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Lithofacies distribution in relation to the geomorphic provinces of Prydz Bay, East Antarctica

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Abstract: Over the past 15 years, Japanese, Australian and Russian expeditions to Prydz Bay have collected about 30 000 km of bathymetric data, 6000 km of sidescan sonar data and more than 250 sediment grab and core samples. These data were used in the present study to compile surficial sediment, bathymetric, and geomorphological maps of the Prydz Bay region. Lithofacies distribution was determined by surficial sediment data analysis using sample matrix (Q-mode) and cluster analysis techniques based on data from 206 sites. Data included percentage biogenic silica (opal), calcium carbonate, gravel, mud, and relative abundance of two diatom species (*Fragilariopsis curta* and *F. kerguelensis*). Five lithofacies are identified from the available data: (1) slightly gravelly sandy mud (g)sM lithofacies, (2) siliceous mud and diatom ooze (SMO) lithofacies, (3) *F. kerguelensis* pelagic ooze lithofacies, (4) *F. curta* gravelly muddy sand gmS lithofacies and (5) calcareous gravel lithofacies. In many areas the lithofacies correlate to geomorphological provinces as defined by previous investigators using 3.5 kHz and sidescan sonar data. In some cases, Holocene SMO sediments are seen to drape over iceberg plough marks, implying that these are relict features. These five lithofacies are likely to dominate most of the East Antarctic shelf region and may be helpful in defining sedimentary successions resulting from ice-sheet advance and retreat over glacial-interglacial cycles.

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Introduction

The Prydz Bay region has featured in several recent debates surrounding the glacial history of East Antarctica. Drilling in Prydz Bay by the Ocean Drilling Program (ODP) in 1989 was primarily concerned with determining the timing of the onset of glacial conditions in East Antarctica (Hambrey *et al.* 1989) and documenting the regional glacial history of sedimentation (Hambrey *et al.* 1994). Discoveries of fossil diatoms, terrestrial plants and species of extinct macrofauna near Davis station (Fig. 1) have been interpreted as indicating much warmer conditions in the middle Pliocene when the East Antarctic Ice sheet may have retreated substantially (Webb *et al.* 1984, Webb 1990, Quilty 1996). If such a warm phase occurred it should have left a signal in the offshore marine sediment record. Stagg (1985), Cooper *et al.* (1992) and O'Brien *et al.* (1995) described prograding sequences deposited on the continental margin during the late Cenozoic that contain a record of glacial history. Information on other events of interest to climate modellers has been reported from Prydz Bay marine deposits; these include evidence for increased sediment yield from East Antarctica associated with the Holocene hypsithermal warm phase that occurred about 9000 to 11 000 yr BP (Ciais *et al.* 1992) reported by Domack *et al.* (1991), the extent of the ice sheet covering the continental shelf during the last glaciation and the timing of its retreat after 18 000 yr BP (Leitchenkov *et al.* 1994, Pushina *et al.* 1997, Harris *et al.* 1996).

In this paper, we present a synthesis of available surficial sediment data from Prydz Bay. Our aim is to produce a general facies model for interpretation of depositional environments and down-core facies successions which are required for palaeoenvironmental studies and the assessment of the spatial and temporal natural variability of Antarctic sedimentary systems.

Geomorphology and sedimentology of the Prydz Bay region

Prydz Bay, though smaller than the Ross Sea and Weddell Sea, is the largest shelf sea on the East Antarctic margin (Fig. 1). The bay receives sediment-laden ice from the Lambert Glacier system, which drains 14% of the grounded ice area of East Antarctica (A. Ruddell, personal communication 1998). Sediments deposited along the axis of the glacier have prograded offshore to form the Prydz Submarine Fan (Fig. 2), a major sediment depocentre that is 140 km wide and extends at least 90 km out to sea (O'Brien & Harris 1995). Previous glacial processes operating on the Prydz Bay seafloor have produced morainal banks and drumlin

