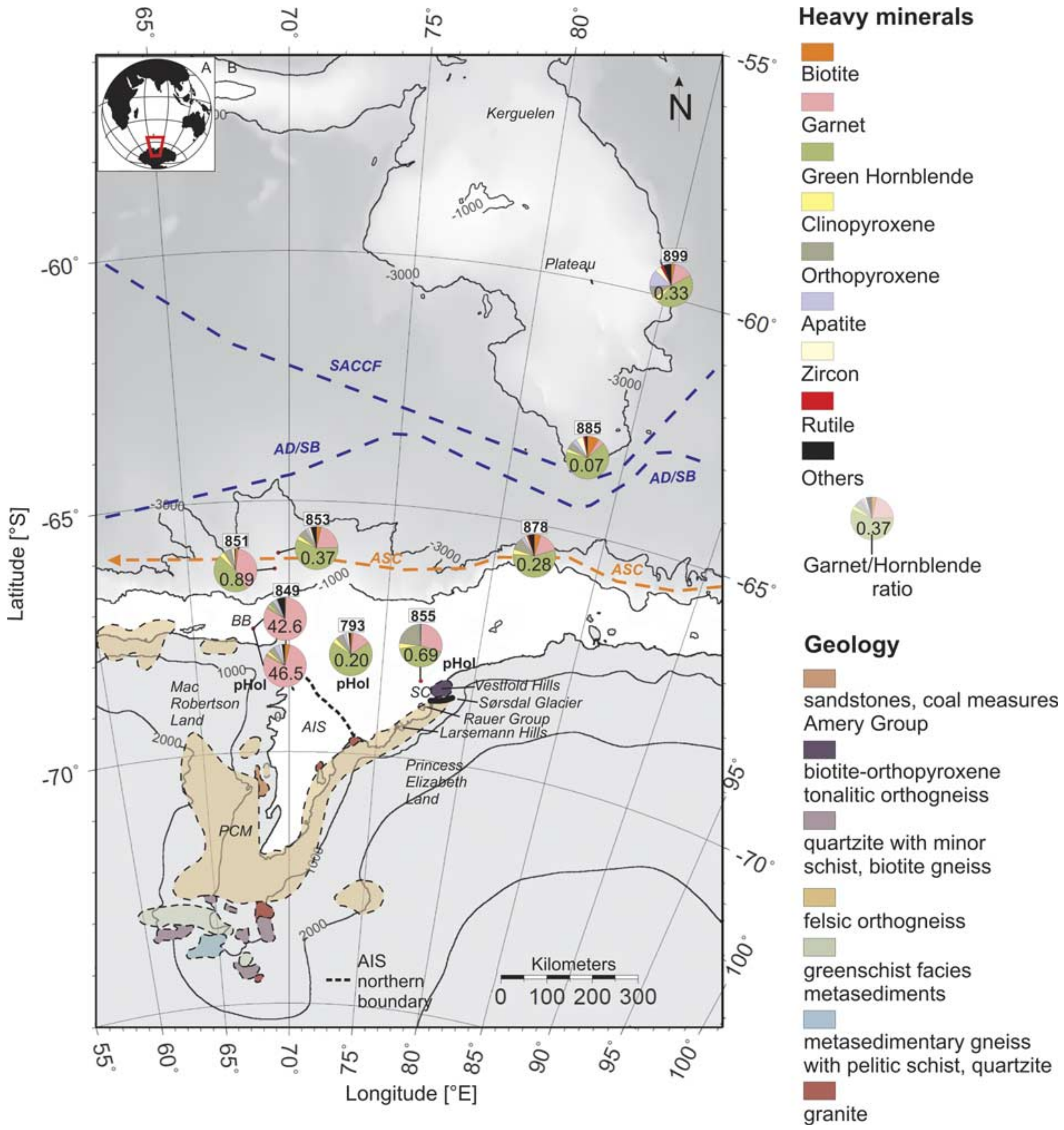

Fig. 3. Map of heavy mineral assemblages determined from sea-bed surface sediments in the Prydz Bay–Kerguelen region and pre-Holocene deposits (pHol) on the East Antarctic shelf. **a.** Location of the investigation area. **b.** Geology of the Lambert Glacier drainage basin and Prydz Bay after Tingey (1991) and Thost *et al.* (1998). AIS = Amery Ice Shelf, BB = Burton basin, SC = Svenner Channel, PCM = Prince Charles Mountains. AD = Antarctic Divergence, ASC = Antarctic slope current, SACCF = southern ACC Front, SB = southern boundary of the ACC. Map scale at 65°S. Map courtesy of Australian Geological Survey Organisation © Commonwealth Australia 1998.

41% in sediment samples from pre-Holocene deposits. Concentrations of kaolinite and smectite in sediment samples from the continental shelf are higher in the pre-Holocene sections compared to the surface samples at the same site, except for samples from Svenner Channel.

Illite chemistry shows distinct variations between strong biotitic to strong muscovitic compositions as indicated by 5/10 Å values that range between 0.07 and 0.64. The highest values are found on the topmost positions of the Kerguelen Plateau (Fig. 2). Results show no significant difference in the geochemical composition of the illites there. To the south, 5/10 Å ratios decrease to values between 0.1 and 0.2 on the continental slope adjacent to Prydz Bay. In Prydz Bay and in Burton basin (unofficial name; Fig. 2), medium 5/10 Å ratios

Table III. Heavy mineral composition of sea-bed surface sediments and pre-Holocene sediment samples (with core depth in centimetres in brackets) from the Prydz Bay–Kerguelen region.

	Bio	Gn	Hb	Cpx	Opx	Ap	Ep+ Czoi+ Zoi	Sill	Stau	Zir	Rut	Opx/Cpx ratio	Gn/Hb ratio	Transl/Op ratio	Transl/Alt ratio	counts
Surface samples																
849-1	0.8	82.9	1.9	1.2	3.5	2.7	0.0	5.8	0.0	0.8	0.0	3.0	42.6	17.1	64.3	257
851-1	2.0	39.8	44.9	4.0	5.4	1.1	0.0	0.7	0.0	2.0	0.0	1.3	0.9	15.3	40.5	445
853-1	3.5	21.0	57.2	3.2	6.4	2.4	1.3	2.7	0.0	1.9	0.5	2.0	0.4	20.9	22.1	376
878-4	4.9	15.6	55.6	3.9	9.2	3.1	2.1	2.1	0.0	1.8	1.2	2.4	0.3	8.9	28.6	487
885-1	8.9	4.7	65.4	2.8	5.6	3.7	1.9	0.0	0.0	5.6	1.4	2.0	0.1	5.6	12.6	214
899-1	2.7	14.5	43.5	4.3	9.0	12.9	3.9	2.0	0.0	4.7	2.4	2.1	0.3	3.3	8.2	255
Pre-Holocene samples																
793 (125)	1.7	13.9	68.9	3.6	5.8	2.4	0.7	0.5	0.5	1.9	0.0	1.6	0.2	12.8	41.1	411
849 (330)	4.0	78.8	1.7	2.3	4.8	4.5	0.0	1.7	0.0	1.7	0.3	2.1	46.5	6.4	39.3	354
855 (1528)	0.2	29.6	42.9	4.0	21.8	0.9	0.2	0.0	0.0	0.2	0.0	5.4	0.7	14.1	60.3	422

Bio = biotite, Gn = garnet, Hb = hornblende, Cpx = clinopyroxene, Opx = orthopyroxene, Ap = apatite, Ep+Czoi+Zoi = sum of epidote, clinozoisite and zoisite, Sill = sillimanite, Stau = staurolilthe, Zir = zircon, Rut = rutile, Transl/Op = ratio of translucent to opaque grains, Trans/Alt = ratio of translucent to altered grains.

of 0.21–0.38 hint to mixing of illites of biotitic and muscovitic composition, while the sediment sample from the pre-Holocene sample in the Svenner Channel exhibits a clear biotitic character.

In addition to clay minerals, non-clay minerals in the clay fraction also show spatial differences. Both extreme values of the quartz/feldspar ratio (minimum 0.1, maximum 2.8) are found in the Kerguelen region. The ratio of hornblende/quartz is relatively uniform in the investigation area with most values ranging between 0.02 and 0.09. The minimum was found in the Burton basin whereas an extraordinarily high ratio of 0.23 was determined on the northern Kerguelen Plateau. A similar regional pattern of extreme values is obtained by analysis of the K-feldspar/plagioclase ratios.

Heavy mineral assemblages

Heavy mineral assemblages were obtained from seven sites (Fig. 3, Table III). Samples from other sites exhibited either low contents of sand-sized material or a pronounced dilution of lithogenic matter with biogenic (primarily opaline) components.

On the continental shelf, the mineralogical composition of sediments from three sites was analysed (Fig. 3). In Prydz Bay it was only possible to isolate heavy mineral grains from the sand fraction of the pre-Holocene deposits. Surface sediments were strongly diluted by biogenic material. In contrast to Prydz Bay, high amounts of sandy material in the Burton basin (Fig. 3) favoured mineralogical analysis of both modern and glacial sediments. Samples from Prydz Bay and Burton basin show conspicuous differences in the content of garnet and hornblende with strong supply of garnet (79–83%) to Burton basin and high amounts of hornblende (42–69%) in Prydz Bay, well expressed in differences of the garnet/hornblende ratio. This ratio can be used to trace back sediments of the open ocean to the two possible source regions: garnet/hornblende < 1 indicates provenance from Prydz Bay, whereas garnet/hornblende > 1 indicates sediment sources on Mac. Robertson shelf (Fig. 3). Heavy mineral assemblages on the continental shelf furthermore can be distinguished by high concentrations of orthopyroxene in the Svenner Channel and lower orthopyroxene contents in the Burton basin (Fig. 3).

Three samples were counted from the continental slope west and east of Prydz Bay. Heavy mineral distributions show similar pictures with slightly increasing garnet/hornblende ratios and slightly decreasing orthopyroxene/clinopyroxene ratios from the east to the west. North of Princess Elizabeth Trough (Fig. 1), at site PS69/885, values of biotite, hornblende and zircon reach their maximum (9%, 65% and 6%, respectively), whereas garnet is of minor abundance. The northernmost site on Kerguelen Plateau, PS69/899, is characterized by the highest amount of apatite in the study area.

Examination of translucent/opaque grains ratio and translucent/altered grains ratio reveals decreasing trends from Svenner Channel to Burton basin and from the shelf to the southern Kerguelen Plateau.