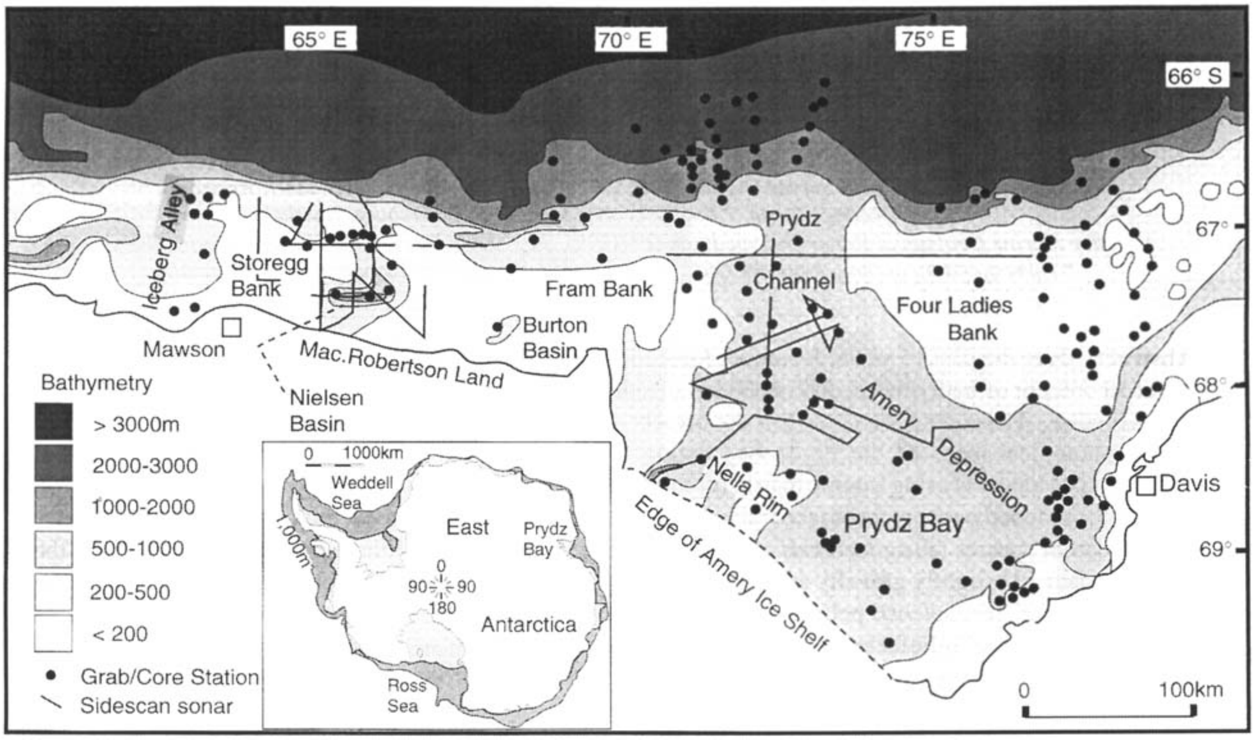

Fig. 1. Bathymetry, station locations and sidescan sonar survey tracks for the Prydz Bay to Mac. Robertson Shelf region. Geographic locations cited in the text are indicated.

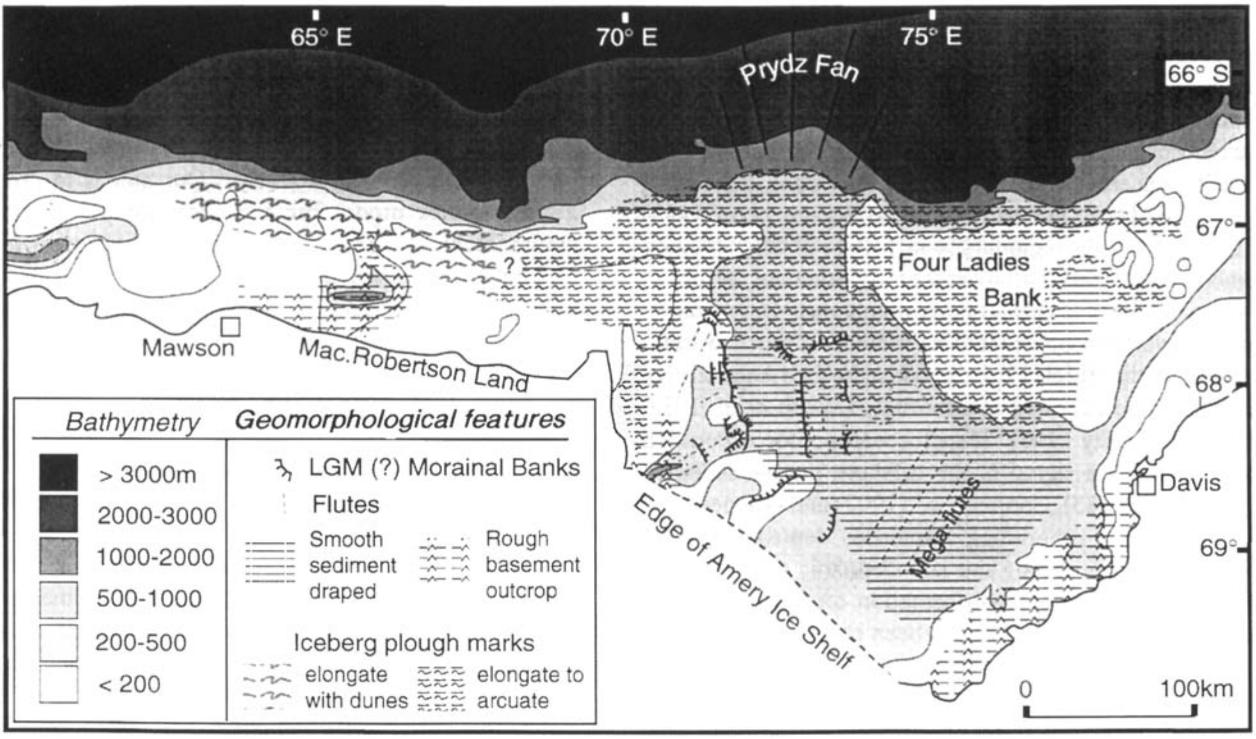

Fig. 2. Summary of geomorphological features and their approximate distribution in Prydz Bay based on 3.5 kHz echo sounding and sidescan sonar data compiled from Harris & O'Brien (1996, 1997), O'Brien (1994), O'Brien & Harris (1996) and O'Brien *et al.* (1997).