Discussion

The interpretation of both clay minerals and heavy mineral assemblages requires understanding of the interaction of different factors that influence the mineralogical composition of the sediment samples with distance from source (e.g. Petschick *et al.* 1996, Diekmann & Kuhn 1999). These factors include:

i) the geology of source rocks in the hinterland, which is responsible for the primary mineralogical composition of the material.

ii) Erosion and weathering conditions, controlled by local climate and hydrographic conditions. According to

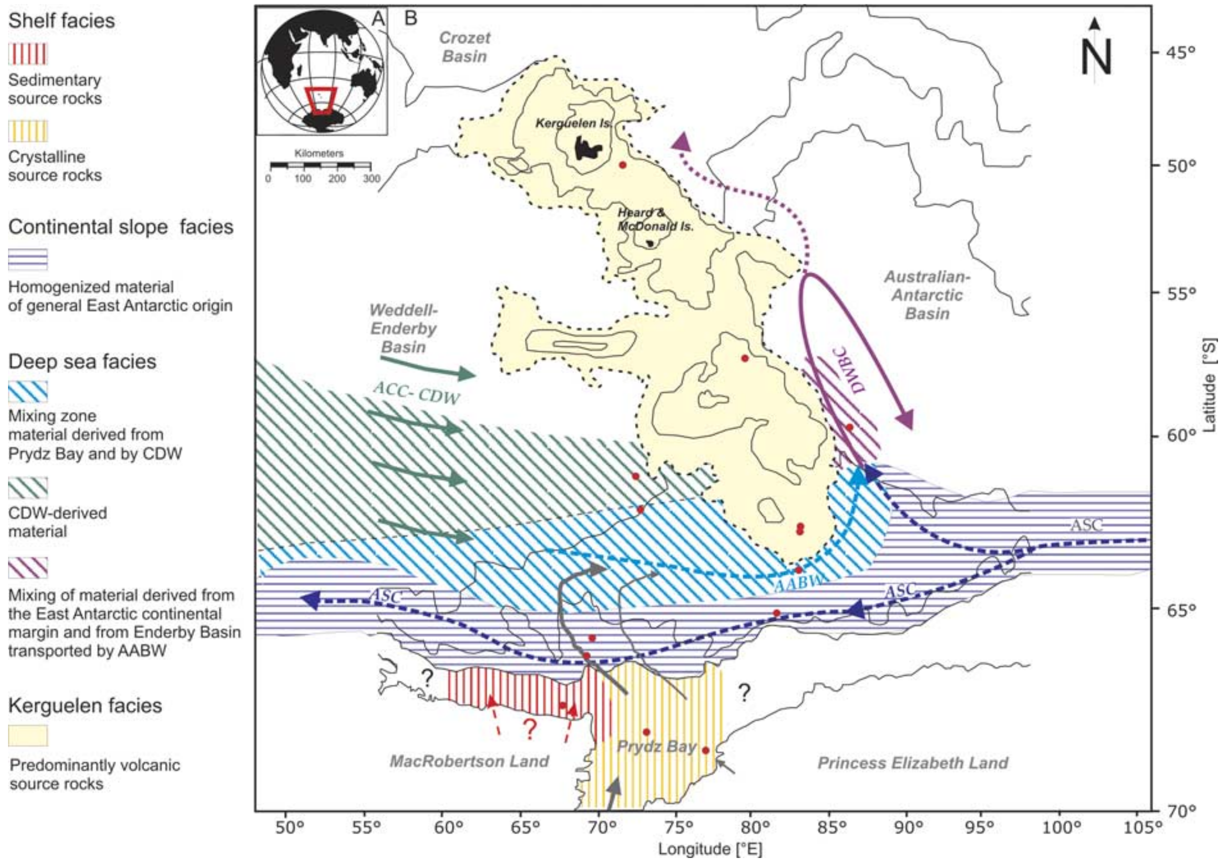

Fig. 4. Synopsis of mineralogical provinces in the Prydz Bay–Kerguelen region. **a.** Location of the investigation area. **b.** On the continental shelf, differences in the mineralogical assemblages are attributed to the primary composition of source rocks. Continental slope province shows clay mineral signatures of East Antarctic provenance homogenized by a strong contour current following the continental slope. In the southern deep sea province terrigenous material is supplied from Prydz Bay (Goodell 1973) and surrounding shelf areas, whereas sedimentation of fines in the northern deep sea province is CDW-dominated. In the area of the deep western boundary current, fines supplied by AABW from the Weddell-Enderby Basin and from the East Antarctic continental margin are mixed. Kerguelen Province comprises generally high smectite contents associated with local transport of pyroclastic material. AABW = Antarctic Bottom Water, ACC = Antarctic Circumpolar Current, ASC = Antarctic slope current, CDW = Circumpolar Deep Water, DBWC = deep western boundary current. Map scale at 65°S.

the mechanical and chemical stability of minerals, mechanical and/or chemical conversion can lead to first in situ modifications of the mineral suite.

iii) Transport by water and ice can cause reduction in grain size and selective enrichment of different mineral groups.

iv) Authigenesis and sediment diagenesis.

Clay minerals

Four clay mineral provinces (Fig. 4) can be distinguished in the study area by combination of similar clay mineral assemblages: a ‘continental shelf province’, ‘continental slope province’, ‘deep sea province’ and ‘Kerguelen Plateau province’. All clay mineral assemblages comprise high concentrations of illites characteristic of an East Antarctic provenance. They are considered as a detrital product of subglacial erosion and weathering products of crystalline rocks in high latitude marine sediments (Petschick *et al*. 1996). Illites in most samples from the continental shelf, the continental slope and from deep sea sediments show neither clear biotitic nor muscovitic signature reflecting the mixing of both illite types. Nonetheless, relatively low 5/10 Å values argue for a preponderance of biotites produced by physical weathering of biotite-rich rocks in the Prydz Bay hinterland, including gneisses, granulites, granites/granitoids and subordinate metamorphosed mafic dykes (Tingey 1991).