features, flutes, and large scale crag and tail features (terminology of Hambrey 1994, p. 104) with large areas of incised bedrock (Fig. 2). Some extensive ridge and swale features (megaflutes) of inner Prydz Bay are up to 10 m high, 2 km across and tens of kilometres long (O'Brien 1994). Sediments are thickest over the outer shelf banks (Fram and Four Ladies banks) and are thin or absent over much of the inner shelf, particularly in south-eastern Prydz Bay (Stagg 1985). Erosional features are most common on this inner section of Prydz Bay, which has been inferred to be a zone of net erosion by O'Brien & Harris (1996). Similarly, the inner and middle portions of the Mac. Robertson shelf have been interpreted as having formed largely through glacial erosion processes (Harris & O'Brien 1996; Fig. 2).

Iceberg plough marks have been studied using 3.5 kHz echo sounding (O'Brien 1994, O'Brien *et al.* 1997) and sidescan sonar data (Harris & O'Brien 1996). These data show that plough marks are common along the outer shelf, particularly over Storegg, Fram and Four Ladies banks. They are elongate to arcuate in plan view and are acoustically opaque to 3.5 kHz echo sounder profiling. Strong bottom currents over the western Fram Bank and Storegg Bank areas have generated large scale, 3-D dunes (terminology of Ashley *et al.* 1990) which are associated with coarse sand and gravel deposits (Harris & O'Brien 1996).

Quilty (1985) mapped the distribution of foraminifers in Prydz Bay bottom sediments using 37 samples and described a calcareous association located over Fram Bank and the Mac.Robertson shelf in the west, and an agglutinated association occurring in central and eastern Prydz Bay. Oceanographic processes, rather than water depth or depth of the CCD, were considered by Quilty (1985) to control the distribution of these associations. Sediments on the outer shelf banks include mainly coarse terrigenous and biogenic components, whereas most sediments recovered from the inner shelf are fine-grained mud and biosiliceous ooze. Areas of dominantly terrigenous sand occur in the Prydz Channel (Quilty 1985).

The distribution of diatoms in 97 surficial sediment samples from Prydz Bay was studied by Taylor *et al.* (1997), who employed statistical techniques to identify four diatom assemblages:

1) a coastal assemblage, located mainly in the south-eastern section of Prydz Bay and characterized by sea-ice diatoms, notably *Fragilariopsis curta*,

2) a continental shelf assemblage located over the inner and middle Prydz Bay and Mac. Robertson shelves and characterized by sea-ice and ice-edge diatoms,

3) an oceanic assemblage located over Four Ladies Bank and the outer shelf to upper slope, characterized by open-water diatoms, notably *Fragilariopsis kerguelensis*, and

4) a Cape Darnley assemblage located over Fram Bank and characterized by heavily silicified sea-ice and open-water diatoms.

The distribution of the assemblages was attributed by Taylor *et al.* (1997) mainly to sea ice conditions (coastal, shelf and oceanic assemblages) and ocean currents which have winnowed the surficial sediments on Fram Bank of fine-grain sizes, leaving a coarse lag deposit (the Cape Darnley assemblage).

Methods

Sediment samples

Over the past 15 years, Australian and Russian expeditions to Prydz Bay have collected more than 250 grab samples and cores. Sediment samples were obtained using various equipment, including Van Veen grabs, Shipek grabs and gravity cores. Grabs generally collect a homogenized sample from the top 10–20 cm of the sediment, and gravity cores are considered to collect a sample which also includes sediments from this interval (top 10–20 cm) if not capturing the sediment/water interface. In the laboratory, 10–50 g sediment sub-samples were wet-sieved to determine percentage gravel (>2 mm), sand (<2 mm, >63 mm) and mud (<63mm) by dry weight, with larger sample volumes used in the case of poorly sorted sediments. Separate sub-samples were analysed at the Australian Antarctic CRC for biogenic opal content using the method outlined by Mortlock & Froelich (1989). Calcium carbonate content was determined by the vacuum-gasometric technique, using a device constructed at the Antarctic CRC according to the plan of Jones & Kaiteris (1983).

Diatoms

Diatoms were prepared following the procedure outlined in Taylor *et al.* (1997) by sub-sampling approximately 0.5 g of sediment from core tops and grab samples, and immersed for three days in 10 ml of 15% H_2O_2 to remove organic matter. They were then centrifuged three times at 2500 revs per minute for 5 min; between each centrifuging, samples were washed in distilled water. Washed samples were diluted (about 1–3 drops per 10 ml distilled water), pipetted onto a glass cover-slip and allowed to dry on a warm hotplate (50°C). Permanent slides were mounted in Norland Optical Adhesive 61 (refractive index 1.56) and cured under ultraviolet light.

Diatoms were identified and counted using a phase contrast Zeiss Standard 20 microscope at 1000x magnification, with an oil immersion objective lens. Each slide was traversed horizontally until 600 valves had been counted. Only cells in which more than half of the valve was visible were counted. For elongate genera, such as *Trichotoxon* and *Thalassiothrix*, only end pieces were counted as these valves are rarely preserved intact. Species abundance is expressed as a percentage for statistical analysis.

Two diatom species were chosen as indicators of the sedimentary environment: *Fragilariopsis curta* and *F. kerguelensis*. *Fragilariopsis curta* is dominant in pack and fast ice communities of Antarctica (Stockwell *et al.* 1991, Scott *et al.* 1994). In surficial sediments of Prydz Bay, it is characteristic of coastal depositional environments where sea ice is present throughout the summer (Taylor *et al.* 1997). The abundance of *F. kerguelensis* has been negatively correlated with sea-ice concentration (Burckle *et al.* 1987). It is typically considered to be an open-water indicator species, dominating summer surface waters between 52–63°S (Burckle & Cirilli 1987, Burckle *et al.* 1987) where temperatures are >0°C (Krebs *et al.* 1987).

Statistical analysis

A variable by sample matrix (Q-mode) was analysed using the cluster analysis option of BioStat II (commercial software) to determine lithofacies distributions in Prydz Bay. Cluster analysis is a multivariate statistical technique aimed at summarizing a large data set by forcing sample sites into discrete groups of clusters, even if the data points are randomly distributed (Shi 1995). The outcome of cluster analysis is a two-dimensional dendrogram, which in this study was used to define cluster groups that are interpreted as lithofacies.

Cluster analysis was carried out using the Bray-Curtis dissimilarity index in association with unweighted pair group average linkage (UPGMA). The Bray-Curtis dissimilarity index is able to analyse matrices with a high zero component (i.e. joint absences; Field *et al.* 1982). UPGMA joins two samples together at the average level of similarity between all members of one group and all members of the other (Field *et al.* 1982).

Lithofacies identified by cluster analysis were further analysed to determine indicator variables. The student Newman-Keuls multiple range test (SNK) in association with a single factor Analysis of Variance (ANOVA) enables those variables which are in significantly higher abundance to be distinguished among cluster groups. SNK calculates the "studentized range" (q) that is based on the pair-wise differences between ranked means of increasing magnitude divided by the standard error (Zar 1984):

$$q = (XB - XA) / SE$$

If q is equal to or greater than the critical value, a,v,k, (where a = significance level, v = error df for the analysis of variance, k = total number of means being tested) then the paired means are significantly different and the indicator is identified (Zar 1984).

Results

Surficial sediment data were compiled from 256 sites and included percentage biogenic silica (opal), calcium carbonate, gravel and mud, with *F. curta* and *F. kerguelensis* expressed as percentage of the diatom assemblage. Folk & Ward's (1957) nomenclature, as modified by Moncrieff (1989) was used for textural descriptions. Data on four or more of these variables were available for only 206 of the sites. Maps of each variable were plotted and hand-contoured to compare and contrast spatial distributions (Fig. 3). Bray-Curtis cluster analysis, with a maximum percentage dissimilarity of 54% (Table I), was then used to identify five lithofacies (Fig. 4):

1) slightly gravelly, sandy mud (g)sM lithofacies,
2) siliceous mud and diatom ooze (SMO) lithofacies,
3) *F. kerguelensis* pelagic ooze lithofacies,
4) *F. curta* gravelly muddy sand (mgS) lithofacies; and
5) calcareous gravel lithofacies.

The slightly gravelly, sandy mud (g)sM lithofacies represents the data from 57 sites distributed across the continental shelf of Four Ladies Bank, western Prydz Bay and the Mac. Robertson shelf (Fig. 4). The lithofacies is characterized by a significant abundance (P<0.0005) of mud (mean abundance 46% of the sediment), sand (mean abundance 52%) and the sea ice diatom *F. curta* (P<0.0005; mean abundance 42% of the diatom assemblage).

The siliceous mud and diatom ooze (SMO) lithofacies (82 sites) is the most extensive lithofacies type in Prydz Bay. It is distributed in the deeper areas of the continental shelf: Prydz Channel, the Amery Depression, Nielsen Basin, Burton Basin, and Iceberg Alley. The lithofacies is characterized by a significant abundance (P<0.0005) of biogenic silica (mean abundance 12%) and mud (P<0.0005; mean abundance 84%). *Fragilariopsis curta* is the dominant diatom species, forming almost 50% of the assemblage.

The *F. kerguelensis* pelagic ooze lithofacies (17 sites)

Table I. Mean abundance (%), analysis of variance (F) and SNK multiple range test of dominant variables in a cluster group.