In the following section the single clay mineral provinces are described:

Continental shelf province - pre-Holocene sediments

The continental shelf province (Fig. 4) comprises distinct variations in the concentration of clay mineral groups in surface and diamict samples. The general increase in smectite and kaolinite in a westward direction particularly hints at a provenance of fine grained material from different sources.

Sediment samples from Svenner Channel (Fig. 2) show very high abundances of illite. 80% illite in the sample is tentatively assigned to the Last Glacial period. The enrichment of Mg-Fe-rich illites in the pre-Holocene sample can be related to biotite-bearing highly metamorphic rocks found on the East Antarctic craton (Tingey 1991). The mineralogy is consistent with the geology in the adjacent hinterland of Princess Elizabeth coast (Fig. 3), which comprises granulite facies felsic and mafic layered orthogneiss, mafic gneisses and schists, minor calcsilicates and metapelitic gneisses (Tingey 1991, Thost *et al.* 1998). A physical degradation in glacial regimes, such as grain size reduction, preserves the chemical and structural properties of the low-ordered biotitic illites that are then supplied to the ocean (Petschick *et al.* 1996).

Sediment samples from Burton basin (Fig. 2) show high contents of kaolinite and smectite, which is remarkable in the study area. Source rocks in the investigation area contain high amounts of feldspar and are therefore suitable to form kaolinite. However, kaolinite cannot be produced under modern weathering conditions. Thus ancient sediments have to be taken into consideration. The only local sedimentary remnants of formerly widespread deposits in the Prydz Bay hinterland are exposed in the area of the Prince Charles Mountains (Fig. 3), where two sedimentary units can be distinguished:

i) Permo–Triassic continental deposits of the Amery Group (red beds, Figs 1 & 3) containing feldspathic sandstones with a kaolinitic matrix (Tingey 1991, Webb & Fielding 1993). This kaolinite is probably a product of early diagenesis (Ehrmann *et al.* 2003). The Permo–Triassic deposits are of fluviatile origin and crop out at Beaver Lake (Fig. 1). The material was probably derived from a rapidly uplifted block of Upper Proterozoic and Archean gneisses (Turner 1991).

ii) Glaciomarine sediments of the Pagodroma Group (Fig. 1), cropping out in the regions of Fisher Massif and Amery Oasis (Hambrey & McKelvey 2000, Whitehead *et al.* 2006). In the latter area the Bardin Bluffs formation is characterized by high kaolinite concentrations of 46–64%. Bardin Bluffs formation constitutes re-worked material from underlying Amery Group strata (Ehrmann *et al.* 2003).

Mineralogical results obtained from the site within Burton basin bear a strong resemblance to results from Bardin Bluffs formation, Battye Glacier formation (Ehrmann *et al.* 2003), Beaver and Radok lakes (Fig. 1; Hultzsch *et al.* 2008) and Permo–Triassic samples (Turner 1991) respectively. Similarities comprise very high kaolinite contents together with enrichment in K-feldspar compared to plagioclase and only very small amounts of amphibole. Medium 5/10 Å values point to a mixture of illites of biotitic and muscovitic composition. Because other source rocks or sediment deposits with analogous mineralogical fingerprints are not known, both Permo–Triassic sedimentary rocks as well as their re-worked analogues are the most likely sources for the provenance of material deposited in Burton basin.

The origin of high amounts of smectite in the diamict of the Burton basin, however, is difficult to explain with an exclusive origin from the mentioned formations. Marine authigenic formation of smectite is generally possible, but hard to assess, because the degree of authigenic smectite formation is subject to the age of the material. Rather, a detrital origin from possible occurrences of volcanic material identified on the continental slope off Cape Darnley (Fig. 1) as revealed by seismic investigations of Stagg (1985) seems possible. The underlying seismic reflectors decrease landward in depth making it possible that volcanic material could be accumulated in shallow depths near Burton basin.

On the continental shelf, the amount of smectite is generally higher in the pre-Holocene deposits compared to modern sediments. The fact that the shelf areas were glaciated to a wide extent during the last glacial stage (Domack *et al.* 1998, Harris & O'Brien 1998) suggests that the smectite preferentially was derived or re-deposited from direct glacial input rather than by dispersal by ocean currents. Apparently there are no sediments known from the Prydz Bay hinterland that bear such high concentrations of smectite with exception of lacustrine sediments deposited in Lake Terrasovoe, Amery Oasis (Fig. 1). Smectite in these deposits holds values between 3 and 69% (Hultzsch *et al.* 2008). According to Hultzsch *et al.* (2008) and other authors (Ehrmann *et al.* 1992, 2003) smectite could have formed by chemical weathering of mafic rocks (e.g. mafic dykes, volcanics or mafic gneisses). Because only a minor number of outcrops of basaltic rocks is known from the Lambert Glacier area, a wider distribution of hidden subglacial mafic rocks must be taken into consideration.

The question arises whether material was transported from the Amery Oasis to Burton basin. By examination of Lambert Glacier ice flow rates and directions (http://earthobservatory.nasa.gov/IOTD/view.php?id=1199, accessed 13 August 2010) and ice drift paths in the Prydz Bay area (Schmitt *et al.* 2004) it becomes obvious that transport of material derived from Amery Oasis by Lambert Glacier to the Burton basin is nearly impossible. Firstly, Beaver Lake is characterized by glacier inflow from Nemesis and Charybdis glaciers (Fig. 1) avoiding a discharge of sediment-laden ice to the main axis of Lambert Glacier. Apart from that, icebergs calving from the Amery Ice Shelf leave Prydz Bay north of Cape Darnley, which forms a natural barrier for direct iceberg drift and IRD release to the Burton basin.

The consolidated character of the pre-Holocene sample from Burton basin points to direct subglacial release of sediment load from grounded ice probably arriving from Mac. Robertson Land. This glacial source would suggest undiscovered kaolinite sources on Mac. Robertson Land. However, it is also possible that consolidated material in the Burton basin represents a natural outcrop of pre-glacial sediments of Cenozoic age exposed by glacial incision. Similar material, underlying glaciomarine sediments of Pliocene to Pleistocene ages, was recovered in eastern Prydz Bay during ODP Legs 119 and 188 (Turner 1991, Cooper & O'Brien 2004). It was also identified on the eastern continental slope off Prydz Bay (Kemp 1972) and in western Prydz Bay according to seismic interpretation (Stagg 1985, O'Brien 1994) and sedimentological information (Domack *et al*. 1998). Additional evidence comes from Nielsen basin and Iceberg alley (unofficial name) located on Mac. Robertson shelf west of Burton basin (Fig. 2). Sediments there contain palynomorphs of early and middle Jurassic, early Cretaceous and middle Eocene age (Harris & O'Brien 1998, Truswell *et al*. 1999). The basins also bear microfossils of definite late Paleocene to Oligocene ages (Quilty *et al*. 1999). However, the exact composition and provenance of the sediment underlying Mac. Robertson shelf is poorly known (Truswell *et al*. 1999) and needs further investigation.

In conclusion, pre-Holocene material recovered from Burton basin has its source in ancient sediments equivalent to the Permo–Triassic sediments of the Amery Group or their re-worked Cenozoic correspondents, possibly hinting at pre-Pliocene sedimentation patterns in the Prydz Bay-Mac. Robertson Land region. In contrast, glacial material recovered in Svenner Channel is probably related to mechanical weathering of rocks cropping out in the direct vicinity of the site.

Continental shelf province - modern sediments

Clay mineral assemblages of modern sediments show more uniform distributions. The samples from Prydz Bay are in particularly good agreement, hinting at a mixing of material by the Antarctic coastal current and Prydz Gyre which certainly strengthened during the Holocene due to decreased ice cover and raised sea level. The Antarctic coastal current also influences the Burton basin, as indicated by lower concentrations of kaolinite and increased illite content compared to the pre-Holocene sample. Nevertheless, the atypically high amounts of kaolinite and smectite provide evidence for either active reworking of pre-Holocene material or ongoing input of sediment from a local source.

The relatively low concentrations of smectite in modern shelf sediments not only indicate a reduced supply of glacial sedimentary input, but could also be explained by size-sorting effects. This would have led to washout of smectites and transport to more distal sites where current velocities are sufficiently low to allow deposition of very fine material (Grobe & Mackensen 1992). In contrast, sites proximal to the grounding line of the ice sheet and reduced current velocities during the Last Glacial period, preserved the smectites from this washout process.

Continental slope province

Clay mineral assemblages of the continental slope province (Fig. 4) are quite uniform laterally and over a range of water depths. Comparison of mineral contents and illite composition from sites east and west of Prydz Bay suggests that input of sediment material from Prydz Bay is a minor influence on the sedimentation of the slope under modern conditions.

An explanation for this lack of sensitivity can be provided by the westward flowing Antarctic slope current. It represents a very powerful contour current with transport of 45 Sv at the Princess Elizabeth Trough (Fig. 1) at speeds of 30–40 cm s^{-1} (Bindoff *et al*. 2000, McCartney & Donohue 2007). That is much more water than is contributed by input from Prydz Bay.

The mineralogy of sediment samples taken from the ASC sphere of influence therefore represents a homogenized picture of East Antarctic provenance with mixing of material supported by several glaciers along the East Antarctic margin. High illite contents with high biotite composition, which are also documented in surface samples from the continental slopes off Terre Adélie and Wilkes Land (Damiani *et al*. 2006), the Lambert Graben area (this paper) to Gunnerus Ridge, Enderby Land (Fig. 2; Diekmann *et al*. 2003), reflect a general source of clayey material associated with the East Antarctic shield. The latter comprises predominantly Proterozoic high-grade metamorphic rocks and granitoids including charnockites (Tingey 1991). Relatively low but constant kaolinite concentrations provide evidence for subordinate but widespread occurrences of ancient kaolinite-bearing sediments in the East Antarctic region. The material is glacially eroded, mechanically weathered and contributed to the ASC by subglacial deposition on the shelves followed by current reworking or by turbidity currents mostly initiated by ice sheet dynamics (Kuvaas & Leitchenkov 1992).

Clay mineral assemblages similar to those of the continental shelf province were also determined by Petschick *et al.* (1996) in surface sediments taken on or proximal to the continental shelf west of the investigation area. It is therefore feasible to connect the continental shelf province with the southern part of the East Antarctic province of Petschick *et al.* (1996).