	(g)sM	SMO	*F. kerg.* ooze	*F. curta* gmS	calc. gravel	F	*P*
$CaCO_3$	0.47	0.85	0.09	1.57	8.03	5.07	<0.005
Si	5.38	11.96	4.62	2.85	2.97	13.87	<0.0005
gravel	2.05	0.45	2.34	5.09	63.49	227.10	<0.0005
mud	46.12	83.94	71.35	17.04	6.06	227.12	<0.0005
F. curta	42.04	47.13	15.06	42.89	41.46	32.39	<0.0005
F. kerguelensis	4.40	1.22	35.11	3.33	7.82	141.20	<0.0005

Degrees of Freedom = 4 206. ANOVA *P* values <0.005 and <0.0005 are indicated. Underlined numbers indicate variables with significantly higher abundance in a cluster group. Facies named in columns 1 to 5 are as defined in text: (1) slightly gravelly sandy mud (g)sM facies; (2) siliceous mud and diatom ooze (SMO) facies; (3) *Fragilariopsis kerguelensis* pelagic ooze facies; (4) *Fragilariopsis curta* gravelly muddy sand gmS facies; and (5) calcareous gravel facies.

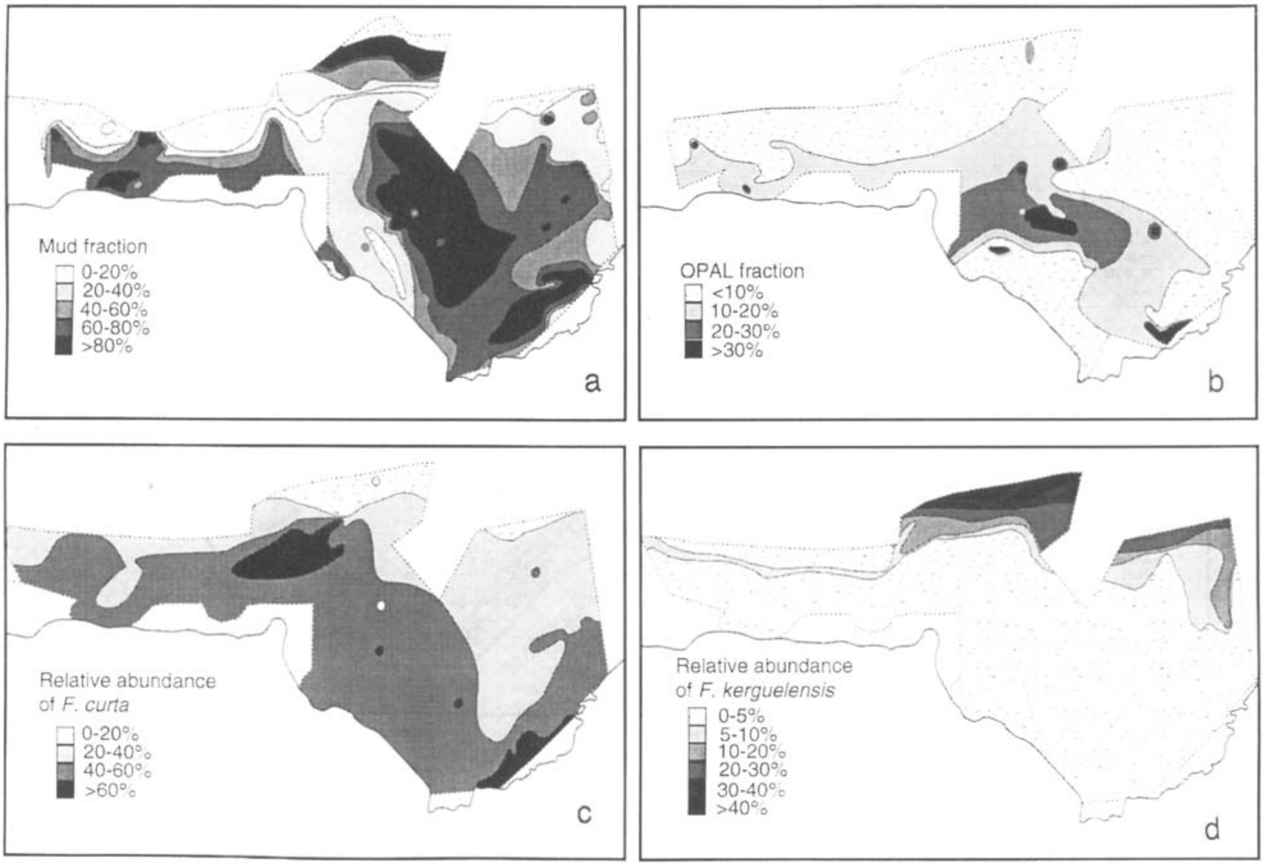

Fig. 3. Hand contoured maps showing the surficial sediment distribution of **a.** mud content (%); **b.** biogenic opal content (%); **c.** abundance of the sea ice diatom *Fragilariopsis curta*; and **d.** abundance of the oceanic diatom *F. kerguelensis*.

occurs offshore of the continental shelf break and includes the Prydz Fan. The planktonic diatom *F. kerguelensis* occurs in significant abundance ($P<0.0005$) (reaching a maximum abundance of 71%). This species is typical of oceanic Antarctic conditions. The mud content averages 71% which is significantly less than in the SMO shelf lithofacies, but greater than in the other lithofacies.

The *F. curta* gmS lithofacies (44 sites) is widely distributed along parts of Fram Bank, Four Ladies Bank, adjacent to the edge of the Amery Ice Shelf and at a few other locations on the inner shelf (Fig. 4). This lithofacies is distinguished by a low abundance of mud (mean 17%) and a relatively high abundance of gravel (mean >5%) and sand (mean 78%), compared with the other lithofacies. The diatom *F. curta* has a mean abundance of 43% of the assemblage and is characteristic of this facies.

The calcareous gravel lithofacies (six sites) occurs on the outer Mac. Robertson shelf and upper slope, and at two isolated sites near the shelf break, adjacent to the top of the Prydz Fan (Fig. 4); they coincide with Quilty's (1985) coarse sediment sites. Calcium carbonate (mean 8%) and gravel (mean 63%) occur in significant abundance and *F. curta* is the dominant diatom species (mean abundance 41%) in this lithofacies.

Discussion

Environmental interpretation of lithofacies

The distribution of facies defined in the present study (Fig. 4) expands upon the earlier work of Quilty (1985) and complements the work of Taylor *et al.* (1997) by introducing percent opal as a variable included in the statistical analysis. Comparing the distribution of lithofacies inferred above (Fig. 4) with the previously described geomorphological zones (Fig. 2) shows several overlapping areas that may indicate spatial variability in sedimentary processes characterizing different environments.

The (g)sM lithofacies coincides with the region of iceberg ploughed seafloor of the outer shelf bank environment. There, the coarse, poorly-sorted sediment is generated by iceberg ploughing, which mixes relict diamict, ice-rafted debris and any Holocene biogenic sediments into an homogenous surface layer. The deposit is characterized in core samples by its massive structure and may or may not have a thin (< 20 cm) overlying SMO layer. The mixing process explains the apparent correlation between low opal values (Fig. 3b) and iceberg ploughing (Fig. 2), because the mixing process dilutes the concentration of opal in surface sediments.

The area covered by the SMO lithofacies appears to

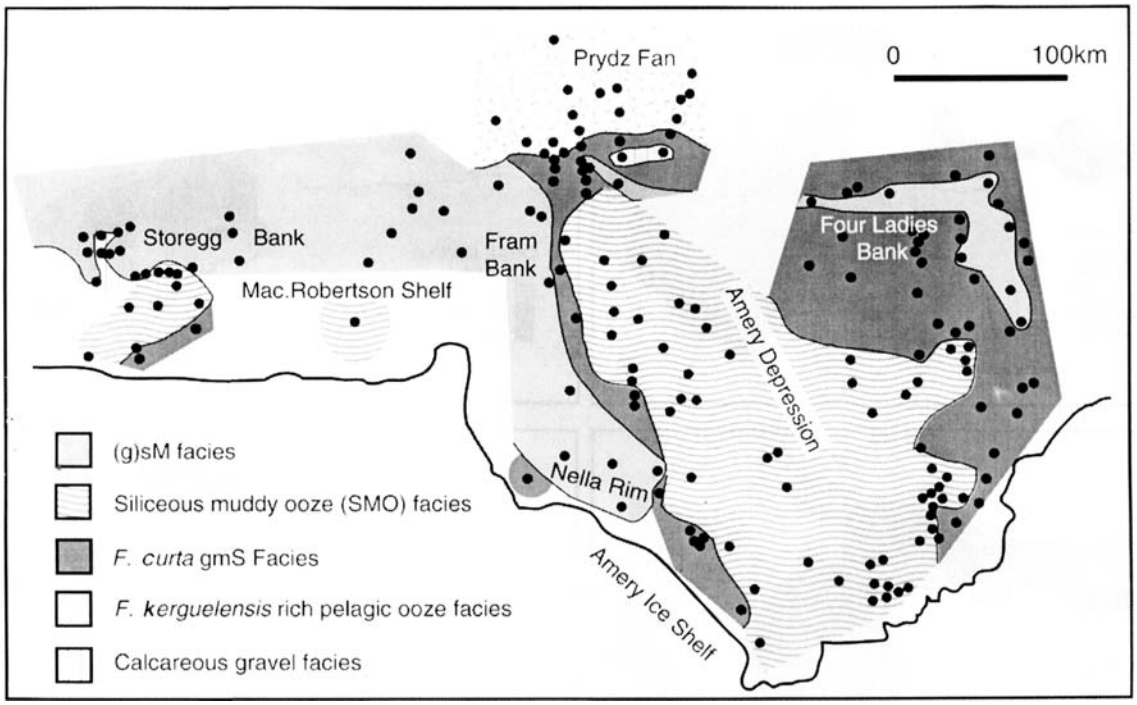

Fig. 4. Distribution of surficial sediment lithofacies as defined in the text.