Kerguelen Plateau province

Clay mineral assemblages from Kerguelen Plateau province (Fig. 4) show moderate to very high concentrations of well-crystallized smectite. Increasing trends of smectite content correlate with shallower water depths and the proximity to volcanic areas, respectively. Similar smectite patterns were observed from volcanic areas in the Atlantic region, e.g. west of the Antarctic Peninsula and its offshore islands, in the area around the South Sandwich Islands and at the South-west

Indian Ridge (Petschick *et al.* 1996). Smectite contents even rise to 90% in the vicinity of young volcanoes such as Deception or Bouvet islands similar to that documented in the investigation area at site PS69/912, northern Kerguelen Plateau. The latter site is close to Iles Kerguelen, which comprises a suite of primarily tholeiithic basalts with subordinate trachyte and Quaternary pyroclastic deposits (Parra *et al.* 1991). Local volcanogenic sedimentation of smectites from Kerguelen Plateau seems very likely. A local source of the clayey material is also suggested by the exceptionally high ratios of K-feldspar/plagioclase, pyroxene/quartz and amphibole/quartz. Whereas amphibole, pyroxene and plagioclase are important constituents of basaltic rocks, K-feldspar is commonly found in felsic extrusive or plutonic rocks, e.g. in trachytes or syenites that crop out on the Rallier du Baty peninsula in the south-western part of Kerguelen (Parra *et al.* 1991). Illites are also very abundant and 5/10 Å values exceed 0.5 typical for Al-rich composition. Low integral widths reflect very good to good crystallinities favouring a detrital source of the illites with only minor structural and/or chemical degradation. According to the ten main clay mineral provinces proposed by Petschick *et al.* (1996), material deposited on Kerguelen Plateau is most probably derived from the circum-Antarctic province. The transport of this material is tentatively assigned to CDW, which represents the dominant water mass of the ACC in the relevant water depths above 2300 m (Orsi *et al.* 1995). According to Petschick *et al.* (1996) illites (together with chlorite) transported by CDW are derived from low-grade metamorphic rocks mainly found in the Andean chain on the Pacific side of the Antarctic Peninsula and southernmost South America (Patagonia).

According to the different provenances of smectites and illites in surface samples recovered from Kerguelen archipelago, their relationships are suggested to illustrate the dominance of either CDW influence or volcanogenetic influence. To the south a very sharp boundary, associated with changes in the dominant water mass, separates the Kerguelen Plateau province from the deep sea province.

Deep sea province

Much work on clay mineral distributions has been done on modern sediments from the deep sea of the east Atlantic and south Indian sector of the Southern Ocean (Moriarty 1977, Petschick *et al.* 1996). In contrast, little information is available for the Southern Ocean between 45° and 100°E. Unfortunately, surface sediment samples obtained for this study could only be retrieved from the region between 65° and 85°E. The deep sea province (Fig. 4) includes information from sites PS69/820, 847, 885 and 899.

Sites PS69/847, 885 in particular and subordinary site 899, bear strong similarities in terms of illite and smectite contents and illite crystallinity. These parameters can be clearly distinguished from those of close-by samples from the Kerguelen Plateau province. The fine-scale spatial separation between sites 847/885 and 899 is probably related to channelized flows of AABW which derive from two main sources (McCartney & Donohue 2007): i) AABW from the Weddell–Enderby basin passes Princess Elizabeth Trough at the southern tip of the Kerguelen Plateau (sites 847 and 885, Fig. 4) and turns northward at about 85°E (Donohue *et al.* 1999). It merges south of site PS69/899 with, ii) water from the continental slope adjacent to the Australian Antarctic Basin, which originate in the Ross Sea and along the Adélie Coast (Donohue *et al.* 1999, Bindoff *et al.* 2000) to form the western boundary current (Fig. 4).

The mineralogical composition of samples from sites PS69/847 and 885, which shows low smectite content, medium 5/10 Å ratios and moderate illite crystallinities (Fig. 2), most resembles to the composition of samples taken from Prydz Bay compared to that of samples taken on a transect from Gunnerus Ridge to Lena Tablemount (Fig. 2; Diekmann *et al.* 2003). This finding indicates, that material supported to the deep sea province at sites PS69/847 and 885 probably derived from the adjacent Antarctica continental margin. Increased input of material from the Antarctic continent is also suggested by generally high contents of terrigenous material (Goodell 1973). Most likely, fine-grained material from Prydz Bay is transported to the sites by dense water, which originates on the shelf (Vaz & Lennon 1996, Tamura *et al.* 2008) and is spilled over the shelf break (Smith *et al.* 1984, Yabuki *et al.* 2006). The dense water mass proceeds to the north-west triggered by the Antarctic slope current and when it enters the latitude of CDW dominance, it is looped to the east by the strong band of the ACC (Fig. 4) where it underlies and mixes with CDW and passes the northern Princess Elizabeth Trough as a boundary current (McCartney & Donohue 2007). The suggestion of Donohue *et al.* (1999) that water masses entering into the deep western boundary current could be sourced from the Weddell Gyre could neither be supported nor negated by this mineralogical study.

Differences in the illite chemistry and kaolinite/chlorite ratio of sample PS69/899 compared to the clay mineral assemblages of sites PS69/847 and PS69/885 hint to mixing with material from another source. In particular, the low 5/10 Å ratio is hard to explain as solely derived from the boundary current south of the Kerguelen Plateau, because of the eastward increasing 5/10 Å trend. In addition, re-deposition of material from Kerguelen Plateau can be excluded, because material obtained from there is clearly of muscovitic composition.