correspond with the smooth, sediment-draped seafloor of central and inner Prydz Bay, and the deeper sections of the inner to middle Mac. Robertson shelf (Fig. 4). It has a comparable distribution to the "shelf" diatom assemblage of Taylor *et al.* (1997). The SMO sediments form a continuous drape over much of this shelf area, particularly thick (> 5 m) and undisturbed in deep, shelf valleys and basins, where it is protected from iceberg and current reworking. Core-top radiocarbon ages from a number of studies confirm that the SMO lithofacies is of Holocene age in inner Prydz Bay (Domack *et al.* 1991, Franklin *et al.* 1995) and on the Mac. Robertson shelf (Harris *et al.* 1996, Harris & O'Brien in press) and this age has been extrapolated to the surrounding SMO deposits. SMO may also drape what are thought to be relict iceberg plough-marks and glacial flute topography observed in sidescan sonographs (see also Domack *et al.* 1998). Hence the present surficial sediment data indicate that a distinction should be made between relict iceberg plough-marks (presumably formed during low sea level to transgressive sea level conditions during the Late Pleistocene to early Holocene) and modern ones. The former are typically SMO-draped, whilst the latter are heterogeneous, expressed in the surficial sediments by the (g)sM and *F. curta* gmS lithofacies.

The *F. curta* gmS lithofacies forms a transitional belt between the (g)sM and SMO lithofacies (Fig. 4), and is also correlated with the zone of iceberg ploughing on Four Ladies and Fram Banks. Thus its origin may be similar to that of the (g)sM facies. Its sea-ice diatom (*F. curta*) content is comparable to that of the SMO and (g)sM lithofacies and its relatively high sand content might be caused by current winnowing of fine grain sizes. The elongate area of low mud content in inner Prydz Bay (Fig. 3a) is located on the landward side of morainal bank deposits (Fig. 2) and appears to coincide with an area of seafloor that exhibits flutes and relict dunes, as seen in sidescan sonar images (the dunes are inferred to be relict because iceberg keel marks over-print the crests in several locations). Hence, these sands may be palimpsest, reworked upwards from the bedforms and into the *F. curta* gmS lithofacies.

As noted above, the *F. kerguelensis* pelagic ooze lithofacies (17 sites) occurs seaward of the continental shelf break and in the vicinity of the Prydz Fan. Texturally, it is classed as a slightly gravelly sandy mud and it is only distinguished from the (g)sM facies by the dominance of the open-ocean diatom species *F. kerguelensis*; it corresponds with Taylor *et al.* (1997) "oceanic" diatom assemblage. Cores collected from this continental slope environment contain abundant turbidites (O'Brien & Harris 1995).

The calcareous gravel lithofacies is confined to two locations: the most shallow portion of Storegg Bank, and a small area adjacent to the shelf break at the apex of the Prydz Fan. Large bedforms were described at the former location by Harris & O'Brien (1996) so it may be that strong bottom currents are a factor in the development of this lithofacies. Radiocarbon dating of calcareous tests from Fram Bank and Storegg Bank confirms that these are Holocene deposits (Rathburn & DeDeckker 1997, Harris & O'Brien in press).

Effects of sea-level change and ice shelf advance/retreat

The purpose of defining the spatial distribution of lithofacies and their environments of deposition derives from the application of Walther's Law, which allows one to infer vertical sediment facies successions. The facies model thus provides a guide for the stratigraphical interpretation of ancient sediment deposits (e.g. Walker 1992). In the present study, a number of environmental factors appear to control the present lithofacies distribution (as noted above), including:

1) the maximum water depth of iceberg turbation,
2) ocean current circulation patterns,
3) sea ice distribution, and
4) the advance and retreat of the Lambert Glacier–Amery Ice Shelf system and adjacent coastal ice sheets.

It is interesting to note that the SMO lithofacies and the *F. curta* gmS lithofacies are juxtaposed in almost all locations, except for a small area on the Mac. Robertson shelf where the SMO and (g)sM lithofacies are adjacent to one another. The *F. curta* gmS lithofacies, in turn, flanks the outer shelf banks, upon which the (g)sM and calcareous gravel lithofacies are found (Fig. 4). Hence the general order of facies succession, from deep basin to shallow banks, is from SMO to *F. curta* gmS to (g)sM and calcareous gravel lithofacies. This succession relates only to the four shelf facies and does not include the *F. kerguelensis* pelagic ooze lithofacies on the continental slope.

Based on this interpretation, it appears that the water depth and influence of iceberg turbation and ocean currents play a major role in the development of the lithofacies. This is demonstrated by the prevalence of the SMO lithofacies in all of the deep water areas of the shelf (Figs 2 & 4). It is only adjacent to the outer shelf banks and Nella Rim (western and inner Prydz Bay) that the three other shelf lithofacies become important (the *F. kerguelensis* pelagic ooze lithofacies is on the slope and hence it is below the depth of iceberg turbation). The influence of ocean currents may be reflected by sediment winnowing, removing fine particles and diatoms and leaving only coarser sand and gravel deposits. This process appears to operate on the outer shelf banks, but also along the Nella Rim and where the (g)sM and *F. curta* gmS lithofacies form a belt along the western side of Prydz Bay (Fig. 4). The origin of this belt is unclear, but perhaps the high sand and low opal content (which differentiates the (g)sM and *F. curta* gmS lithofacies from the SMO lithofacies) is caused by the input of terrigenous sediment derived from meltwater plumes, flowing north and being deflected by the clockwise-rotating Prydz Bay gyre (Nunes Vaz & Lennon 1996). A relatively high terrigenous sediment influx would dilute the biogenic opal content of the sediments.