It seems more consistent with the evidence, that biotite-like illites are directly derived from a branch of the Antarctic slope current that bifurcates in the south-western Australian Antarctic Basin (Donohue *et al.* 1999) and contributes to the western boundary current. Although no modern clay mineral data are available from the continental slope off Wilhelm II Land and Queen Mary Land to test this assumption, the following data hint at similar illite compositions as obtained from the continental slope off Prydz Bay:

i) illite chemical compositions and crystallinities of surface samples recovered from the continental slopes off Terre Adélie (Damiani *et al.* 2006), Prydz Bay (this paper) and Gunnerus Ridge (Diekmann *et al.* 2003) spanning about 110° of longitude are very similar and reflect the homogenization of material by the Antarctic slope current.

ii) The geology of the hinterland along these areas (Tingey 1991) is assumed relatively uniform with little input of material that might alter the clay mineral signature along the Antarctic slope current path (see continental slope province section).

Consequently, the clay mineral assemblage of site PS69/899 provides a sedimentological clue to the oceanographic circulation pattern in the southern Kerguelen region summarized by McCartney & Donohue (2007).

Other important oceanographic features in the investigation area are the southern ACC Front (SACCF) and the southern boundary of the ACC (SB). The latter roughly follows the Antarctic Divergence (Fig. 1). The influence of the SACCF and SB is possibly responsible for the differences in clay mineral assemblages obtained from sites PS69/847 and PS69/820. The fine fraction of the latter site is enriched in smectite and chlorite. Illites comprise a more muscovitic composition. In conjunction with results obtained from the CDW-dominated site PS2603 (Diekmann *et al.* 2003), it therefore seems very likely, that clayey material deposited at site PS69/820 is of overall CDW provenance. The decreasing trend of smectite content to the east is attributed to subordinate contribution of illites with AABW from Prydz Bay or adjacent areas. Following these mineralogical indications and observations by Park *et al.* (2009), the sharp boundary between CDW-dominated flow at site PS69/820 and AABW dominated flow at site PS69/847 (see above) could be attributed to the deep prolongation of the SACCF or the southern boundary of the ACC. However, the position of both the SACCF and southern boundary of the ACC is still under debate (e.g. Orsi *et al.* 1995, Park *et al.* 2009).

Heavy minerals

Heavy minerals are a valuable tool for determining the provenance of ice-rafted or fluvial-derived material, because they are more resistant to destruction by transport or chemical weathering than their lighter counterparts (e.g. Diekmann & Kuhn 1999).

The heavy mineral assemblages in the study area are very similar to each other, apart from the sample recovered from site PS69/849. Green hornblende comprises the dominant species, and shows highest abundance in the pre-Holocene sample from central Prydz Bay (Fig. 3, Table I). Green hornblendes are ubiquitous components of many intrusive and metamorphic rocks. In conjunction with observation of high amounts (commonly 15–40%) of translucent to reddish garnets, this reflects the preponderance of high-grade metamorphic rocks in the Lambert Glacier drainage area. In particular, erosion of amphibolite-facies and granulite-facies rocks exposed in the northern Prince Charles Mountains (Fig. 3) leads to enrichments in hornblende in the heavy mineral assemblages. The predominance and survival of chemically unstable hornblende is additionally attributed to its very good preservation because of the polar arid conditions during rock breakdown and thus restricted chemical weathering.

The overall East Antarctic signal, however, is modified in places by material supplied from local sources. In eastern Prydz Bay, for example, sedimentary material was probably derived from Vestfold Hills (Fig. 3). The latter mostly consist of Archean granulite facies gneisses intersected by mafic dyke swarms (Tingey 1991). Intermediate metavolcanic rocks and metagabbros, in connection with Mossel gneiss and layered paragneisses of the Chelnok supracrustal assemblage, which mostly consist of garnet, biotite, orthopyroxene, quartz and feldspar (Tingey 1991), obviously account for about 15% higher orthopyroxene and garnet contents in pre-Holocene sediments from Svenner Channel compared to central Prydz Bay (Fig. 3). According to Stone *et al.* (1993), cosmogenic exposure ages of Vestfold Hills suggest that Last Glacial ice advances where peripheral to the oases. As a result, the inner part of Vestfold Hills has not been glaciated since before the late Pleistocene. Any later glacial influence was due to expansion of the Sørsdal Glacier (Fig. 3), which will have made it probable that rock types found in Vestfold Hills extend into the Sørsdal drainage basin and may thus account for the mineralogical composition of late Quaternary material deposited in the Svenner Channel. In connection with moderate smectite contents attributed to derivation from mafic source rocks (as indicated by the interpretation of clay minerals), a grain-size-independent transport mechanism suggesting movement by ice is most plausible.

In Burton basin it seems probable that the composition of source rocks has overprinted the widely present East Antarctic heavy mineral signature. The main constituent of the heavy mineral assemblages here is garnet, which is characterized by high resistance in terms of chemical and mechanical weathering. Its extreme enrichment to about 80% clearly indicates repeated recycling of sediments, which originated from the breakdown of primary metamorphic rocks in the Lambert Graben drainage area. Sediments of the Beacon Supergroup, for example, contain garnet as a major constituent of the heavy mineral fraction (Diekmann & Kuhn 1999) and may be the major and parent source of sediments in the Burton basin. Following the interpretation of clay minerals in this paper and results from palynomorphs provided by Truswell *et al.* (1999)

and Quilty *et al.* (1999), the underlying sediments of Mac. Robertson shelf could be of Eocene age. According to Truswell *et al.* (1999) deposition of material close to the outcrop of the source sediments is most probable. By comparing the pre-Holocene with the modern heavy mineral assemblage from Burton basin, no major differences can be recognized. This situation could be ascribed to a stable source region, as well as similar transport mechanisms during pre-Holocene and modern times. In any case, input of material derived from Prydz Bay or other source regions is of negligible importance. This can be discounted, because sea ice and icebergs calving in Prydz Bay are observed to make their way to the west, north of the continental shelf break (Schmitt *et al.* 2004), as indicated by generally increased hornblende contents in sediments from the continental slope off Mac. Robertson Land. This observation could, to a certain extent, also explain the northward trend of increased hornblende content at the expense of garnet with water depth.

Although heavy minerals are a valuable tool for determining the provenance of ice-rafted debris along the Antarctic margin (Diekmann & Kuhn 1999), in the study area other sedimentary processes may also influence the dispersal of sand-sized heavy minerals. It must be considered, that the dominant transport media for sand-sized material deposited on the continental slope are sediment gravity flows, especially turbidity currents (Kuvaas & Leitchenkov 1992). Within these density flows sorting of material takes place according to the hydraulic characteristics of the grains. By comparing the density and shape of garnet and hornblende, conclusions can be drawn about the transport width of these minerals in liquefied sediment flows. Garnet shows higher density ($\rho = 3.5–4.3\ \mathrm{g\,cm^{-3}}$) and rounded shape whereas hornblendec is characterized by platy habit and has densities of $3.0–3.4\ \mathrm{g\,cm^{-3}}$. According to these physical properties, hornblende is indicated to have a greater transport range than garnet, which is likely to lead to it accumulating in the lower part of the continental slope.

In the region of Kerguelen Plateau, most of the sandy material is suggested to have been derived from Prydz Bay by iceberg drift (Schmitt *et al.* 2004). Heavy mineral assemblages resemble those of site PS69/793. Despite these similarities, local input of material should not be disregarded, because the amount of apatite at site PS69/899 exceeds values from all other sites by about 9% (Table III). Apatite may have been derived from biotite-hornblende pyroxenites that represent constituents of Kerguelen volcanic rocks (Parra *et al.* 1991). Additional evidence for volcanic composition of the source material is given by slightly elevated zircon and rutile values, although apatite, zircon and rutile are also common constituents of calc–alkaline rocks such as granodiorite. Calc–alkaline rocks, however, are not found on Iles Kerguelen.

In summary, heavy mineral assemblages in the Prydz Bay–Kerguelen region generally reflect an East Antarctic provenance of the material. Specific divergences from the overall East Antarctic signature were only detected in samples proximal to areas where source rocks with completely different primary composition crop out.

Conclusions and outlook

Clay minerals and heavy mineral assemblages in modern sea-bottom surface sediments in the area between Prydz Bay and the Kerguelen Plateau trace the sedimentary sources and transport routes of glacigenic detritus delivered to the ocean.

Clay mineral assemblages

Clay mineral assemblages in the study area generally reflect an Antarctic source. In pre-Holocene deposits of the continental shelf, contrasting clay mineral assemblages mirror glacial input or alluvial input from local sources, respectively. During modern times, in contrast, clay minerals in the Prydz Bay region have been transported by ocean currents and were used to characterize four provinces, which reflect different transport and depositional regimes. Local clay mineral signatures around the Antarctic, influenced by source rock composition, have been homogenized by the Antarctic slope current. Beyond the continental slope, the Antarctic clay mineral signature reaches northward into the region of the Kerguelen Plateau, where it becomes modified by the Antarctic Circumpolar Current and local input of volcanic material.

Heavy mineral assemblages

Heavy mineral assemblages in the Prydz Bay–Kerguelen region are exclusively delivered from the East Antarctic shield. On the continental shelf it is possible to distinguish between different local sources of the ice-rafted material. Heavy mineral grains of the fine sand fraction are mainly transported by glaciers as basal debris and then supplied to the ocean by drifting icebergs. In some regions such as the continental slope, however, heavy mineral transport and re-deposition by debris flows or turbidity currents cannot be excluded. In these cases, sorting of heavy minerals according to their hydrodynamic properties must be taken into account.

Application of clay minerals and heavy minerals for further palaeoenvironmental reconstructions

For the investigation of late Quaternary East Antarctic Ice Sheet dynamics and connected ocean-atmosphere processes, clay minerals and heavy minerals are appropriate tools, although with some limitations.

The use of heavy mineral assemblages for investigations of the provenance of ice-transported material is only suggested for sediments from the continental shelf. In this area, heavy mineral distributions appear to match the primary mineralogy of source rocks. In areas distal to the source region, greater challenges in provenance analysis are anticipated. The material of various source rocks is mixed on its way to final deposition by sediment reworking processes leading to homogenization of heavy mineral assemblages. It is thus difficult to clearly differentiate between primary signatures north of the continental shelf.

In the region influenced by the Antarctic slope current, the uniform clay mineral signature of sediments provides an opportunity to track back past changes in the local input of material to the continental slopes. Alternations between contour current activity and turbidity current events can be documented, assuming turbidites with a distinct mineralogical composition. Therefore, future investigations of late Quaternary East Antarctic Ice Sheet dynamics and bottom water changes in particular should focus on the area west of Prydz Bay off Mac. Robertson Land, where clay mineral and heavy mineral assemblages of the continental shelf show significant differences to those from the continental slope. The documentation of turbidity events there could provide information about the timing of advancing ice sheets that bulldoze material over the shelf edge or on turbidity events triggered by dense water pulses.

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