In general terms, the combined influence of currents and iceberg turbation on the outer shelf banks explains why these areas have a high mean sand content of 82% for the *F. curta* gmS facies and 52% for the (g)sM facies, compared to only 16% for the SMO facies, located in the deeper shelf basins. In contrast, removal of small diatoms by currents and iceberg turbation on the banks results in the mean opal content being relatively lower in the *F. curta* gmS and (g)sM lithofacies (2.9% and 5.4%, respectively) as compared with the SMO lithofacies (12.0%).

We consider that the four shelf lithofacies defined here (Fig. 4) provide the basis for an Antarctic shelf facies model, which can predict variations in the facies distribution from deep (>500 m) shelf basins to shallow shelf banks. The model predicts, for example, that the result of a fall in relative sea level, an increase in the size and keel depth of icebergs and/or an increase in the intensity of ocean currents on the shelf banks is the expansion of the *F. curta* gmS and the (g)sM lithofacies at the expense of the SMO lithofacies. Conversely, a rise in relative sea-level, decrease in the size and keel depth of icebergs and/or a decrease in the intensity of ocean currents on the shelf would favour the expansion of the SMO lithofacies at the expense of the *F. curta* gmS and the (g)sM lithofacies. Since iceberg turbation might be expected to rework older deposits to a depth of several metres into the sediment pile, the preservation potential of the SMO lithofacies is not as great in the bank-marginal areas as it is in the deeper shelf basins (areas that are sheltered from any iceberg or ocean current effects). The four shelf lithofacies cover an area of approximately 100 000 km^2, and they may be representative of much of the Antarctic continental shelf.

With progradation of the continental shelf (e.g. Hambrey, 1991), the *F. kerguelensis* pelagic ooze lithofacies on the slope (foreset beds) is overlain by the other four shelf lithofacies (topsets). Shelf lithofacies are primarily deposited during interglacials because expansion of the ice shelf to the continental shelf break during glacial maxima precludes their deposition. It is important to note that it is the position of the calving line (and not the grounding line) that governs the location of the open marine/sub-ice shelf facies boundary. The facies succession beneath the floating ice shelf (between the calving line and the grounding zone) has been discussed elsewhere (Powell *et al.* 1996, Domack *et al.* (1998), Harris & O'Brien in press, Domack & Harris in press) and is beyond the scope of this paper. If, during an episode of glacial expansion, the ice sheet were to become grounded at the shelf break it would rework and probably obliterate much of the shelf lithofacies topset beds (but not the *F. kerguelensis* pelagic ooze lithofacies on the slope; Fig. 4). Interestingly, however, seismic data from outer Prydz Bay show that topset beds are indeed preserved in some sections. Cooper *et al.* (1991) described unit PS.1 as a flat-lying unit which covers most of the north-east part of the shelf, composed of Upper Miocene to Holocene diamictite and diatom ooze, and which is "apparently the topset strata for the seaward prograding reflectors of unit PS.2A". Given a similar depostional environment, such topset strata would be expected to contain the same shelf lithofacies that have been defined in the present study. The preservation of outer shelf topset beds is also consistent with the scenario of an ice sheet which is grounded only on the middle to outer Prydz Bay shelf during glacial maxima, and not at the shelf break; such a scenario is proposed by Domack *et al.* (1998) for the last glacial maximum.

Conclusions

Sample matrix (Q-mode) and cluster analysis techniques have been applied to surficial sediment data from 206 sites to define five lithofacies:

1) slightly gravelly sandy mud, (g)sM lithofacies,
2) siliceous mud and diatom ooze (SMO) lithofacies,
3) *F. kerguelensis* pelagic ooze lithofacies,
4) *F. curta* gravelly sandy mud lithofacies, and
5) calcareous gravel lithofacies.

The SMO lithofacies corresponds generally to smooth, sediment-draped seafloor whereas the (g)sM, *F. curta* gmS and calcareous gravel lithofacies correlate to iceberg ploughed geomorphic provinces. Iceberg ploughing causes mixing of surficial sediments and current winnowing processes give rise to an apparent reduction in surficial sediment opal concentration. In some cases, the occurrence of Holocene SMO sediments and iceberg plough marks overlap, implying that the plough marks are relict features. The facies succession from deep shelf basins to shallow banks implies that SMO should overlie (g)sM and *F. curta* gmS lithofacies as a result of sea level rise, decrease in ocean current intensity and/or reduction in iceberg keel depth. Given that the facies and facies successions defined here cover an area of approximately 100 000 km^2 in the Prydz Bay region, they are probably typical of the Antarctic continental shelf wherever deep (>500m) basins and shelf banks occur.

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